PLANNING OF DISTRIBUTED GENERATION IN DISTRIBUTION NETWORK  
CONSIDERING MARGINAL CAPACITY COST

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ABSTRACT
Distribution generation (DG) in distribution network will bring about sunk cost due to lower utilization efficiency of existing power supply equipment, which is not paid enough attention. In this paper, a DG planning method considering marginal distribution capacity cost (MDCC) is proposed in order to improve utilization efficiency of supply capacity and promote optimal allocation of power resources. Influence of DG as reinforcement alternative on MDCC is considered, and the calculation method of MDCC is proposed to reflect the charges and utilization efficiency of nodal capacity. On this basis, heuristic algorithm to lower MDCC is used to determine the site and capacity of DG. Furthermore, influence of DG on network loss and short circuit current are also considered. Finally, the results of an actual case about a 35/10kV distribution system show the rightness and validity of the proposed method.

INTRODUCTION
Distributed Generation (DG) is now paid more and more attention for its merits such as economy, flexibility, energy saving and environmental protection. The planning models of DG and their solution methods have been proposed in some published literatures [1]~[4], but the sunk cost brought about by DG is seldom concerned. Recent research mainly concentrates on maximization of economic benefit and optimization of the location and capacity of DG. How to improve utilization efficiency of supply capacity and promote optimal allocation of power resources are seldom discussed.

Long-run incremental cost (LRIC) based on unused capacity is proposed in reference [5]. The proposed approach produces forward-looking charges that reflect both the extent of the network needed to service the generation or load, and the degree to which the network is utilized. On the basis of LRIC theory, the calculation method of MDCC considering the influence of DG as reinforcement is proposed in this paper.

This paper is organized as follows: Section 2 describes the mathematical formulation of the proposed MDCC calculation method. Section 3 proposes the planning method of DG considering MDCC. Section 4 gives an actual case to validate the proposed method. The paper’s conclusions are drawn in the last section.

MDCC OF DISTRIBUTION SYSTEM

INCREMENTAL COST
Fig.1 is a sample of radial distribution system. If a network node \( i \) supports a power load \( L_i \) and its supplying branch has a capacity \( C_i \). Then the number of years it takes to grow from \( L_i \) to \( C_i \) for a given load growth rate \( d_i \) can be determined from (1)

\[
T_i = \frac{CL_i}{d_i^i} + \frac{\Delta C_i}{d_i^i} \tag{1}
\]

where \( d_i \) is the load growth rate.

Fig.1 A sample of radial distribution system

\[
C_i = L_i(1 + d_i^i) \tag{2}
\]

where \( r \) is the discount rate.

With an increment of load \( \Delta L \) at node \( i \), the future investment for reinforcement will be brought forward from year \( T_i \) to year \( T_i' \).

\[
C_i = (L_i + \Delta L)(1 + d_i^i) \tag{3}
\]

Accordingly, the present value of the investment will be changed to

\[
P_i' = \frac{F_i}{(1 + r)^T_i'} \tag{4}
\]

So the incremental cost of the branch with an increment of load \( \Delta L \) is determined as follows.

\[
\Delta c_i = \frac{P_i' - P_i}{\Delta L} \tag{5}
\]

When \( \Delta L \to 0 \), \( \Delta c_i \) is the partial derivative of \( P_i' \) with respect to \( L_i \), that is

\[
\Delta c_i = \frac{\partial P_i'}{\partial L_i} \tag{6}
\]
CALCULATION OF MDCC

RATIO OF OCCUPIED CAPACITY

In an actual distribution system, the load at node $i$ is subject to the capacity of the supplying equipment. In this paper, ratio of occupied capacity, denoted by $H_{i}$, is adopted to characterize the occupied ratio of the load at each node to the supplying capacity.

Suppose the ratio matrix of occupied capacity is $H_{ij}$, $H_{ij}$ represents the occupied ratio of the load at node $i$ to the capacity of branch $j$. Obviously, if $j$ is not the supplying branch of node $i$ (see fig.1), $H_{ij}$ equals 0. For more details, please refer to reference [7].

CALCULATION METHOD

Suppose $\Omega$ is the set of the upper nodes of $i$ (including node $i$), then MDCC of node $i$ is given by

$$MDCC_{i} = \sum_{k,j} \Delta C_{j}H_{ik}C_{i/F}$$

where $\Delta C_{j}$ and $H_{ik}$ is explained as above, $C_{i/F}$ is the equivalent coefficient for future value discounted back to annual value.

Fig.2 is the illustration of a DG with the capacity $C_{DG}$ connected to the system. The upper branch of node $i$ is $k$ and the capacity of branch $k$ is subject to

$$C_{k} \geq \sum_{j \in \Phi_{k}} L_{j} - C_{DG}, \quad k \in \Omega_{i}$$

where $C_{k}$ is the capacity of branch $k$, $\Phi_{k}$ is the set of the lower nodes of $k$ (excluding node $k$).

![Fig.2 Illustration of DG as reinforcement alternative](image)

Rearranging equation (8) gives

$$C_{k} + C_{DG} \geq \sum_{j \in \Phi_{k}} L_{j}, \quad k \in \Omega_{i}$$

From the point of supplying capacity, the effect of DG as reinforcement alternative is equivalent to advancing the capacity of all the branches upper to the node to which the DG is connected. This can be demonstrated by equation (9) and Fig.3.

![Fig.3 Equivalent effect of DG as reinforcement alternative](image)

On this basis, MDCC considering DG as reinforcement alternative can be calculated from (1) to (9).

PLANNING OF DG CONSIDERING MDCC

APPLICATION OF MDCC

MDCC can be used to pricing unit capacity of each node and reflect the utilization efficiency of nodal capacity. For a node with bigger value of MDCC, the utilization degree for nodal capacity is more intense and the occupied cost of the new incremental load is higher. Such node should be given prior consideration for reinforcement.

Suppose $f_{DG}$ represents the fixed cost for unit capacity of DG, $v_{g}$ represents the generation cost of DG, $v_{p}$ represents electricity purchasing cost from transmission grid. Then the variable cost can be expressed as $v_{g} - v_{p}$. The annual cost for unit capacity of DG as reinforcement alternative, denoted by $c_{DG}$, can be determined from (10)

$$c_{DG} = f_{DG}C_{i/F} + (v_{g} - v_{p})\tau_{DG}(1 - \epsilon_{loss})$$

where $\tau_{DG}$ represents utilization hours for maximal capacity, $\epsilon_{loss}$ represents the contribution coefficient of reduction on network loss with DG connected to the system.

As described above, the value of MDCC can be reduced by connection of DG as reinforcement to the system. The economic feasibility can be judged by comparing the value of MDCC to $c_{DG}$, the main judgment criterion is as follows:

(a) if $c_{DG} < MDCC$, feasible for DG as reinforcement, else, uneconomic;
(b) connecting DG to the node with the biggest value of MDCC, then recalculating the value of MDCC for each node and judging on adding DG or not by the new values of MDCC;
(c) if the values of MDCC for all the nodes are less than $c_{DG}$, stop.

CONSTRAINT CONDITIONS

Connection of DG as reinforcement alternative will increase the short circuit capacity of the distribution system, and thus will influence safe operation. This paper takes the worst situation into account, that is, three-phase short circuit occurring nearby the transformer. The short circuit current $I_{f}$ should be subject to

$$I_{f} \leq I_{f}^{\max}$$

where $I_{f}^{\max}$ is the maximal breaking current of the circuit breaker.

According to the current operation mode of the distribution system, feeding from DG to upper nodes is not considered.

$$C_{DG} \leq I_{f} \quad (for \ every \ DG)$$

FLOW OF DG PLANNING

On the basis of the description above, the flow of DG planning can be summarized as follows. The flowchart of the proposed method is given in Fig.4.
Step 1: input parameters, select the nodes for connection of DG in advance and construct the node set $\psi$;
Step 2: calculate $MDCC$ of each node;
Step 3: select the node with the biggest value of $MDCC$ (suppose it is $k$);
Step 4: compare the value of $MDCC$ with $c_{DG}$, if $c_{DG} < MDCC_k$, connect the DG with capacity $\Delta kW$ to node $k$; else, end;
Step 5: calculate the short circuit current after the connection of DG, judge whether meeting (11)–(12) or not, if yes, update the network and goto step 2. else, end;
Step 6: judge whether $\psi$ is empty set, if yes, end. else, goto step 3

Start

Calculate $MDCC$ of each selected node in $\psi$

$MDCC_i = \max_{i \in \psi} \{MDCC_i\}$

$N$: $MDCC_i > c_{DG}$

Update the network

$Y$

Connect a DG ($\Delta kW$) to node $k$

Short Circuit Calculation

Meet (11)–(12)?

$Y$

Remove node $k$ from $\psi$

$N$

$\psi = \emptyset$

End

Fig. 5 Electric diagram of a 15-node distribution system

Fig. 4 Flowchart of the proposed planning method

CASE STUDY

Fig. 5 is the electric diagram of a 15-node 35/10kV distribution system. The purchasing cost from the 35kV system is 0.04$/kWh. The annual growth rate of the 10kV system's load is 3%. Suppose the discount rate is 8%.

To ensure that the capacity is sufficient to meet the needs of growth of load, DGs are considered to connect to the system. Suppose unit capacity cost of DG for investment
and operation are 500$/kW and 0.05$/kW respectively, utilization hour for maximal capacity of DG is 4000h and operation period is 8 years. According to (10), annual cost for unit capacity of DG ($DG) is 127$/kW.

On the basis of the planning method above, a DG with the capacity 700kW is considered to be connected to node 6 while a 500kW DG connected to node 15. The results of the recalculation are listed in Tab.1. The value of MDCC for node 6 and 15 is reduced to 123$/kW and 126$/kW respectively. The values of other nodes are also reduced, but less than the nodes to which DGs are connected to.

Let $MDCC_s = \frac{\sum L_i * MDCC_i}{\sum L_i}$, $MDCC_s$ represents average marginal capacity cost of the distribution system. After the connection of DG (700+500=1200kW), $MDCC_s$ is reduced from 103$/kW to 87$/kW, that is, for every connection of DG with the capacity 100kW, $MDCC_s$ can be reduced 1.33$/kW. This shows that connection of DG as reinforcement can promote the utilization efficiency of the supply capacity.

**CONCLUSION**

MDCC can be used to reflect the utilization efficiency of nodal capacity. The planning method considering MDCC proposed in this paper can help to promote optimal allocation of power resources and improve utilization efficiency of supply capacity. The investment of distribution system construction can be delayed or reduced by DG connected to the system upon this method. On the other hand, using this method can also help to avoid lower utilization efficiency of current equipments because of unreasonable sites for DG.

For complicated distribution system, calculation method of MDCC is given in this paper based on the theory of incremental cost, which relies on current situation of distribution system and the increasing trend of electric load. This method is more feasible in actual projects compared with the method restricted to the configuration of the planning network.

Heuristic algorithm is used to optimize the connection manner of DG. By comparing the value of MDCC and annual cost for unit capacity of DG, the capacity and site of DG is then determined at the end of the flow. Network loss and short circuit current are considered as constraint conditions in the proposed method.

The case illustrated in the final of the paper gives the application of the planning method in actual distribution system. The result shows that connection of DG as reinforcement can promote optimal allocation of power resources and improve the utilization efficiency of the supply capacity. Moreover, it demonstrates the method and flow of determining the capacity and site of DG to gain the optimal situation of the network.

**REFERENCES**


**BIOGRAPHY**

Feng PAN was born in Shanghai, China on Oct.17,1979. He received his master degree in department of Electrical Engineering, Shanghai Jiaotong University in 2005. Now he is an engineer in Shanghai Southern Power Supply Company, working on planning and operation of distribution system.