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Multi-objective Optimization of the Allocation of DG Units considering technical, economical and environmental attributes

***Abstract**. A multi-objective optimization model which effectively replicates different perspectives is presented to address the optimal allocation of DG units. To offer diverse solutions, NSGA-II is applied to the nonlinear, combinatorial three-objective optimization problem. The encouraging simulation results suggest that the proposed approach not only optimally allocate DG units with benefits of reducing power loss, improving system's reliability and decreasing pollutant emissions simultaneously but also provide alternative options and facilitate to make more rational evaluations.*

***Streszczenie.** Artykule zaproponowano model optymalizacji wielo-zadaniowej na potrzeby rozmieszczenia rozproszonych generatorów energii. Dla zapewnienia różnorodności aplikacji, zastosowano algorytm NSGA-II do nieliniowej, kombinacyjnej optymalizacji trzyzadaniowej. Przedstawiono wyniki badań symulacyjnych potwierdzających skuteczność działania, ograniczenie strat mocy i redukcję emisji zanieczyszczeń. (**Optymalizacja wielozadaniowa rozmieszczenia rozproszonych generatorów energii – parametry techniczne, ekonomiczne i środowiskowe**)*

Keywords: Distributed generation (DG), Multi-objective optimization, NSGA-II, Optimal allocation
Słowa kluczowe: generacja rozproszona, optymalizacja wielo-zadaniowa, NSGA-II, optymalne rozmieszczenie

1 Introduction

Multi-objective optimization (MOO) has been extensively studied and widely applied to many real-world problems most of which are indeed multi-objective in nature. In scientific and engineering area, optimization problems that have more than one objective function are rather common. In such problems, the involved objectives are normally non-commensurable or even conflict with each other, which means that the solution to a MOO problem is not a single solution but a set of different trade-off solutions that represent the best possible compromises among the objectives [1]. In the current energy planning in particular, the optimal allocation of distributed generation (DG) units in the distribution networks represents a challenging MOO problem, which consists of technical, economical and environmental objectives.

Fuel-cells, biomass, micro-turbines, small hydroelectric and other forms of renewable energy technologies such as wind turbine generators and photovoltaic systems have been introduced as DG [2,3]. With energy and environmental challenges, DG has attracted special attention all over the world, has been playing important role in electric power systems and its estimated share will increase significantly in the near future. From social perspective, the integration of DG will play a significant role in environment improvement since most of them are environmentally friendly. While, they require capital cost. Obviously, the more capacity the more cost. From the power systems owners' perspective, for economic operation, they would prefer smaller DG investments that provide a larger reduction in losses, to the detriment of environmental benefits. DG units can be inside a customer's facilities or be installed at a predefined load point and brings benefits to the owner, but as a whole system, being allocated improperly can give rise to excessive loss and can overheat feeders, and harm system reliability. The conventional distribution systems have been constructed without considering DG's integration. Consequently, some problems emerge from its penetration and the system with penetrated DG must be kept within operational and design limits at all times to provide good-quality energy and avoid damage to the equipment. Thus, the technical impacts of DG and its negative effects on power system can limit its integration and restrict the associated economical and environmental benefits. Therefore, the optimal allocation of DG units in the distribution system is fundamental to enable the DG for making the best contribution, such as loss reduction, reliability promotion, emissions decrease with acceptable investment. With so many and conflicting objectives of interest, a multi-objective formulation with a set of technical and operating constraints can effectively replicate different perspectives of the DG units' allocation problem.

However, vast literature devoted to single-objective optimization of allocating DG units, such as power loss reduction [4,5], emissions decrease [6], maximizing penetration of DG [7,8], minimizing the total cost [9] and improving reliability [10]. While in [11-13] certain weighted multi-objective index was formulated. The commonality of such researches is that a MOO problem is converted to a weighted single-objective problem. In a sense, these methods are still single-objective optimizations and the only one best solution fails to provide the designer with alternative options. Furthermore, the weighted multi-objective index cannot accurately reflect the relationship between the various objectives, and the corresponding weights are difficult to determine due to lack of enough information about the problem. In contrast the whole Pareto front generated by MOO algorithms provides a wider range of possible solutions to choose from. The optimal allocation of DG units with the consideration of multiple objectives is a complicated non-linear constrained optimization problem with non-smooth and non-convex characteristics. MOO algorithms that can concurrently optimize a number of conflicting and competing objective functions should be employed for such MOO problems to allow for the best allocation of DG units [14,15].

The optimal allocation of DG requires appropriate model and optimization tool to ensure that the integration of DG can maximize its benefits. Many studies have been done on the problem of optimally allocating DG units in the distribution systems, while the study considering technical, economical and environmental simultaneously and providing flexibility with a variety of diverse choices has not been fully explored. This paper proposes a new MOO model including technical, economical and environmental objective functions to find optimal solutions for the locations and capacities of DG units to be installed in the current distribution system. Since technical characteristics of distribution systems and the pollutants emissions have found comparable importance with respect to the investment and operation cost, this study constructs such a MOO model subjected to technical limits (e.g. power balance constraints, voltage constraints, feeder transmission capacity constraints, etc.) and operating limits (e.g. DG penetration constraints, DG-unit size constraints).

Instead of converting the multiple objectives into a weighted single objective or treating one objective as a constraint at a time, Non-dominated Sorting Genetic Algorithm-II (NSGA-II), which can easily deal with incommensurable objective functions, is applied to the proposed MOO model to generate tradeoff solutions among these objectives with different preferences.

The effectiveness and feasibility of the proposed approach are demonstrated by determining the optimal allocation of micro-gas turbine units in IEEE 33-bus system. The simulation results reveal that the proposed approach provides a viable way to reach tradeoffs and facilitates the decision maker to make more rational alternatives. Comparison with no DG units installed has also been carried out which indicates the significant technical, economic and environmental benefits with optimally allocated DG units, such as loss reduction, emissions decrease, reliability improvement and voltage promotion, etc..

2 Multi-objective Optimization Model

The optimal allocation of DG units is referred to determine the optimal capacities of DG to be installed at appropriate locations by considering the technical, economical and environmental issues comprehensively while satisfying various complicated equality and inequality constraints. Suppose bus 1 is slack bus, and no DG unit is installed. The decision variables can be represented as $[P_{DG2}, P_{DG3}, \ldots, P_{DGNbus}]^T$. If $P_{DGi}=0$, $i=2,3\ldots N_{bus}$, it means that no DG unit is installed at bus *i*. The objectives and constraints of the MOO problem are formulated in this section.

2.1 Objective 1

Since most of the conventional electrical energies are generated from fossil fuels, power generation becomes the leading source of greenhouse gases and pollutant emissions. This has led to severe environmental problems. Recently, with such increasing concerns on air pollution and global warming and from the perspective of sustainable energy development, DG has become an important alternative of energy and has been expected to play more significant role in the global energy future. The main emissions of atmospheric pollutants discharged by fossil-fueled thermal plants are SO_2, CO and nitrogen oxides NO_x, and the main greenhouse gases is CO_2. Table I and II [16] lists emission characteristics of several electric generating technologies and the emissions' environmental values and penalty for pollution. Compared with the traditional thermal power, the emissions discharged by DG technologies are dramatically lower. Traditionally, the generation cost generally consists of construction cost and operation cost, without environmental cost. This fails to reveal the DG's environmental value and results in unbalanced development of clean and unclean energies.

The environmental cost of emissions, C_{ENV}, consists of the environmental value (environmental quality reduction and ecological destruction, etc.) of pollutant emissions and penalty for pollutant emissions [16]. Suppose several types of DG being integrated into the distribution system, then the environmental cost of emissions resulted from *M* different DG combination can be formulated as follows:

$$(1)\quad C_{ENV} = \sum_{m=1}^{M} \alpha_m E_{DG,m} \sum_{g=1}^{G} Q_{em,g,m} (V_{ENV,g} + P_{ENV,g})$$

where $E_{DG,m}$ is the total annual energy generated by *m*th DG in kWh; *G* represents types of pollutant emissions; $Q_{em,g,m}$ denotes emission quantity of *g*th gas by *m*th DG in kg/kWh; $V_{ENV,g}$ and $P_{ENV,g}$ are the environmental value and penalty for *g*th gas in ＄/kg, respectively; α_m is the fraction of the total annual energy output from the *m*th DG. Obviously,

$$(2)\quad \sum_{m=1}^{M} \alpha_m = 1$$

Table 1. Emission characteristics of several electric generating technologies (g/kWh)

Technology	SO_2	NO_x	CO_2	CO
Thermal power	6.48	2.88	623	0.1083
micro-gas turbine	0.000928	0.6188	184.0829	0.1702
Fule cell	0	<0.023	635.04	0.0544
Photovoltaic	0	0	0	0
Wind	0	0	0	0

Table 2 Environmental value standard of pollutant emission and penalty for pollutant emission (＄/kg)

Emission	SO_2	NO_x	CO_2	CO
Value	0.75	1.00	0.002875	0.125
Penalty	0.125	0.250	0.00125	0.020

In [17], the unit-cost of energy generated by a renewable (non fuel-burning) energy system is obtained by adding the capital recovery cost and operation & maintenance cost per unit of energy. Let C_f denote the fuel cost per unit of energy (for renewable DG, C_f =0). The composite cost of energy, C_{ENE}, obtained from the combination can be expressed as follows:

$$(3)\quad C_{unit,m} = \frac{r(1+r)^{T_m}}{(1+r)^{T_m}} \frac{C_{INDG,m}}{87.6 k_{DG,m}} + C_{OM,m} + C_{f,m}$$

$$(4)\quad C_{ENE} = \sum_{m=1}^{M} \alpha_m C_{unit,m} E_{DG,m}$$

where $C_{unit,m}$ indicates the unit-cost of energy generated by *m*th DG in ＄/kWh; *r* is the fixed annual interest rate in per-unit; *T* is amortization in year, C_{INDG} denotes installation (capital) cost in ＄/kW; k_{DG} is annual capacity factor in per-unit [17], C_{OM} represents operation and maintenance cost in ＄/kWh.

The generation cost and benefits should include environment indices. The first objective of the MOO model is to minimize the total cost f_{cost}, including the annual generating cost and environmental cost, which can be express as follows:

$$(5)\quad \min \quad f_{\cos t} = C_{ENE} + E_{ENV}$$

2.2 Objective 2

Power company has a loss reduction incentive and improperly allocated DG can give rise to excessive loss and can overheat feeders. Thus, power loss is a key and greatly concerned index in the problem of DG units' allocation. Therefore, the second objective is to minimize the total active power loss of the system, f_{Ploss}, expressed as follows:

$$(6)\quad \min \ f_{Ploss} = \sum_{k=1}^{N_{bra}} G_k(i,j)[U_i^2 + U_j^2 - 2U_i U_j \cos\theta_{ij}]$$

where N_{bra} is the total number of branches in the system; $G_k(i,j)$ denotes the conductance of branch *k* which connects bus *i* and bus *j*; *U* and *θ* are voltage magnitude and voltage angle, respective, $\theta_{ij} = \theta_i - \theta_j$.

2.3 Objective 3

As stated in Section I, integrating DG could harm system reliability if it is improperly placed, especially in modern society, the probability of occurrence of voltage collapse is significantly greater than before. Voltage stability index (VSI) of the system is chosen to evaluate the sensitivity to the voltage collapse in a distribution system [18]. For branch *k*, the VSI can be expressed as follows:

$$(7)\quad VSI_k = 4[(X_{ij}P_j - R_{ij}Q_j)^2 + (X_{ij}Q_j + R_{ij}P_j)^2] \big/ U_i^4$$

where: R_{ij} and X_{ij} are resistance and reactance of branch k, respevtively; P_j and Q_j denote the total active and reactive power injected to the receiving bus j of branch k.

VSI_k should be no more than 1.0 and the branch at which the value of VSI approaches 1.0 is more sensitive to the voltage collapse. Thus, the second objective function can be described as

(8) $$\min\ f_{VSI} = \max(VSI_{1,}VSI_{2,}...VSI_{Nbra})$$

2.3 Constraints

The optimal allocation of DG units is the process of optimizing locations and capacities of DG units in order to minimize the three objectives expressed by (5), (6) and (8) subject to a set of equality and inequality constraints.

Power balance constraints: power balance constraints with DG, which are equality constraints and include two nonlinear recursive power flow equations, can be formulated as follows:

(9) $$\begin{cases} P_{Gi} + P_i + P_{DG,i} - P_{L,i} = 0 \\ Q_{Gi} + Q_i + Q_{DG,i} - Q_{L,i} = 0 \end{cases}$$

where P_{Gi} and Q_{Gi} active and reactive power generated by generators at bus i, respectively; P_i, P_{DGi} and P_{Li} are active power injected into bus i, active power of installed DG and active power load at bus i, respectively; Q_i, Q_{DGi} and Q_{Li} represent reactive power, reactive power of installed DG and reactive power load at bus i, respectively. P_i and Q_i can be formulated as follows:

(10) $$\begin{cases} P_i = U_i \sum_{j=1}^{N_{bus}} U_j (G_{ij} \cos\theta_{ij} + B_{ij} c \sin\theta_{ij}) \\ Q_i = U_i \sum_{j=1}^{N_{bus}} U_j (G_{ij} \sin\theta_{ij} + B_{ij} \cos\theta_{ij}) \end{cases}$$

where N_{bus} is the total number of buses in the system; $B_k(i,j)$ is the susceptance of branch k.

Voltage operational tolerance limits: They include the lower and upper voltage magnitudes at all buses. For bus i, voltage limits can be expressed as

(11) $$U_{i\min} \le U_i \le U_{i\max}$$

Feeder transmission capacity constraints: Power flow through any distribution feeder must comply with the thermal capacity of the line, that is

(12) $$S_k \le S_{k\max}$$

where S_k represents the transmission capacity of branch k.

DG penetration capacity constraints: Limit on total power generated by DG subject to a penetration level:

(13) $$\sum_{i=2}^{N_{bus}} P_{DGi} \le \eta P_{load}$$

where P_{load} is the total power load in the system; η represents the penetration rate and its value is predefined between [0,1].

DG-unit size constraints: the total DG's capacity at bus i should be no more than P_{DGmax}, the maximum active power of DG-unit capacity to be installed at bus i.

(14) $$P_{DGi} \le P_{DG\max}$$

From equations described above, it can be seen that a wide range of technical, economical and environmental objectives are formulated and the MOO model has nonlinear equality constraints defined by power flow equations, it also has nonlinear optimization objective, minimization of the system loss. Hence, it is a non-convex optimization problem. Effective MOO algorithms should be applied to this non-convex, nonlinear, combinatorial problem.

3 Brief Introduction of NSGA-II

As stated, some heuristic technique suited to deal with non-convex combinatorial problems should be applied to the MOO problem. NSGA-II proposed by Deb et al. [19], is able to find Pareto-optimal solutions and has been demonstrated as one of the most efficient multi-objective evolutionary algorithms for MOO on a number of benchmark problems. The main advantages of NSGA-II lie in its low time complexity of *O(NlogN)* where *N* is the population size and parameterless sharing scheme. The algorithm uses the fast non-dominated sorting technique and a crowding distance to rank and select the population fronts. Then, the algorithm applies crossover and polynomial operators to combine the parent-population and its offspring generated as next generation. Finally, the best individuals in terms of non-dominance and diversity are selected as the solutions. The algorithm can be outlined as follows and its detailed implementation procedure can be found in [19].

Step 1: Initialization. Generate a random population of *N* chromosomes and sort the initialized population.

Step 2: Selection of parents based on tournament.

Step 3: Generation of offsprings with operation of crossover and mutation.

Step 4: Non-nominated sorting the combination of parents and offsprings. Rank the population and compute the crowing distance of each chromosome.

Step 5: Generation of new population according rank and crowding distance.

Step 6: If maximum iterations is met, stop and save non-non-nominated Pareto-solutions. If not, go to Step 2.

4 Case Study

IEEE 33-bus system [20], a radial feeder system as illustrated in Fig. 1, is selected as a test case. The initial active power loss is 0.2015 MW, the VSI is 0.0996 and the initial voltage magnitudes are shown in Fig. 3. In the case study, the lower and upper voltage magnitudes at all buses are 0.95p.u. and 1.0 p.u., respectively. The penetration rate is 0.5. Candidates of DG units' installation locations include bus 4, 8, 14, 18, 22, 25, 30, 32 and 33. Suppose that only micro-gas turbine is considered to be integrated, its power factor is 0.92. Environmental value standard of pollutant emission and penalty for pollutant emission refer to Section II.

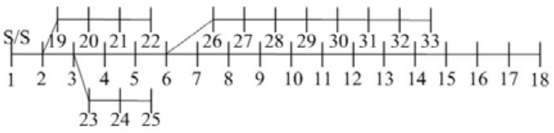

Fig. 1. Single line diagram of IEEE 33-bus system.

Fig. 2 illustrates the Pareto solutions produced by NSGA-II in the three-objective space. It shows that the proposed method can provide different solutions to meet the need of different decision-makers with different preferences. Compared with the initial power loss and VSI, the integration of DG reduces the loss and improves the VSI of the system.

To illustrate the benefits with optimally allocated DG units, five solutions are selected and their corresponding active power loss, annual pollutant emissions and VSI are compared with the originals as shown in Table III. Inspection of comparisons presented in Table III shows that the integrated DG can effectively reduce the total active loss, decrease the pollutant emissions (except CO) and improve the reliability of the system. It also indicates the benefits drastically depend on allocation of DG units in the system.

Besides, a significant beneficial impact on improvement of voltage can be verified with an acceptable allocation of DG units. Voltage magnitudes of each bus corresponding to the selected solutions are demonstrated in Fig. 3. As shown in Fig. 3, once the system is integrated with DG, the voltage of each bus is prompted. And the voltage magnitude of the bus, where DG units are installed, and those of its nearby buses are prompted significantly and the larger size the better promotion, i.e., bus 22, 25, 32.

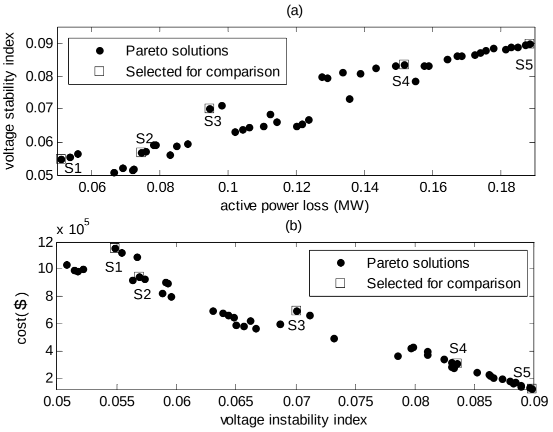

Fig.2. Pareto solutions in the three-objective space.

Table3 Selected solutions and corresponding objective-values and VSIs compared with the originals

Selected solutions		S1	S2	S3	S4	S5
Allocation information	bus 4	0	0	0	0	0
	bus 8	0.12	0.11	0.09	0.16	0
	bus 14	0.29	0.14	0	0.05	0
	bus 18	0.14	0.2	0.18	0.02	0
	bus 22	0	0.27	0.23	0.2	0.2
	bus 25	0.38	0.23	0.07	0.1	0
	bus 30	0.47	0.03	0	0.03	0
	bus 32	0.38	0.51	0.13	0.02	0
	bus 33	0.07	0	0.28	0.03	0
	Total	1.85	1.49	0.98	0.61	0.20
loss reduced by		74.69	62.65	45.76	26.54	6.42
VSI improved by		44.98	44.13	30.81	20.77	9.83
Emissions reduced by	SO_2	51.07	41.26	27.37	16.94	5.44
	NO_x	40.93	33.09	22.00	13.59	4.34
	CO_2	37.12	30.03	19.98	12.34	3.93
	CO	-23.16	-18.52	-11.95	-7.54	-2.59

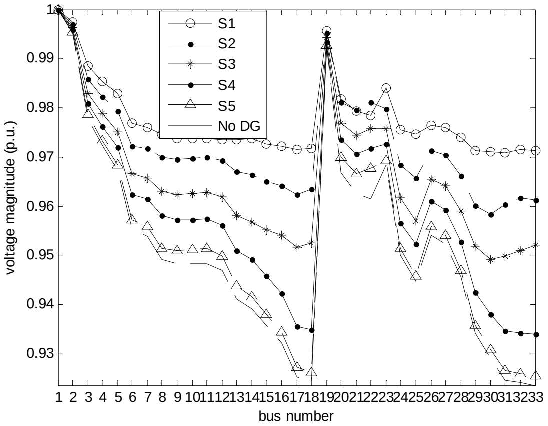

Fig.3. Voltage magnitudes of each bus corresponding to selected solutions.

5 Conclusion

In this paper, a MOO model with consideration of technical, economical and environmental attributes is presented to address the optimal allocation of DG units. The proposed model which effectively replicate different perspectives of the DG units' allocation problem, concurrently optimize the cost of DG's installation and operation as well as environmental cost, the reliability and total active power loss of the system subjected to technical and operational constraints. Instead of converting the three-objective problems into a weighted single-objective problem or treating one objective as a constraint, NSGA-II is employed to act optimizer to find the best allocation of DG units and generate a set of tradeoff solutions. According to the case study, NSGA-II has been successfully applied to MOO of DG units' allocation, producing a wider range of Pareto-optimal solutions so that the decision makers can have a more flexible and reasonable choice. The Pareto solutions also provide information on the trade-offs and correlations between objectives. The simulation results and comparisons demonstrate the economic, technical and environmental benefits with correctly allocating DG units, such as decrease in the power loss, promotion of voltage magnitudes, improvement of reliability and reduction on pollutant emissions. Since the integration reduces the power loss and compensates part of load, this decreases stress of the feeders and increases duration of lifetime of the equipment.

In summary, the approach proposed permits the MOO of DG units and provides a flexible platform in which different objectives and constraints can be considered.

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