OPTIMAL PLANNING OF DISTRIBUTION SYSTEM CONSIDERING DISTRIBUTED GENERATORS

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ABSTRACT

This paper presents a methodology for substation optimal planning considering DG for peak shaving. Utility can take effective demand-side management (DSM) to encourage customer-owned DG to participate in peak load shaving, and it can also construct utility DG to meet the peak load demand. In this paper, the impact of DG on peak load shaving is analyzed, and DG is taken as a complement to T&D system to meet load demand, which is considered in the substation planning. Substations sizing and location and new-built utility DG capacity is optimized using Particle Swarm Optimization (PSO), in which supply area of each substation is obtained by Voronoi diagram method. Case study shows that planning result considering DG for peak shaving can defer T&D system expansion so that considerable investment can be saved. Especially for those areas with high cost of T&D system construction, constructing DG to meet peak load demand would be a more economic way.

INTRODUCTION

Nowadays the need for saving fossil energy and minimizing carbon dioxide emission have been providing the impetus for the integration of distributed generators (DG) into distribution system, which has led to a great impact on the characteristics of the network. One of the impacts that should be paid attention to is the potential of DG to shave peak load. DG can be devided into two categories by ownership: utility DG owned by electric service companies that is used for peak load shaving or emergency power support, and customer-owned DG with a potential to participate in peak shaving. It has been proved that if utility DG are dispatched effectively or demand side management (DSM) is carried out to encourage customers to participate in peak load shaving (e.g. raise the DG electricity paying price at peak load), the peak-valley difference of the power system can be decreased [1,2].

DG provides a new way for meeting the increasing load demand. If this peak shaving effect of DG could be considered in the system planning stage, T&D system construction can be deferred in some extent so that investment can be saved [3].

Taking DG as a complement to T&D system, a new methodology for substation optimal planning considering DG's peak shaving effect is proposed in this paper. This is a multi-objective and nonlinear optimization problem. Particle Swarm Optimization (PSO), one of the most widely-used intelligent methods for optimization, is used to solve the optimization of substations and utility DG, in which the supply area of each substation is obtained by Voronoi diagram method. Case study shows that investment of planning schemes provided by the proposed methodology can be decreased in contrast with conventional method.

LOAD FORECASTING CONSIDERING DG FOR PEAK SHAVING

In conventional methods, substations are planned according to the peak load forecasting result during the planning target years. While in distribution system with DG, if DG is considered for peak shaving, substation can be planned according to a load level lower than the original peak load [4].

The capacity of DG that can be regarded to shave peak load should be considered in the worst condition. Intermittent DG like photovoltaic and wind turbines should not be considered in the planning stage due to their unstable output. While DG with stable output like fuel cell, micro-turbine, diesel generator, etc, can be counted as having the peak shaving capability. Considering that not all the customers may respond to DSM, a factor called *DSM respond factor,* f_R, is proposed to indicate the degree of DG participating in peak shaving in respond to DSM, which is defined as the ratio of total capacity of DG that can join in peak shaving and the total capacity of DG with stable output.

Then L_{peak}', the system peak load considering DG in the planning area can be determined by:

$$L_{peak}' = L_{peak} - f_R \cdot P_{DG}^{C,stb} - P_{DG}^{U} \quad (1)$$

where L_{peak} represents system peak load without considering DG, $P_{DG}^{C,stb}$ represents the total capacity of customer-owned DG with stable output; P_{DG}^{U} is the total capacity of utility DG for peak shaving.

OPTIMAL SUBSTATION PLANNING MODEL CONSIDERING DG

The problem of substation optimal planning considering DG for peak shaving studied in this paper can be described as: given the load level and capacity of customer-owned DG in the planning target years, taking the total cost minimization as the objective, determine the capability, location and supply area of new-built substations, and the capacity of utility DG and within supply area of which substation they should be built.

The total annual cost, the minimization of which is taken as the objective of the model, includes the annual capital cost and operation cost of the new-built substations and utility DG, and the annual capital cost of lines. The objective function can be written as:

$$\begin{aligned}\min F = &\sum_{i=1}^{n}\left(f_{sub}\left(S_i\right)\cdot r_{CFR} + u_{sub}\left(S_i\right)\right)+ \\ &\sum_{i=1}^{m}\left(f_{DG}\left(P_i\right)\cdot r_{CFR} + u_{DG}\left(P_i\right)\right)+ \\ &c_{line}\cdot r_{CFR}\left(r, N_a\right)\cdot \sum_{i=1}^{n}\sum_{j\in J_i} l_{ij}\end{aligned} \quad (2)$$

where F represents the total annual cost; n and m represents the number of new-built substations and utility DG; $f_{\text{sub}}(\cdot)$ and $u_{\text{sub}}(\cdot)$ is the annual capital cost and operation cost of substation; S_i and P_i is the capacity of the i^{th} substation and DG, respectively; c_{line} is the annual capital cost of unit length of line; l_{ij} is the length of the j^{th} line in the supply area of the i^{th} substation; J_i is the set of components within the supply area of the i^{th} substation; $r_{\text{CFR}}(r,N_a)$ is the Capital Recovery Factor, a ratio used to calculate the present value of an annuity for a payback period of Na years at the interest rate r [8].

The aforementioned objective function should be subject to the following constraints:

(1) Substation load rate constraint

$$\eta\cdot\sum_{j\in J_i} L_{j,\max} - f_R\cdot\sum_{k\in J_i} P_{DG,k}^{C,stb} - \sum_{l\in J_i} P_{DG,l}^{U} \le S_i\cdot\cos\phi\cdot\gamma\left(n_i\right) \quad (3)$$

where η is the load coincident factor; $L_{j,\max}$ is the maximum load at the j^{th} load point; $P_{DG,k}{}^{C,stb}$ and $P_{DG,l}{}^{U}$ represents the output of the k^{th} customer-owned DG with stable output and the output of the l^{th} utility DG at time of peak load, respectively; $\cos\Phi$ is the power factor of the substation; $\gamma_{\max}(\cdot)$ is the maximum allowable load rate of transformers.

(2) DG capacity constraint

$$\sum_{k\in J_i} P_{DG,k}^{C} + \sum_{l\in J_i} P_{DG,l}^{U} \le k\cdot\eta\cdot\sum_{j\in J_i} L_{j,\max} \quad (4)$$

where $P_{DG,k}{}^{C}$ is the capacity of the k^{th} customer DG within the supply area of the i^{th} substation, including stable DG and unstable DG, i.e. all DG should be counted; k is the maximum allowable ratio between total DG capacity and peak load within the substation supply area. In order to ensure that DG connection will not cause system shortcut circuit and power quality exceeds limits, most DG connection related standards give clauses providing allowable DG penetration level.

(3) Power supply distance constraint

$$\max_{j\in J_i} l_{ij} \le R_{\lim} \quad (5)$$

where $\max l_{ij}$ is the maximum power supply distance of the i^{th} substation; R_{lim} is the maximum allowable power supply radius.

(4) Transformer capacity constraint

$$s_i \in Z_A \quad (6)$$

where s_i is the capacity of transformers; Z_A is the capacity set of available transformers.

SUBSTATION SUPPLY AREA DIVISION BASED ON VORONOI DIAGRAM

Voronoi diagram was first proposed by Russian mathematician G. Voronoi in 1908. Now it has been widely used in many research areas correlated with geometry information, especially in areas of spatial analysis and facility geographic site selection [5, 6].

Suppose a set of planar base points $P = \{p_1, p_2, \cdots, p_n\}$, $3\le n\le\infty$, then the Voronoi polygon of base point p_i can be defined as:

$$\begin{aligned}V\left(p_i\right) = \{&x\in V\left(p_i\right) \mid d\left(x, p_i\right)\le d\left(x, p_j\right), \\ &j = 1, 2, \cdots, n; j\ne i\}\end{aligned} \quad (7)$$

Polygon $V(p_i)$ is also called the V polygon. V polygons of all the base points comprise the Voronoi diagram. Each base point corresponds to a unique V polygon. The distance from base point p_i to any point with in its V polygon is shorter than the distance from any other base point p_j ($j\ne i$) to points within the V polygon of p_i.

There is an analogy between Voronoi diagram and substation supply area division [7]. The general idea of using Voronoi diagram to divide supply area of substations is that to draw Voronoi diagram taking the substation sites as base points, then the edges of V polygons corresponds to the supply area boundaries of substations, as shown in Fig.2. It can be ensured by using Voronoi diagram that the distance from a substation to any load point within its supply area is shorter than the distance from any other substations to load points of this substation, so that lines investment can be minimized [8].

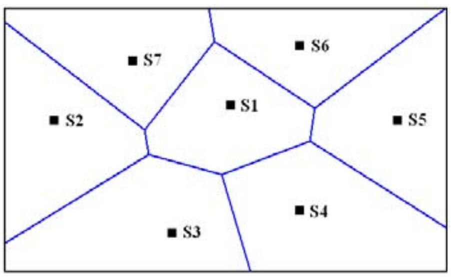

Fig.2. Supply area division based on Voronoi diagram

SOLUTION ALGORITHM BASED ON PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is used in this paper to solve the problem of optimal substation planning considering DG. Reference [9] gives an introduction to PSO in detail, which is not repeated in this paper.

The basic steps of the solution algorithm based on PSO proposed in this paper are shown in the following flow chart.

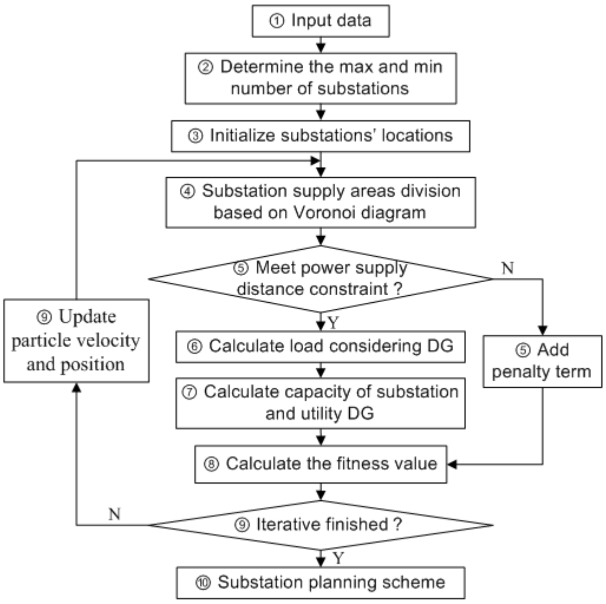

Fig.3 Solution algorithm based on PSO

In Step 2, the range of substations number should be determined to narrow the searching range, which can be calculated by:

$$n_{\min} = \text{int}\left(\frac{L_{peak} - k \cdot L_{peak}}{S_{\max}\cos\phi \cdot \gamma_{\max}}\right)$$
$$n_{\max} = \text{int}\left(\frac{L_{peak}}{S_{\min}\cos\phi \cdot \gamma_{\min}}\right) \quad (8)$$

where $n_{\max}$ and $n_{\min}$ is the upper and lower limit of substation number; int(•) is the rounding function; $S_{\max}$ and $S_{\min}$ represents the maximum and minimum capacity in the available transformer set, respectively; $\gamma_{\max}$ and $\gamma_{\min}$ are the corresponding load rate.

In Step 5, if supply area division of substations is not feasible for the power supply distance constraint, a new fitness function with penalty term is constructed, which can let particles going off the constraint automatically eliminated. The constructed fitness function can be written as follows:

$$\min fitness = F + \sigma\sum_{i}^{N_{sub}} \max\left[0, \left(\max_{j\in J_i} l_{ij} - R_{\lim}\right)\right]^2 \quad (9)$$

where F is the objective function of the problem described in Equation (2); σ is the penalty factor.

In Step 6 and Step 7, calculate the peak load in planning target years within each substation supply area according to the supply area division, and then calculate the capacity of each transformer and utility DG according to Constraint (1), (2) and (4).

CASE STUDY

The aforementioned optimization methodology is implemented in Matlab and is applied to an example of a new-built region to illustrate the application of the model and the verification of the proposed methodology.

System Data

The future load of the 27.3km^2 planning area consists of resident load, commercial load and small scale industry load, which can be divided into 56 units. The forecasted peak load is 685MW. The available transformer capacity is 31.5MVA, 40MVA and 50MVA. The allowable maximum load rate of 3-transformer substation is 65%. The maximum allowable power supply radius of 10kV is 3km.

The total capacity of customer-owned DG with stable output is 20MW. DSM respond factor f_R is 0.8. Available utility DG to be constructed is diesel generator, the investment cost of which is 247 $/kW and the operation & maintenance cost is 0.75 $/kW per year. The project year N_a is 30 years and the interest rate r is set at 8%.

Results and Analysis

Optimization using the methodology proposed in this paper is performed in two scenarios, one considering DG for peak shaving, and the other not considering DG. In the former scenario, 9 substations are planned to be built with a total capacity of 1029MVA, and 21.6MW utility diesel DG is planned to be built to meet the load demand. While in the latter scenario without considering DG, 10 substations are planned to be built with a total capacity of 1119MVA. The sitting and supply area division of substations in the two scenarios are shown in Fig. 2 and Fig.3. Table 1 shows the detail configuration of substations and utility DG. And comparison of total annual cost in the two scenarios is shown in Table 2.

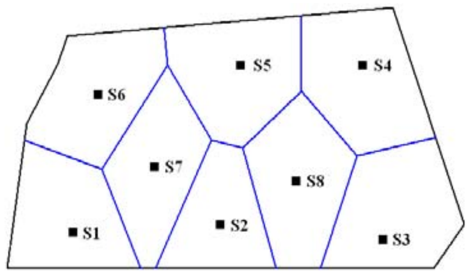

Fig.2 Substation planning result considering DG

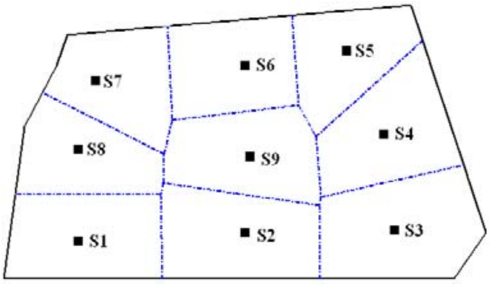

Fig.3 Substation planning result without considering DG

Table.1 Configuration of substations and utility DG

TS	Load (MW)	DG^C (MW)	DG^U (MW)	TS capacity (MVA)	Load rate
Scenario 1: considering DG					
S1	77.6	0	0	3×40	64.7%
S2	94.7	0	0	3×50	63.1%
S3	71.6	3.2	7	3×31.5	65.0%
S4	75	0	0	3×40	62.5%
S5	92.4	3	0	3×50	59.6%
S6	99.5	4.8	0	3×50	63.1%
S7	72.3	5	5.9	3×31.5	65.0%
S8	101.9	0	4.4	3×50	65.0%
Scenario 2: not considering DG					
S1	76.1	--	--	3×40	63.4%
S2	70.3	--	--	3×40	58.6%
S3	60.8	--	--	3×31.5	64.3%
S4	88.5	--	--	3×50	59.0%
S5	85.4	--	--	3×50	56.9%
S6	75.0	--	--	3×40	62.5%
S7	58.6	--	--	3×31.5	62.0%
S8	94.0	--	--	3×50	62.7%
S9	76.3	--	--	3×40	63.6%

Note: DG^C and DG^U represent customer-owned DG and utility DG, respectively; TS represents transformer substation.

Table.2 Total annual cost of planning result

	Scenario 1: considering DG	Scenario 2: not considering DG
TS capital cost and operation cost ($)	2,903k	3,372k
Line capital cost ($)	1,485k	1,427k
DG^U capital cost and operation cost ($)	310k	0
Total annual cost ($)	4698k	4801k

Comparing with the planning result without considering DG, result considering DG for peak shaving has made an increase of $59k annual line capital cost and $332k annual cost on new-built utility DG, however the annual capital cost and operation cost of substation has reduced $469k due to the cut down of 1 substation, so that the total annual cost can save $103k.

CONCLUSION

A new methodology for substation optimal planning considering DG for peak shaving has been proposed in this paper. The impact of customer-owned DG with stable output that can participate in peak load shaving under DSM has been considered, and utility DG has been taken as a complement to T&D system to meet load demand, and this has been considered in substation planning in this paper. Optimization of substations and utility DG has been implemented using PSO, in which the supply area of each substation is divided by Voronoi diagram method ensuring minimum line investment based on given substation locations. Case study shows that planning result considering DG's peak shaving effect can put off T&D system to postpone so that considerable investment can be saved. Especially for those areas with high cost of constructing new substations, constructing DG to meet the load demand would be a more economic way.

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