Electrical Power and Energy Systems 73 (2015) 465–474

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Multiobjective optimization and decision-making for DG planning considering benefits between distribution company and DGs owner

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ARTICLE INFO

Article history:
Received 15 February 2014
Received in revised form 3 March 2015
Accepted 5 May 2015

Keywords:
DG
Multiobjective optimization
Planning
Decision-making

ABSTRACT

Environmental concerns and fossil fuels uncertainties have resulted in promotion of multi-source and multi-type distributed generation (DG). However, the development of DG has brought new challenges to distribution system. This paper proposes a multiobjective optimization and decision-making methodology for determining size and site of multi-source and multi-type DG in distribution networks. The proposed method is based on the combination of analytical method and multi-objective optimization method and set pair of analysis (SPA). The comprehensive analysis of the loss sensitivity factor, voltage profile and reliability gave DG candidate locations. The multi-objective optimization method is based on an already-known but suitably modified Non-Dominated Sorting Genetic Algorithm (NSGA) to solve the constructed formulations, which include maximizing benefits of DG owner and Distribution Companies (DisCo) while meeting some constraints. The objective not only includes costs for DG investment, DG operation and maintenance, purchase of power by DisCo but also involving quantization for improvement of losses, voltage, reliability, etc. SPA, which is a multi-attribute decision analysis, is applied to obtain the synthetic priority of pareto solutions and carry out rank stability analysis. Furthermore, the proposed technique is applied to 37-bus distribution network. The results show that the proposed method is fast, reliable and available to determine size and site of DG as well as balance benefits between DG owner and DisCo.

Introduction

With the strengthening of environmental protection consciousness and sustainable development, distributed generation (DG), which generally consists of various types of renewable resources and is defined as electric power generation within distribution network or on the customer side of the system, has been focus and hotspot in the research area of electrical engineering [1,2]. The integration of DG into the distribution system is one of the most important applications. However, DG access affects the power flow and voltage conditions on the system equipment. These impacts may be either positive including voltage support, loss reduction, transmission and distribution capacity release, improved utility system reliability and power quality or negative like harmonic, voltage sag, increment of fault currents and losses, which depend on the distribution system operating conditions and DG characteristics [1–4]. Therefore, the appropriate installation of DG units into an existing distribution system plays a crucial role in fully exerting DGs advantages as well as restraining disadvantages [3–5].

At the moment, there have been considerable works with respect to the allocation of DG units in the distribution system. The various approaches on DG planning in the published literatures can be listed as the analytical approaches [6–8], single or multiobjective optimization method based on the meta-heuristics approaches [9–11] and the method of combining both of them [12,13]. In the published analytical studies, the optimal size and location of DG are determined mainly by analyzing or exactly calculating the systematical total losses. These analytical studies only considered the loss improvement brought by DG, and most of them have unrealistic assumptions like uniformly, increasingly, centrally distributed load profiles, which may cause erroneous solution for the real systems.

In the optimization method, previously many efforts have been devoted to one objective formula. In order to minimize the DisCo' investment and operating costs as well as payment toward loss compensation [12], presented a model of DG capacity investment to obtain DG size and site that meets the peak demand forecast.

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http://dx.doi.org/10.1016/j.ijepes.2015.05.019

In [14], objective function was established by minimizing the sum of feeder investments, DG investments, energy loss cost and the additional cost of DG for peak cutting. A model for use in the problem of multistage planning of energy distribution systems including DG was presented in [15].With the advent of electricity market and the development of artificial intelligence optimization techniques, the multiobjective optimization models become recently more and more attractive. In [6], the problem is formulated with two distinct objective functions, namely, social welfare maximization and profit maximization. Ref. [11] proposed four objectives formulation including cost of network upgrading, cost of power losses, cost of energy not supplied, and cost of energy required by the served customers to permit the planner to decide the best compromise for the siting and sizing of DG resources into existing distribution networks. Considering the technical impacts of DG on distribution networks, [16] presented a multiobjective performance index for distribution networks with DG such as reliability, power quality, and loss. A multi-objective model of DG planning with the consideration of investment costs, benefits and tradeoffs associated with DG in terms of connection, losses and network deferral, was proposed in [17]. From the perspective of profits brought from DG [13], introduced three technical indexes (i.e. voltage bettered index, power loss bettered index and environment bettered index) into the multiobjective formulations for maximizing DG benefits under certain constraints.

As far as having published documents are concerned, most have the common characteristics such as only *PQ* constant type of DG is considered, the optimization models are constructed from perspective of the unilateral (Either DisCo managing the existing distribution network or Independent Power Supplier (IPS) owning DG), the multiobjective optimization give the pareto solution set which need to be determined by the planning and construction workers. However, not only there have been a number of DG technologies available in the market today, but also there will be more and more investors to participate in investing DG with the decline of DG technology cost and the gradual improvements of regulations. It must be an inevitable trend for multi-type and multi-resource to access the grid. Therefore, the coordination of interests between different investors is a fundamental and urgent work. In addition, the consumers will put forward higher request for power quality due to the advent of the fierce competitive electricity market. In order to continue to keep a leading role in the market competition, DisCo has to give a commitment of continuous and reliable power supply for customers, which is directly related with benefits for DisCo. All of these bring about many new challenges for DG planning.

Provided that DisCo has to permit DG access by a certain proportion due to country's policy, this paper presents a multiobjective optimization and decision-making methodology for determining the type, location and sizing of multi-source and multi-type in medium voltage power distribution networks. The candidate locations of DG were given by calculating active power loss incremental factor, analyzing the systematical voltage change and reliability requirements. Two objective functions were introduced to maximize the benefits for both DG owner (that is IPS) and DisCo. The multi-objective optimization method is based on an already-known but suitably modified NSGA to realize simultaneous optimization of DG type, location and sizing. Additionally, the set pair analysis is introduced to carry out multiobjective decision-making analysis direct to the multiple solutions for multiobjective optimization results.

The rest of the paper is organized as follows: The next section describes the method of determining DG candidate locations set. A widely used loss sensitivity factor method is presented in this section. Section 'Multiobjective formulation' gives introductions of two objective formulations subjected to some constraints. The proposed optimization model allows maximizing the DG cost benefit ratio while maximizing benefits from improving grid not only including costs for DG investment, DG operation and maintenance, purchase of power by the distribution company but also involving the quantization for improvement of distribution system such as power losses, voltage quality, reliability, and environment. In section 'Optimization algorithm and decision-making analysis', a novel and fast multi-objective optimization technique and decision-making analysis methodology are proposed to determine type, location and size of DG in distribution network. Section 'Nu merical example' portrays the test distribution systems used in the paper. Numerical results along with some observations and discussions are also included in this section. Finally, the major contributions and conclusions of the paper are summarized in Section 'Conclusion'.

Determination of DG candidate locations set

Loss, voltage profile and reliability impacts of DG on the distribution network have been studied in plenty of previous literatures. The important conclusions that can be drawn from the published literatures are that appropriate size and location of DG connected with distribution system can decrease losses, improve voltage and enhance the reliability, but the situation in their best improvement is not uniform (i.e. the installation scheme of DG size and location in which losses reduction may be the optimal is not necessarily the best alternative in which voltage improvement can arrive at the optimal).

This paper determines DG candidate locations set by calculating the sensitivity factor of real power loss with respect to real power injection from DG, studying the change of voltage profile employing base case load flow and analyzing the reliability impacts of DG on distribution network, and etc.

DG candidate locations based on loss sensitivity factor

Loss sensitivity factor method has been widely used to solve the capacitor allocation problem [18]. Its application in DG allocation is new in the field and has been reported in [8,19]. Considering with the size, complexity and specific characteristics of distribution networks, this study employed the loss sensitivity factor proposed in [8] to determine candidate locations of DG. The sensitivity factor of the total power loss with respect to the *i*th bus injected real power (α_i) in [8] is given by

$$\alpha_i = \frac{\partial P_L}{\partial P_i} = 2[\mathbf{R}]^T \left[\mathbf{M} \cdot Re(\mathbf{I}) \cdot \frac{\cos(\theta_i)}{|V_i|} + \mathbf{M} \cdot Im(\mathbf{I}) \cdot \frac{\sin(\theta_i)}{|V_i|} \right] \quad (1)$$

where θ_i is the angle of *i*th node voltage. V_i is the ith node voltage. $Re(\mathbf{I})$ and $Im(\mathbf{I})$ denote real and imaginary parts of equivalent load current vector **I**, respectively. **R** is the branch resistance vector is given in (2). **M** is a matrix related with the bus-injection to branch-current (*BIBC*) matrix, and its construction algorithms can be found in [8].

$$[\mathbf{R}]_{n\times 1} = [R_1, R_2, \ldots, R_n]^T \quad (2)$$

Sensitivity factors are evaluated at each bus, firstly using the values obtained from the base case power flow. The buses are ranked in descending order of the values of their sensitivity factors to form a priority list. The top-ranked buses in the priority list are the alternatives locations which have effective obviously on the reduction of system losses.

DG candidate locations based on voltage profile

Voltage profile change is one of DG influences on the distribution networks. Just as the same impacts of power loss, the voltage may be enhanced or decreased which is related to the location, size and type of DG. The important conclusions from the published literatures are that the voltage profiles are enhanced when it happens following scenarios

- *PQ* types of DG, whose active and reactive power are constant, access the buses expect the slack bus in distribution system when DG injects reactive power to the grid instead of absorbing reactive power from the grid.
- *PU* types of DG, whose active power and voltage are constant, connect to the buses in distribution system where the voltage magnitude is lower than that of DG.

Therefore, integrating with DG type, the bus of lower voltage magnitude is taken as DG alternatives locations according to base load flow. The buses are ranked in descending order of voltage magnitude. The low-ranked buses in the priority list are the alternatives locations.

DG candidate locations based on power supply reliability

Power supply reliability is the primary concern for utilities. Currently, many documents have reported DG influences on systematical reliability. Calculation results show that the interconnection of some controllable DG to the distribution network can greatly improve the power supply reliability of the distribution network, but other uncontrollable DG like wind power access to the distributed power distribution system may enhance or deteriorate affect the reliability of the system due to their random fluctuations. For the controllable DG, a conclusion from [20,21] is that DG only affects the reliability of some buses in DG island. Therefore, this paper selects the buses, at which the requirements for the reliability is higher, as the DG candidate locations and only studies *PU* and *PQ* types of DG which injects reactive power to the grid.

Determination method of DG candidate locations set

DG access not only concerns the connected bus, but also has a deep influence upon nearby buses, which requires that DG layout should not be excessive concentration. And restricted by the geographical position and local natural resources, DG installation locations are limited. Besides, it is still associated with the penetration of DG permitted by DisCo as well as profits of DG owner. Therefore, the maximum number of DG installation location is used to represent the allowable ceiling, which is given by the Parties through mutual negotiations. Here DG candidate locations set is proposed to determine one DG installation location when carrying out multiobjective optimization, which is conducive to DG distribution uniformity on the line as well as to avoid effectively excessive concentration of DG layout. DG candidate locations set can be obtained by partitioning method according to the topological structure of distribution system and the maximum number of DG installation location. The method of determining DG candidate locations set include three steps.

Step 1: to obtain DG candidate locations based on the sensitivity factor of real power loss, voltage profile and the reliability requirements. DG candidate locations include such buses as the top half of sensitivity factor, the low half of voltage magnitude and all the high reliability.

Step 2: to partition distribution network into *k* area, which is the maximum number of DG installation location. Partitioning method is to carry on the load calculation starting from the end of line according to depth-first search strategy. For one area, its sum of bus load is approximately equal to the value of the total load divided by *k*. Fig. 1 shows the schematic of partitioning distribution network. When the maximum number of DG installation location is equal to two, area A1 and A2 are shown in Fig. 1.

Step 3: to form DG candidate locations sets by combining candidate locations in view of partitioning area. One candidate location set, which is corresponding to one area, is formed by abandon and combination of having selected alternative locations. The principle of abandon and combination is issued mainly on as following:

- To abandon the candidate locations which are not located in installation locations area.
- To reserve all the candidate locations based on power supply reliability for the sake of security.
- To keep back the candidate locations which come from loss sensitivity factor and voltage profile.

Based on this method, all the candidate location set is given according to the number of DG installation locations. Let take Fig. 1 as an example to explain the formation of candidate location set. Assuming that candidate locations from loss sensitivity factor are [10 9 15 14 6 7 13 12], candidate locations from voltage profile are [10 9 15 6 5 13 12 8], candidate locations for higher reliability requirements are [11,7], then for A1, abandon [15] due to absence of in A1, reserve [7] based on power supply reliability, reserve [10,9,6] because they is included in candidate locations from both loss sensitivity factor and voltage profile. One candidate location set corresponding to A1 is [10 9 7 6].Then, when performing multiobjective optimization, only one location from A1 is selected as possible installation location. That is, if 9 is chosen, 10, 7, 6 must be not optional.

Multiobjective formulation

Due to the environmental concerns and fuel cost uncertainties associated with the use of conventional energy sources, the attention has been directed toward implementing DG units in distribution systems. Moreover, with decrease of DG cost and perfection of the laws and regulations, investment in DG is a very attractive option for various crowds such as the consumer, DisCo, Independent Power Suppliers (IPS), etc. From the view of IPS owning DG, the problem of this paper is to find a Pareto front for the siting and sizing of DG in the existing distribution networks attached to DisCo. The multiobjective functions are given with two distinct objective functions in Eq. (3), namely, DG cost benefit ratio of IPS (B_{IPS}) maximization and profits for DisCo (B_{DisCo}) maximization so as to obtain compromise benefits between DisCo and IPS. The detailed description of each objective function is as follows:

$$\max J = \max[B_{IPS}, B_{DisCo}] \tag{3}$$

DGs cost benefit ratio of IPS

DGs cost benefit ratio of IPS is the ratio of annual benefits to annual cost of investing in DG. The benefits include the earnings obtained from selling electricity and the policy subsidies from the governments due to the employment of renewable energy or improvement of environment. The cost includes investment cost, fixed operation and maintenance cost, variable energy generation cost. All future costs and benefits are discounted to the present time (with a discount rate *r*) to yield a net present value. The objective function is the following by

$$B_{IPS} = \frac{B_{ANN}}{C_{INV}} \tag{4}$$

$$B_{ANN} = 8760\sum_{i=1}^{N}(\rho_{DGi} + \rho_{APi})P_i^{rate}CF_i \tag{5}$$

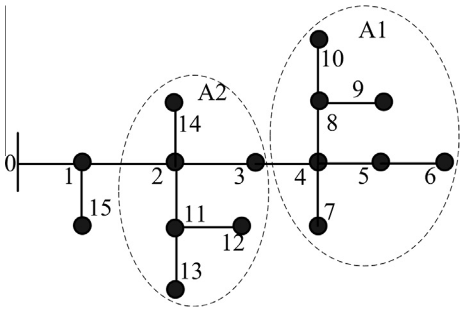

Fig. 1. Schematic of DG installation locations area.

$$C_{INV} = \sum_{i=1}^{N} \alpha_{DGi} * P_i^{rated} * C_i^{fixed} + 8760 \sum_{i=1}^{N} C_i^{op} * P_i^{rated} * CF_i \tag{6}$$

where B_{ANN} is the average annual yield of IPS investment in DG. C_{INV} is the annual investment cost. N is the number of installation DG. ρ_{Dgi} is the power price of the ith DG that DG IPS sells energy to the DisCo (yuan/kW h). ρ_{APi} is the subsidies of the ith DG granted for policy considerations (yuan/kW h). P_i^{rate} is the rated installed capacity from the ith DG. CF_i is the capacity factor for the ith DG. α_{DGi} is the annually present value factor of the ith DG. C_i^{fixed} and C_i^{op} are respectively the annually fixed investment cost (yuan/MVA) and the hourly operation and maintenance cost (yuan /MVA) for the ith DG.

Profits for DisCo

For the profits of DisCo, the analysis considers two main policy scenarios of DisCo as described below.

- The DisCo is contracted to buy a fixed amount of power from the transmission grid through bilateral contract with fixed price
- The DisCo buys the power from the IPS investing in renewable DG without any requirement in accordance with certain proportion of the policy limit.

Therefore, the model is the sum of the economic, environmental and technical benefits brought by DG access to the distribution networks. It can specifically reflect not only the systematical real power loss reduction, voltage profile improvement, environment change, network upgrading deferral, reliability enhanced, but also the difference of payment from the central transmission grid and IPS. The detailed expression is shown by following

$$B_{DisCo} = \Delta B_{Ploss} + \Delta B_{Impu} + \Delta B_{\text{Reli}} + \Delta B_{Upda} + \Delta B_{Envi} + \Delta B_{Sub} \tag{7}$$

where B_{DisCo} is the average annual yield of DisCo due to DG access to the distribution network. ΔB_{Ploss}, ΔB_{Impu}, ΔB_{Reli}, ΔB_{Upda} and ΔB_{Envi} are orderly the annual benefits for real power losses reduction, voltage quality enhance, change of energy not supplied, and deferral of network upgrading and environmental protection. ΔB_{Sub} is the annual benefits due to the energy price difference between the transmission grid and IPS.

Annual benefits for power losses reduction

The real power losses reduction is the difference of real power losses between with DG and without DG. The annual benefits for real power losses reduction is calculated by

$$\Delta B_{Ploss} = \rho_{GP} \Delta P_{loss} \tau_{\max} \tag{8}$$

where ρ_{GP} is the price of purchasing energy from the main grid (yuan/kW h). ΔP_{loss} is the power loss difference between with DG and without DG under the condition of peak load. $\tau_{\max}$ is the maximum load's loss hours, which means the equivalent hours that is the ratio of the annual electricity loss to power losses under the condition of peak load [22].

Annual benefits for voltage quality enhance

The advent of power market reform has result in the fact that management of distribution system separated from that of transmission system. In order to improve the competitiveness and vitality, DisCo will have to give a promise that they provide their customers with a reliable and continue electricity supply. While the importance of maintaining a voltage level constant and close to a nominal value are based on both the quality of power supply and economical and technical factors such as avoiding increases in losses, overheating of conductors, and malfunction of equipment, which are directly related with the profits for DisCo. Consequently, DisCo reinforces their power systems in order to have better control over voltage variations [23]. Here the compensation for users obtained by the statistical approach and the prolonging for life of equipment estimated by empirical approach are considered as quantitative indicators on voltage quality. The annual benefits for voltage quality enhance is as follow.

$$\Delta B_{Impu} = \sum_{j \in \Phi} (\lambda_{wj} - \lambda_{woj}) B_{jmu} \tag{9}$$

$$\lambda_j = \begin{cases} 1 & V_j^{rated}(1-\alpha) \leqslant V_j \leqslant V_j^{rated}(1+\alpha) \\ 0 & \text{others} \end{cases} \tag{10}$$

where the λ is a binary variables. The subscript *woi*, *wi* are without and with DG, respectively. B_{jmu} is the annual earnings from prolonging for the service life of equipment, reducing compensations for users, etc. due to the systematical voltage enhance. Φ is the load node set required having higher requirements for voltage quality. α *is* the significance level. V_j and V_j^{rated} are the real voltage magnitude and the nominal voltage at the ith load node.

Annual benefits for change of energy not supplied

DG can lead to significant reliability improvements of loads in the islanded network under condition that automatic sectionalizing switches and reclosers can restrict the area of influence of a fault during the fault phase [20,21]. In other words, DG access can offset part cost incurred when there is unserved power in the distribution system. Here the cost of the energy not supplied is used to measure the economic losses incurred by power customers during the period of power interruption or electric load constraint. And annual benefits for change of energy not supplied are employed to quantity reliability improvement. The following Eqs. (10) and (11) is adopted.

$$\Delta B_{\text{Reli}} = \rho_{uc} * (EENS_{woi} - EENS_{wi}) \tag{11}$$

$$EENS = \sum_{i=1}^{n} (\lambda_i * T_i * P_i) \tag{12}$$

where *EENS* is the Expected Energy not Supplied. ρ_{uc} is the cost of the energy not supplied. It can be estimated by statistics of customers' outage costs in accordance with the terms of the contract or DisCo's economic losses due to decline in sales for electricity. λ_i is the load fault rate (number of faults per year). n *is* the number of nodes in the isolated island. T_i is the average durations of the fault (hour per time). P_i is the load value in the isolated island. The method and equations for λ_i and T_i can be found in [20,21].

Annual benefits for deferral of network upgrading

As a consequence of placing DG in a system, branch currents may diminish in some sections of the network, thus releasing more capacity, but in other sections they may also increase to levels beyond distribution line limits. In order to give the information of DG influence on line capacity, here annual benefits for deferral of network upgrading are employed to find the difference between system with and without DG. And benefits for deferral of network upgrading are quantified by reconstruction, residual, management costs.

$$\Delta B_{Upda} = \sqrt{3}C_{mar}U_{av}\sum_{i=1}^{N_b}(|I_{wi} - I_{woi}|) \quad (13)$$

where C_{mar} is annual investment costs for lines renovation (yuan/kW h). It can be estimated by computing previous line transformation cost and capacity amplification value. N_b is the number of branches in the network. U_{av} is the average nominal voltage. I_{wi} and I_{woi} are the branch currents in distribution system with and without DG, respectively.

Annual benefits from environmental change

In this century, environmental issues have reached a point that ignoring them is not an option. Since electricity production has a real impact on air emissions like CO_2, SO_2, CO, and NO_x, environmental impact should be important part of the DG planning problem. The emission function can be presented as the sum of all types of emissions considered with suitable pricing or weighting on each pollutant emitted [13]. In present study, only emission CO_2 is taken into account because the amount of other emission is direct proportion to that of CO_2 emission. The environmental improvement was investigated in annual benefits from environmental change in (13)

$$\Delta B_{Evin} = (E_{woi} - E_{wi})C_{Envi}\beta \quad (14)$$

where E_{woi} is the annual electricity from main grid without DG (kW h). E_{wi} is the annual electricity from main grid with DG (kW h). β is the amount of CO_2 emission per unit electricity (kg/kW h). C_{Envi} is CO_2 emission tax rate (yuan/kg).

Annual benefits due to the energy price difference

Apparently, the cost of renewable DG is currently higher than that of traditional energy, which will reduce the revenue of DisCo. But in order to achieve sustainable development of energy industry, the government will adopt preferential policies to guide some important support the development of the renewable energy such as providing policy-oriented compensations, improving bounty and penalty from environmental management. Therefore,

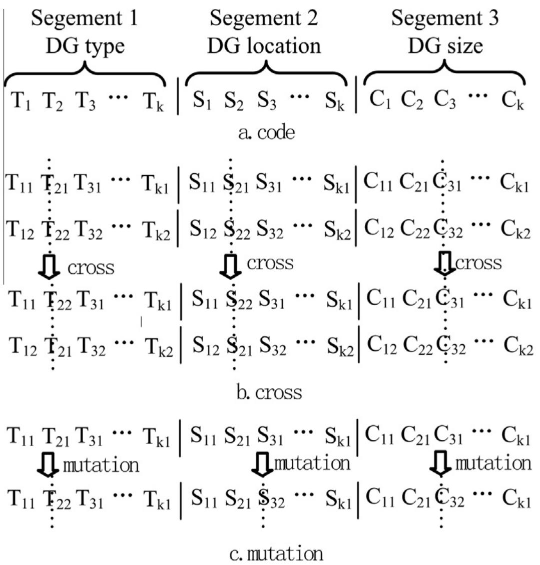

Fig. 2. The segmented chromosome management of GA.

this paper assumes DisCo buys the power from the renewable DG without any requirement in accordance with certain proportion of the policy limit. And simultaneously, the market price fluctuations are not taken into account for the sake of simplicity although it does exist in a competitive market environment. Eq.(15) is adopted to calculate annual benefits due to the energy price difference between the main grid and DG.

$$\Delta B_{Sub} = \rho_{GP}(E_{woi} - E_{wi}) - 8760\sum_{i=1}^{N}\rho_{DGi}P_i^{rate}CF_i \quad (15)$$

The constraints

The optimization problem is subject to various operating constraints to satisfy the electrical requirements for the distribution network, DG operation, etc. These constraints are discussed as follows.

Power balance constraint

The total power generated must supply the total load demand and the transmission losses

$$P_{sub} + \sum_{i=1}^{N}P_{DGi} = P_{Loss} + P_{Load} \quad (16)$$

where P_{sub} is the power from the transmission grid. P_{DG} is the power of the DG connected to the distribution system. P_{Loss} is the transmission losses. P_{Load} is the total load demand.

Maximum and minimum limits of nodal voltage

The nodal operation voltage is constrained between its minimum and maximum limits.

$$V_i^{\min} \leqslant V_i \leqslant V_i^{\max}, i \in \Omega \quad (17)$$

Distribution line capacity limits

Power flow through any distribution feeder must comply with the thermal capacity of the line

$$S_{ij} \leqslant S_{ij}^{\max} \quad (18)$$

where S_{ij}, S_{ij}^{max} are respectively the real line capacity and the maximum line capacity.

Maximum number of DG installation location

The maximum number of DG installation location is defined as the ceiling of allowable DG connected location. As described in the previous sections, besides the geographical position and local natural resources, DG installation location is still associated with the penetration of DG permitted by DisCo as well as profits of DG owner. Therefore, here it is given by the Parties through mutual negotiations.

$$N_{DG} \leqslant N_{DG}^{\max} \quad (19)$$

where N_{DG}, N_{DG}^{max} are respectively the real number and the maximum number of DG installation location

Maximum penetration of DG units in the system

The maximum penetration limit is calculated based on the total load demand in distribution system

$$\sum_{i\in\Omega_g}P_{DGi} \leqslant k\% * \sum_{i\in\Omega_L}P_{Li} \quad (20)$$

where Ω_g is the nodal set of DG. $k\%$ is the maximum penetration limit as a percentage of the peak load. Ω_L is the nodal set of load in distribution network.

Optimization algorithm and decision-making analysis

The optimization problem is constrained, nonlinear, with mixed integer variables (due to the discrete size of DG units), and its computation is fairly complicated thanks to the multiobjective and power flow problem. In this section, an already-known but suitably modified NSGA [24] is used for finding the noninferior solutions of the multiobjective optimization algorithm and a multiobjective decision-making based on the set pair analysis [25,26] is proposed to obtain the synthetic priority of pareto solutions and the stable interval of the entire sequence program.

The modified method based on NSGA

Compared with NSGA approach, the proposed modified method based on NSGA mainly refers to Genetic Algorithm (GA) implementation. That is, genetic code and genetic operators are achieved by the segmented chromosome management, as shown in Fig. 2, whose purpose is to improve the GA's local searching capacity, accelerate the convergence rate and effectively prevent the premature convergence.

Population code

In line with characteristic of DG planning involving type, size and siting of DG, the first important aspect of a correct GA implementation is the coding of the potential solution. That is, each solution is coded by using three segments, which orderly represent DG type, DG location and DG size. Each segment is a vector, whose size is equal to maximum number of installation DG units, in which each element is represented by means of decimal encoding. In addition, it is noted that, in the segment of DG size, the nonzero values is for the size of DG unit while 0 is for no presence of DG unit.

Select strategy

In order to ensure convergence towards the Pareto-optimal set as well as to achieve a covering of the whole range of the non-dominated solutions, a hybrid selection strategy containing elitist-preserving approach and dual tournament selection is employed in the algorithm. Elitism strategy is to copy a small proportion of the fittest candidates, unchanged, into the next generation to guarantee fast convergence and combat problems of losing optimal solutions. Dual tournament selection is the simplest tournament selection involving randomly picking individuals from the population and staging to a tournament to determine which one gets selected. Here not only it can be implemented efficiently, but also it is amenable to reaching a covering of the whole range of the non-dominated solutions.

Cross and mutation

Cross and mutation are used to produce the next generation. Integrating with the characteristic of chromosomes coding, the method of segmented point cross and mutation, which mean that type, location and size of one father chromosome is corresponding to that of another father for cross and mutation (as shown in Fig. 2), are put forward to achieve chromosomes evolution and searching. At the same time, the new produced chromosomes must satisfy all kinds of constraint.

The multiobjective decision-making based on SPA

Pareto solutions for multi-objective optimization planning can provide some referential or optional schedules for both of parties from which the decision-makers can choose a most suitable one according to the certain situation or through consultations and dialogs. However, considering with diversity of Pareto solution, it is hard to find a mutually satisfying and convincing solution out of numerous schemes. Furthermore, because the distribution network planning with DG is affected by many random and uncertain factors, the scheme from multi-objective function deviates from the real case. Therefore, the integrated decision-making method

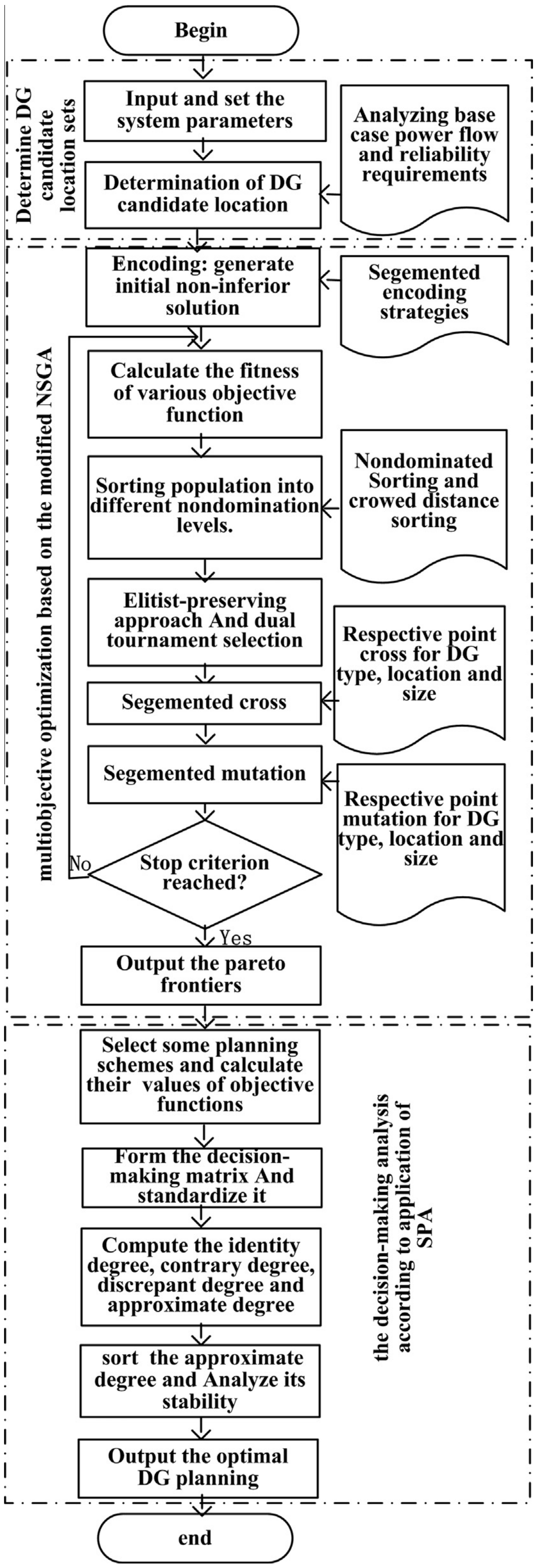

Fig. 3. The flowchart of DG optimization and decision-making.

based on SPA is proposed to make the synthetic priority of pareto solutions and show the influence of uncertainty on schemes.

SPA and its application in multiobjective decision-making

The set pair analysis (SPA) theory, proposed by Zhao Keqin, is a identical-discrepant-contrary (IDC) decision analysis method, which has been successfully applied in engineering application and decision support system. The core of this decision theory is to make a comprehensive decision by combining certainties decision with uncertainty decision. It involves three aspects such as identical degree, discrepant degree and contrary degree when analyzing decision objects. Identical degree is to consider harmony and identity between two decision objects, while discrepant degree is to solve mutual contradictory and opposite. And contrary degree is to investigate both interrelations and constraints between decision objects. Zhao Keqin applied connection degree to represent them. Assume that A and B are Sets. Then $\{A,B\}$ is a Set Pair H. The connection degree of H is shown in Eq. (21) [26,27].

$$\mu = a + bi + cj, \quad a + b + c = 1 \tag{21}$$

where μ is the connection degree. a, b, c, respectively, represents identical degree, discrepant degree and contrary degree. As coefficient of discrepant degree, i is between -1 and 1, i.e. $i \in [-1, 1]$, which depends on the situation. j is coefficient of contrary degree and is specified as -1. More information of i and j and Computing can be find in [25,26].

According to the ideas of Set Pair Analysis (SPA) and characteristics of multiobjective decision-making problems, SPA in this paper is applied to sequence pareto solutions and its stability analysis. In the course of reasoning, indexes as identical degree, contrary degree, discrepant degree, approximate degree are taken into account. The approximate degree γ is expressed as Eq. (22):

$$\gamma = \frac{a}{a + c} \tag{22}$$

The procedure of multiobjective decision-making based on SPA

Integrated with the specific circumstances of pareto solutions, the procedure of multiobjective decision-making based on SPA is as follow:

Step 1: select DG planning programs in pareto solutions from the multiobjective optimization, and calculate corresponding income value of various objective functions.

Step 2: form the decision-making matrix, where row number represents the number of multiobjective and column denotes down the number of pareto solutions. The element in matrix represents the value of multiobjective corresponding to planning scheme. Then standardize it by Linear Projection Method (LPM), whose mathematical model is shown in Eq. (23)

$$y_{kr} = d_k x_{kr} + e_{kr} \tag{23}$$

where k, r are the numbers of multiobjective and pareto solutions. d, e are constants to be determined. The positive index, which is the larger the value the better the scheme, employ Eqs. (23) and (24) to determine d, e. On the contrary, the negative index, which is the smaller the value the better the scheme, employ Eqs. (23) and (25) to determine d, e [27].

$$y_k = \begin{cases} 1 & x_k = 2\max\{x_r\} \\ 0 & x_k = \frac{1}{2}\min\{x_r\} \end{cases} \tag{24}$$

$$y_k = \begin{cases} 1 & x_k = \frac{1}{2}\min\{x_r\} \\ 0 & x_k = 2\max\{x_r\} \end{cases} \tag{25}$$

Step 3: obtain the best and the worst solution from the standardized decision-making matrix and compute the identity degree, contrary degree, discrepant degree and the approximate degree by Eqs. (26)–(29).

$$a_r = \frac{1}{n}\sum_{k=1}^{n} \frac{h_{kr}}{u_k + v_k} \tag{26}$$

$$b_r = \frac{1}{n}\sum_{k=1}^{n} \frac{(u_k - h_{kr})(h_{kr} - v_k)}{(u_k + v_k)h_{kr}} \tag{27}$$

$$c_r = \frac{1}{n}\sum_{k=1}^{n} \frac{u_k v_k}{(u_k + v_k)h_{kr}} \tag{28}$$

$$\gamma_r = \frac{a_r}{a_r + c_r} \tag{29}$$

where u, v is the optimal and the worst solution. n is the total of pareto solutions. h is the income value to be evaluated programs.

Step 4: get the priority level of planning programs based on approximate degree and its stability analysis. The sort principle is that the larger approximate degree is the better planning program. The stability analysis is to analyze the uncertainty impact through the small change of coefficient of the discrepant degree i. While maintaining original sort, the interval of coefficient i is determined by Eqs. (30) and (31) [28].

$$\begin{cases} i \in [0, 1] & c_q b_p - c_p b_q \leqslant 0 \\ 0 \leqslant i \leqslant \min\left\{\frac{c_p a_q - c_q a_p}{c_q b_p - c_p b_q}, 1\right\} & c_q b_p - c_p b_q > 0 \end{cases} \tag{30}$$

$$\begin{cases} i \in [-1, 0) & c_q b_p - c_p b_q \geqslant 0 \\ \max\left\{-1, \frac{c_p a_q - c_q a_p}{a_q b_p - a_p b_q}\right\} \leqslant \Delta i < 0 & c_q b_p - c_p b_q < 0 \end{cases} \tag{31}$$

where p, q is the number of planning scheme, and their approximate degrees satisfy with $\gamma_p < \gamma_k$. The stable interval of the entire sequence program refers to the intersection for the results given by pairwise comparisons analysis.

The framework for DG optimization and decision-making

The proposed approach for DG siting and sizing include three stages such as determination of DG candidate location sets, multi-objective optimization based on the modified NSGA and decision-making analysis according to application of SPA. The flowchart of this approach is shown in Fig. 3.

Numerical example

Test system and simulation parameters

To demonstrate the performance of the proposed method, simulation is carried out on the 37-bus system. Its topological structure is shown in Fig. 4 and the branch, load parameters are be founded in [9].

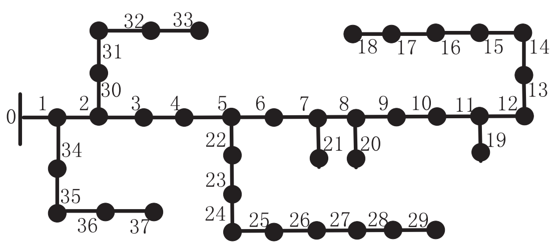

Fig. 4. The topological structure for 37-bus system.

Table 1
Parameters for the alternative DG.

DG Code	DG Type	Size for unit DG (kW)	Investment cost (wan yuan/kW)	O&M cost (yuan/kWh)	Emission cost (wanyuan/kg)	Capacity factor	Discount coefficient	Policy subsidies (yuan/kW h)	The price of energy (yuan/kW h)	Failure rate of DG (time/year)	Average interruption duration of DG (h/time)
T1	PQ	100	1.3	0.032	0	0.35	0.1006	0.25	0.55	5	50
T2	PV	44	4.56	0.013	0	0.29	0.0843	0.25	0.65	2	25
T3	PQ	200	1.82	0.320	0.2	1.0	0.1006	0	0.52	1	10
T4	PQ	60	0.98	0.195	0.3	1.0	0.1006	0	0.52	1	10

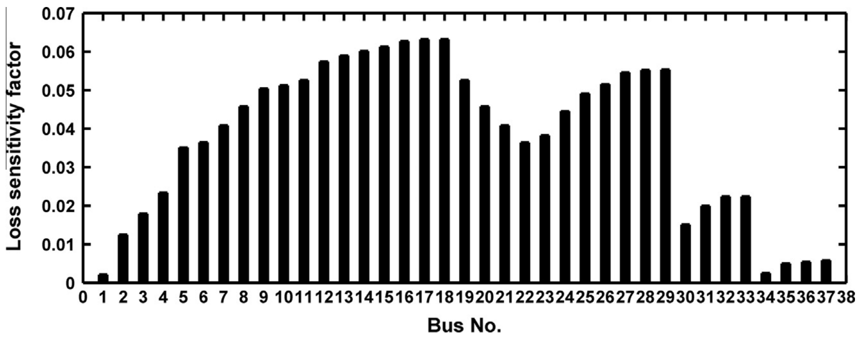

Fig. 5. The loss sensitivity factor at various nodes for 37 bus distribution test system.

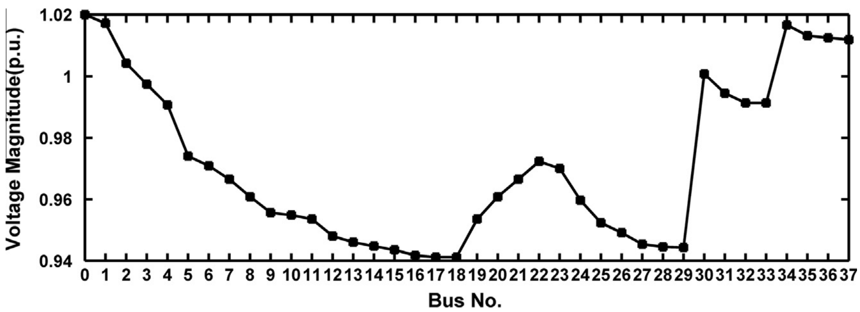

Fig. 6. The voltage magnitude at various nodes for 37 bus distribution test system.

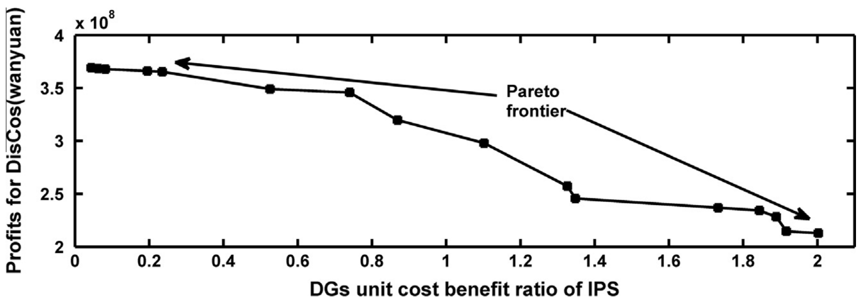

Fig. 7. Distribution of Pareto-optimal solutions for multiobjectives.

The main GA parameters in our tests are: 0.9 for select rate; 0.9 for crossover rate; 0.05 for mutation rate; 100 for chromosome numbers; 30 for max genetic generation. The maximum penetration limit of DG is 15% of total load demand in distribution network. There are four kinds of DG to be considered as alternative DG, while the maximum number of DG installation location is four. For PQ DG, power factor is 0.9. For PV DG, the voltage magnitude is 1.0(p.u.). Other parameters of DG are listed in Table 1.

Furthermore, the employed method of power flow calculation is the improved back/forward sweep method proposed in [29]. And we assume that voltage base is 10 kV, power base is 10MVA and convergence accuracy is 10^{-4}. Maximum and minimum limits of the nodal operation voltage are positive and negative 7% of the nominal voltage, respectively. The fault rate on distribution feeder is 0.05 time per kilometer per year, and average interruption duration for each time is 5 h. For DisCo, the fixed price of buying power from the transmission grid is 0.35 (yuan/kW h) while that of buying from power from IPS is 0.57 (yuan/kW h). The unit cost on CO_2 emission (C_{Envi}) is 1000 yuan. The annual earnings B_{jmu} due to the voltage improvement is 5000 yuan, the significance level α is 0.05. Conversely, a 5000 yuan fine is implemented when the voltage decline.

Table 2
The objective function values for trade-off Pareto-front solutions.

No.	DG type	DG access nodes	DG capacity (kVA)	DGs cost benefit ratio of IPS	Profits for DisCo (wanyuan/yr)
1	T1	28	200	2.002	21281.01
2	T1, T1	27, 8	100, 100	1.916	21468.79
3	T1, T1	27,11	100, 200	1.888	22827.62
4	T1, T1, T1	29, 9, 6	100, 200, 100	1.843	23432.89
5	T1, T1	15, 7	100, 100	1.732	23687.75
6	T1, T2	10,6	200,44	1.347	24552.23
7	T2, T1	29, 6	44, 200	1.326	25723.97
8	T2, T1	16,10	44, 100	1.101	29797.13
9	T1, T4	26,11	100, 60	0.868	31967.92
10	T1, T2, T4	26,11,7	100, 44,60	0.739	34875.25
11	T2	17	44	0.525	34909.73
12	T1, T3	8, 6	100, 200	0.235	36530.85
13	T4, T3, T1	26,9, 6	60, 200,100	0.194	36607.44
14	T3, T2	15, 7	200,44	0.082	36784.02
15	T2, T4, T3,T4	16, 27, 10,20	44, 60, 200,60	0.061	36829.36
16	T3, T2, T3	15,26,8	200,44, 200	0.043	36910.43

Results and discussion

To demonstrate the model and the proposed optimization algorithm, the simulation is carried on Matlab 2008rb. The Figs. 5 and 6 show the loss sensitivity factor and the voltage magnitude at various nodes for 37 bus distribution test system, respectively.

Here, the larger halves of the loss sensitivity factor are chosen as DG candidate locations. The bus number is [18 17 16 15 29 28 14 13 27 12 26 25 11 10 9 24]. Conversely, the lower halves of the voltage amplitude are selected for DG candidate locations. The bus number is [18 17 16 15 14 13 12 29 28 27 11 19 26 10 9 25 10 8 20]. Furthermore, DG candidate locations for higher reliability requirements are [6 7 23 20]. Therefore, [18 17 16 15 14 13 12; 29 28 27 26 25; 11 10 9 8 20; 21 23 6 7] is considered as the final DG candidate location sets by combining the adjacent nodes according to the maximal DG installation number.

The Fig. 7 presents the Pareto-frontier when genetic operation reaches twenty times. And some objective function values for trade-off Pareto-front solutions are listed in Table 2.

According to the objective function values for trade-off Pareto-front solutions shown in Table 2, the standardized decision-making matrix obtained from Pareto-optimal solutions is shown as following

$$\mathbf{M}^T = \begin{bmatrix} 0.0054 & 0.4157 \\ 0.0100 & 0.4145 \\ 0.0151 & 0.4137 \\ 0.0434 & 0.4109 \\ 0.0535 & 0.4097 \\ 0.1263 & 0.3841 \\ 0.1802 & 0.3788 \\ 0.2126 & 0.3375 \\ 0.2711 & 0.3032 \\ 0.3274 & 0.2387 \\ 0.3329 & 0.2201 \\ 0.4293 & 0.2065 \\ 0.4573 & 0.2024 \\ 0.4686 & 0.1928 \\ 0.4755 & 0.1713 \\ 0.4972 & 0.1684 \end{bmatrix}$$

The optimal solution set U and the worst set V are obtained by the decision matrix. That is, $U = [0.4972, 0.4157]$; $V = [0.0054, 0.1684]$. According to Eqs. (26)–(29), the identity degree, contrary degree, discrepant degree and the approximate degree for different schemes are shown in Table 3. By analyzing table 4, the programmatic prioritization is 16, 15 14, 2, 1, 6, 13, 3, 5, 7, 12, 4, 8, 11, 9, 10. The intervals of the coefficients keeping the sort stability are $[-0.59,1]$, $[-0.626,1]$, $[-1,0.695]$, $[-1,0.344]$, $[-0.12,1]$, $[-0.036,1]$, $[-1,0.057]$, $[0.244,1]$, $[-0.016,1]$, $[-0.006,1]$, $[-1,0.016]$, $[-0.451,1]$, $[0.015,1]$, $[-1,0.154]$, $[-1,1]$, $[-1,1]$. So the stable interval of the entire program is $[-0.006, 0.016]$.

By analyzing comprehensive simulations results, some conclusions are listed as following:

- The change in types, locations and sizing of DG, two objective function values also change. Generally speaking, the solution of increasing one objective function values will decrease another objective. It is difficult that two objective function values simultaneously arrive at the optimal at one solution.
- The application of DG candidate location set can give the suitable candidate, which reduce greatly the size of search space of GA and improve the performance of algorithm.
- The proposed modified NSGA can solve efficiently constrained, nonlinear multiobjective optimization problem. And the solution approach presented here is simple, fast, reliable and efficient.

The multiattribute decision-making analysis method here based on SPA can implemented sorting of pareto solutions. The application of SPA can touch on the uncertainties and the stability analysis of programmatic prioritization can determine the interval of the coefficient i maintaining original sort.

Table 3
The identity degree, contrary degree, discrepant degree and the approximate degree for different schemes.

Scheme	Identity degree(a_k)	Contrary degree(b_k)	Discrepant degree(c_k)	Approximate degree(γ_k)
1	0.639	0.000	0.361	0.639
2	0.620	0.025	0.355	0.635
3	0.631	0.052	0.316	0.666
4	0.628	0.070	0.302	0.675
5	0.604	0.100	0.297	0.671
6	0.520	0.200	0.280	0.650
7	0.530	0.211	0.259	0.671
8	0.529	0.263	0.208	0.718
9	0.500	0.309	0.190	0.724
10	0.504	0.323	0.173	0.744
11	0.454	0.368	0.178	0.719
12	0.404	0.399	0.197	0.672
13	0.395	0.397	0.208	0.655
14	0.369	0.306	0.325	0.532
15	0.365	0.220	0.415	0.468
16	0.361	0.000	0.639	0.361

Conclusion

This study presents a multiobjective optimization and decision-making analysis method which can be used to determine the siting and sizing of multi-source and multi-type DG when considering with the benefits for both DG owner and DisCo. The proposed optimizing decision-making processes included determination of DG candidate location set, multiobjective optimization and decision-making analysis for Pareto. The application of DG candidate location set can give the suitable search space of GA which yields significant savings in computation. The constructed multiobjective formulations reflect and take care of the benefit of different groups. And the proposed decision-making analysis method based on SPA provides decision-support for different interest groups. The simulations demonstrated the proposed methodology is simple, faster and more robust. And it is more suitable for allocation of multi-sources and multi-types DG in a given distribution networks as well as available to balance of benefits between DGs owner and (DisCo).

Acknowledgements

This work was supported in part by National Natural Science Foundation of China (NSFC) (No. 51377162), Hebei Science Research and Development Project of China (No. 13215206) and Hebei Natural Science Foundation of China (No. F2015204090).

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