Combined Optimal Placement of Solar, Wind and Fuel cell Based DGs Using AHP

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Abstract: The integration of distributed generations (DGs) into grid has a great importance in improving system reliability. Many methods were proposed in the literature for finding best locations for DG placement considering various criteria. Sometime, it becomes difficult for combined placement of different kinds of renewable based DGs, such as solar, wind and fuel cell. The criterion of minimizing total system cost was used previously by many researchers for locating the optimal sites for DGs using OPF formulations. In this case, three different cost functions are formulated for different kinds of renewable energy sources (RESs). By taking combined cost function of all the RESs in the OPF to identify location for each different kind of sources becomes very cumbersome task. It would be difficult to find the exact locations for various kinds of RESs that is where to place which type of RESs. In order to solve this difficulty, three different objectives have been considered separately for determining the optimal locations for each kind of RESs using mixed integer nonlinear programming (MINLP) method. Having many alternatives with these three objectives, analytic hierarchy process (AHP) has been used to make a decision over getting the optimal locations for these different kinds of RESs. The proposed method for finding the optimal locations of solar, wind and fuel cell based DG placement has been demonstrated on 15 node distribution systems.

Keywords: *Analytic hierarchical process, Distributed generation, Mixed-integer non-linear programming, Optimal power flow, Renewable energy sources*

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1. Introduction

The electric energy requirement has been rapidly increasing day by day throughout the global, Hydro and fossil fuel plants will continue to be the chief sources of electric supply for a few years. Electric supply authorities are likely to pay more attention to improve the generation technologies. Before the innovation of large generating units, small DGs were in use to supply electricity. But, due to economy of scale large generating systems were developed and the electricity is supplied at a cheaper price. However, there has been revival of interest in connecting DG to the distribution network. DG is often used to illustrate a small-scale electricity generator which can be owned and operated generally by customer to achieve sufficient volume of energy maintain the quality and reliability in electricity supply. It can be RESs, based on wind, photo-voltaic, biomass, fuel cell or hydroelectric power. RES may be either connected to the local electric power grid or isolated from the grid in stand-alone applications. RES plays an important role in providing clean energy along side reducing carbon foot prints, and hence a crucial constituent of future developments. The penetration of DGs in the network helps in achieving voltage control, reduction of power losses and improvement of system reliability.

Optimal location for the placement of DGs with minimization of losses using gradient and second order methods is presented in [1]. In [2], a linear programming approach to determine optimal allocation of embedded generation on distribution networks is proposed. Optimal location and sizing of distributed generation in a distribution networks using Genetic Algorithm (GA) is discussed in [3]. The allocation and sizing of DGs for social welfare maximization and profit maximization using Locational marginal price (LMP) is proposed in [4]. Optimal placement of distributed generation for profit maximization, reduction of losses and improvement in voltage regulation at various load buses in the distribution network is shown in [5]. In [6], a GA based methodology for optimal DG allocation and sizing in distribution systems, in order to minimize network losses, and guarantee high level of reliability and voltage improvement was proposed. A method to allocate and determine the size of DG for minimization of the active losses of the feeders using tabu search algorithm is presented in [7]. In [8], Analytical Hierarchical Process (AHP) is used to decide the hierarchy of the planning process and members constituting the hierarchy are allowed to rate each other and relative grading of weights is discussed. AHP method is used to solve the DG planning with uncertainties and a different objective in a DG planning problem is discussed in [9]. The application of solid oxide fuel cell (SOFC) systems to generate electric power and thermal energy required for residential use is discussed in [12].

In this work, the planning of RESs has been carried out by using a hybrid method consisting of both optimization and analytic hierarchy process. Three different optimal power flow (OPF) problems have been formulated and solved using the mixed- integer non-linear programming (MINLP) method, which provides optimal bus locations for RES at various load serving nodes and ranking of each of the optimal bus location for the system. With numbers of alternative bus locations and rankings obtained from three OPF formulations, the overall priority indices have been obtained by using Expert Choice based on an analytic hierarchy process algorithm. The results of AHP clearly indicate the ranking of optimal location for various kinds of RESs. The effectiveness of the proposed approach has been tested on 15 node distribution systems [15].

2. Problem Formulation

For the planning of various kinds of RESs, three different OPF formulations have been used. The different objectives used in these formulations consider the minimization of cost of fuel cell, photo-voltaic system and wind turbine generation. With each of these objectives, the ranking of RES source locations has been obtained. Optimal placement of RES can provide both economical and operational advantages. The OPF formulations are given below.

2.1. Objective function

The three objective functions can be mathematically expressed as follows.

Case A: Minimizing fuel cell cost:

$$C_{fuel} = C_c + C_f + C_m \quad (1)$$

Case B: Minimizing solar system cost:

$$C_{solar} = C_{O\&M} * LF + (C_{CC} * FCR)/8760 * CF \quad (2)$$

Case C*: Minimizing wind energy system cost:*

$$C_{wind} = (FCR * ICC)/AEP_{net} + AOE \quad (3)$$

where $C_c = C_{fc} * (i_r(1+i_r)^n)/((1+i_r)^n - 1)$ (4)

$$C_f = (\gamma_{ng} * P_{dgi})/\eta \quad (5)$$

$$AOE = LLC + (O\,\&\,M + LRC)\,/\,AEP_{net} \qquad (6)$$

2.2. Equality Constraints

The network for the transmission of electric energy is modeled using the power balance equation at each node in the network. These include the usual load flow equations at each node and the power balance equation as given below.

$$P_{gi} - P_{di} = P_i \qquad (7)$$

$$Q_{gi} - Q_{di} = Q_i \qquad (8)$$

$$PLT = \sum_j P_{Lj} \qquad (9)$$

$$QLT = \sum_j Q_{Lj} \qquad (10)$$

2.3. Inequality Constraints

These constraints have considered the following.

Real and reactive power generation limits:

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \qquad (11)$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \qquad (12)$$

Voltage and angle limits:

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad (13)$$

$$\delta_i^{\min} \le \delta_i \le \delta_i^{\max} \qquad (14)$$

Distribution generation limits:

$$u.*P_{dg}^{\min} \le P_{dg} \le u.*P_{dg}^{\max} \qquad (15)$$

where C_{fuel} is fuel cell cost function, C_{solar} is solar system cost function, C_{wind} is wind energycost function, C_c is annual investment cost, C_{fc} is total purchasing cost, γ_{ng} is the price of natural gas, η is the electrical efficiency, C_m is maintenance cost expressed as 4–10% of the purchasing cost, P_{dgi} represent DG generated power at bus i, $C_{O\&M}$ is the operating and maintenance cost, LF represent levelizing factor, C_{CC} shows the capital cost, FCR is fixed charge rate, CF is capacity factor, ICC represents initial capital cost, AEP_{net} is net annual energy production, AOE represents annual operating expenses, LLC and LRC are land lease cost and levelized replacement cost, i_r represents annual interest rate, n represents lifespan in years, P_i and Q_i represents active and reactive power injection at bus i, P_{Lj} and PLT represent individual real line loss and total real system loss, Q_{Lj} and QLT represent individual reactive line loss and total reactive system loss, P_{gi}, Q_{gi}, P_{di} and Q_{di} are real and reactive power generation and demand respectively, P_g^{min}, P_g^{max}, Q_g^{min} and Q_g^{max} represent limits on real and reactive power generations, V_i and δ_i are the voltage magnitude and angle at the *i* th bus, V_i^{max}, V_i^{min}, δ_i^{max} and δ_i^{min} are the maximum and minimum limits on voltage magnitude and angle at bus *i*, *u* is the binary vector {0,1} that represent the absence and presence of DGs sources at a bus and P_{dg}^{max} and P_{dg}^{min} are limits of generated power from DG.

3. Analytic Hierarchy Process (AHP)

AHP is introduced by Saaty in [10]. AHP is a decision-making tool, which helps in finding goals or objectives among alternative courses of action. It is a systematic method for comparing a list of objectives and the alternative solutions satisfying respective objectives. First, pair wise comparisons are made between the objectives and, then, between alternative solutions with respect to each objective. For pair wise comparison, some weights are also assigned according to the importance, or preference of the objectives or the alternatives. A comparison of objectives/alternatives *i* and *j* utilizes a value b_{ij} , defined in Table 1.

Table 1. Relative importance, preference, or likelihood (b_{ij}).

1	Objective *i* and *j* are of equally importance
3	Objective *i* is weakly more important than *j*
5	Objective *i* is strongly more important than *j*
7	Objective *i* is very strongly more important than *j*
9	Objective *i* is extremely more important than *j*
2,4,6,8	Intermediate values

Further, if $b_{ij}=k$, then $b_{ji}=1/k$

Considering a decision-making problem to prioritize *m* alternatives with *n* objectives, the AHP algorithm has been shown in Table 2.

Table 2. Pairwise comparison matrix of objectives.

	*obj*1	*obj*2	…	*obj*n	Priority
ob_{j1}	b_{11}	b_{12}	…	b_{1n}	p_1
ob_{j2}	b_{21}	b_{22}	…	b_{2n}	p_2
.	.	.	.	.	.
.	.	.	.	.	.
ob_{jn}	b_{n1}	b_{n2}	…	b_{nn}	p_n

The relative weights of objectives can be computed as normalized geometric means of the rows (which are very close to the eigenvector corresponding to the largest eigenvalue of the matrix). The geometric means are computed as

$$h_i = \sqrt[n]{\prod_{j=1}^{n} b_{ij}} \tag{16}$$

The relative weight (priority) of the *i* th objective is obtained as

$$p_i = \frac{h_i}{\sum_{i=1}^{n} h_i} \tag{17}$$

Similarly, the pairwise comparison matrix can be defined for alternatives with respect to each objective. Therefore, with *m* alternatives for the *k*th objective, the priority of the *i*th alternative is obtained as

$$h_{ki} = \sqrt[m]{\prod_{j=1}^{m} b_{kij}} \tag{18}$$

$$p_{ki} = \frac{h_{ki}}{\sum_{i=1}^{m} h_{ki}} \tag{19}$$

The overall priority of the *m*th alternative is obtained as

$$p_m = \sum_{i=1}^{n} \sum_{k=1}^{n} p_i \, p_{km} \tag{20}$$

4. Case Study

The proposed hybrid method for RESs planning has been demonstrated and analyzed on 15 node distribution system [15]. The MINLP method has been used to obtain the optimal locations of DGs for each case separately. For ranking of optimal DG locations, all of the available DGs are taken simultaneously. In case A, which minimizes fuel cell generation cost with five numbers of DGs, the optimal locations are found at buses 13, 15, 12, 11, and 10. Reducing the maximum available source to four, buses 13, 15, 12, and 11 are found as the optimal locations. Hence, it can be concluded that bus 10 was ranked last, i.e., fifth. Again, by reducing the available sources to three, buses 13, 15, and 12 are found as the optimal locations, and, hence, bus 11 is ranked as fourth. Similarly, by reducing the available DGs, the ranking of optimal locations are obtained.

Table 3. Ranking of RESs locations based on different objective and overall locations.

Rank	Case A	Case B	Case C	Overall locations
1	13	12	15	15
2	15	11	14	13
3	12	10	13	14
4	11	9	12	12
5	10	13	11	11

Considering case B, which minimizes photo-voltaic generation cost, with five numbers of DGs, the optimal locations are found at buses 12, 11, 10, 9, and 13. While considering case C, which minimizes wind turbine generation cost, with five numbers of DGs, the optimal locations are found to be bus 15, 14, 13, 12, and 11. Table 3 shows the ranking of DG locations with different objectives (cases A, B, and C) are found and overall ranking for these three cases obtained by using the AHP. The scheme for obtaining the optimal locations of DGs is given in Figure 1. It can be observed from Table 3 that, with each objective, different rankings of optimal locations are obtained with a few common bus locations. Thereafter, as

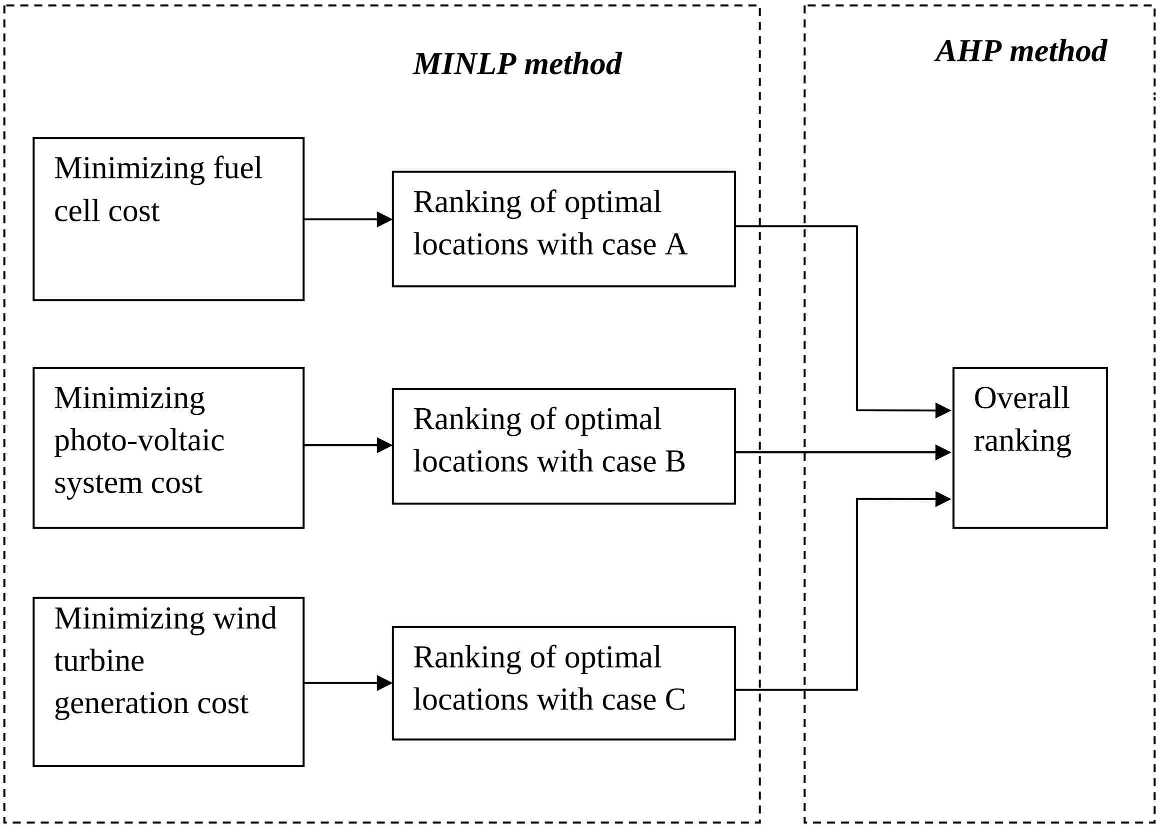

Fig. 1. Flow diagram of the hybrid method used for RESs planning.

given in the flow diagram in Figure 1, AHP algorithm is used to compute the overall ranking of optimal bus locations for RESs placement. The ratings considered for various types of RESs are 5 kW, 20 kW and 50 kW for fuel cell, photo-voltaic system and wind turbine generation system, respectively. Figure 2 shows the performance sensitivity graph with respect to criteria and goal. The objectives and alternatives are represented by the vertical and horizontal bars, respectively. The intersection of the alternative line graphs with the vertical criterion lines shows the priority of the alternative for the given objective, as read from the right axis labeled Alt%. The objective priority is represented by the height of its bar as read from the left axis labeled Obj%. The overall priority of each alternative is represented on the OVERALL line, as read from the right axis. It is observed from the graph that the suitable locations for wind, solar and fuel cell are 15, 13, 14, 12, 11, 10 and 9. The highest priority has been given to wind energy system whereas the solar system has got the lowest priority as shown in Figure 2. Finally we can conclude that wind energy system is the best for bus 15, fuel cell system is best suited for bus 13, wind energy system is best suited for bus 14 and solar energy system is best suited for bus 12, 11, 10 and bus 9, respectively.

Figure 3 shows the dynamic sensitivity of the different optimal bus locations, which indicates the priority in percentage for a particular bus. As per the Figure 3 the priority of bus 15, 14, 13, 12, 11, 10 and 9 is 28.4% (highest), 16%, 20.5%, 15.5%, 11.3%, 5.3% and 3% (lowest), respectively. Figure 4 shows the percentage of location for various types of RESs in the system. From this figure, it can be observed that 63.7% of the location is supplied by wind energy sources, 10.5% by solar energy and remaining 25.8% by fuel cell energy system.

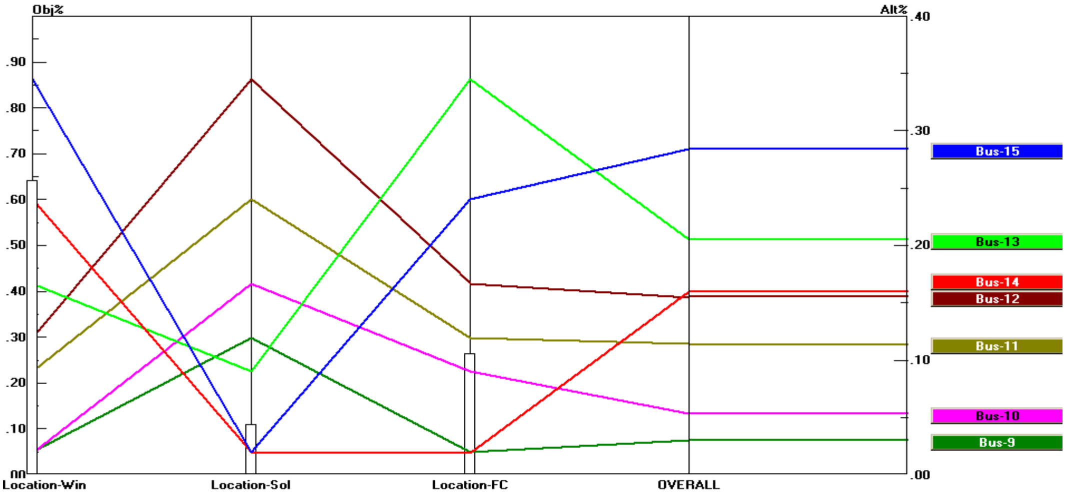

Fig. 2. Performance sensitivity graph with respect to criteria and goal.

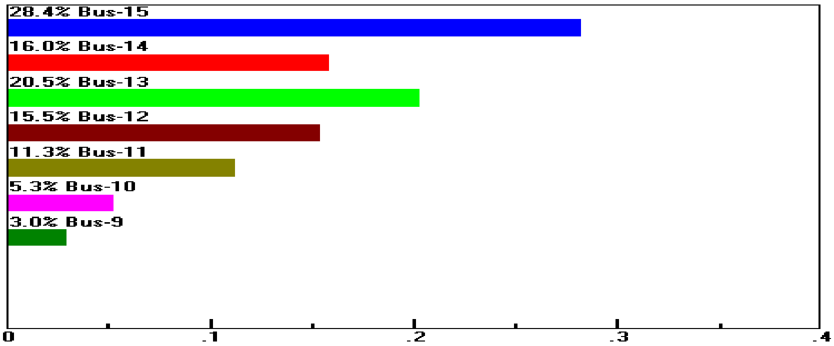

Fig. 3. Dynamic Sensitivity of the nodes.

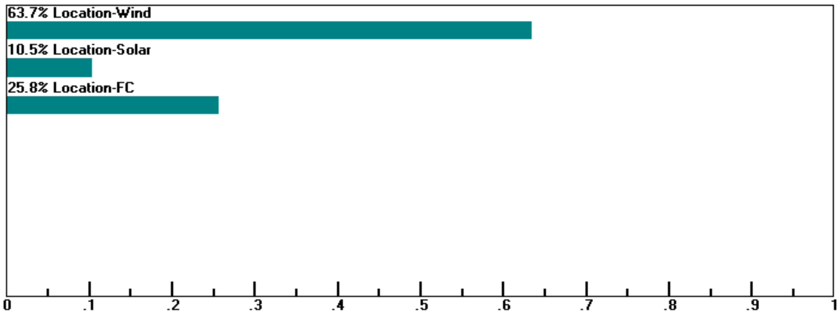

Fig.4. Distribution of RES locations based on different objective.

5. Conclusion

This paper proposes a hybrid method for DG planning taking various kinds of RESs simultaneously into account. This approach consists of two steps. In first step, the ranking of optimal locations are obtained by using MINLP method with an objective of minimizing the cost of respective RES. It has been observed that some of the optimal locations found to be same for different kinds of RESs, and which creates confusion over the placement of various types of RESs. Then, in second step AHP is used to distinguish the locations for various kinds of RESs by identifying the exact optimal location for a particular type of RES. These locations also indicate the placement and type of RESs. The results clearly indicate the overall ranking of bus locations and the type of energy sources to be placed there. In this planning work, wind, solar and fuel-cell energy has been used in the ratio of 63.7%, 10.5% and 25.8%, respectively. If this sharing of various RESs changes then, the locations for different kinds of RESs also changes.

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