Optimal Siting and Sizing of Distributed Generators in Active Distribution Network

Haijun Xing, Xin Sun, Yang Fu, and Haozhong Cheng

Abstract**-- This paper proposes a distribution generation (DG) siting and sizing model in active distribution network (ADN). The objective is to minimize the total cost, including investment, operation and maintenance cost. The proposed model is transferred to Mixed Integer Second-Order Cone Programming (MISOCP) model based on distribution network forward backward-sweep power flow equation and constraint relaxation. The CVX platform and GUROBI solver are used for the solving. The scenario analysis is used for the uncertainties of load and distributed generation (DG). Different amount of operation scenarios is considered in order to analyze the effect of non-network solution to the final planning result and total investment. The planning results with and without consideration of active managements, the planning results with and without taking environment profits into consideration, are compared and analyzed. The proposed methodology is verified with modified IEEE 33-bus example.**

Index Terms**--active distribution network, distribution network siting and sizing, distributed generation, second-order cone programming.**

NOMENCLATURE

A. Sets and Indices

ψ_j	Set of the alternative DG installation site.
ψ_D	Set of the alternative DG type.
ψ_n	Set of the load.
ψ_b	Set of the branch.
Φ_j	Set of the original DG installation site.
y	Index of time interval in each day.
t	Index of the year.
i, j, m, n	Index of the bus.

B. Variables and Functions

C^{inv}	Total investment cost of DG installation.
C^{om}	Operation and maintenance cost of the system.
Z_k^{DG}	Installation numbers of unit capacity DG on bus k.
$Z_k^{DG,\max}$	Maximum permitted number of unit capacity DG on bus k.
$P_{k,rated}^{DG}$	Rated capacity of unit DG on bus k for installation.
$P_{g,rated}^{DG}$	Rated capacity of unit DG on bus g originally existed.
C_k^{DG}	Investment cost of unit capacity kh type DG.
P_t^{loss}	Total power loss at time t.
$f_k^{DG}(\cdot)$	DG cost function of kth type DG.
C_t^P	The electricity price at time t.
C_t^{DSM}	The electricity price to compensate to the users participating in DSM at time t.
C_k^{env}	The environment benefit of unit capacity DG generation in substitution of traditional coal-fired generation.
$C_{k,m}^{DG}$	The yearly maintenance cost of unit capacity of kth type DG.
V_n, $V_n^{\min}$, $V_n^{\max}$	Separately bus voltage, lower and upper limits of bus voltage on bus n.
I_{ij}, $I_{ij}^{\max}$	Separately current flow and upper limit of current flow on branch (i, j).
$P_{n,rated}^{L}$	Rated active power of load on bus n.
P_j^L, Q_j^L	Actual active and reactive load power on bus j.
$P_{j,\max}^{L}$	The maximum active load on bus j based on load profile.
P_j^{DSM}, Q_j^{DSM}	Load active and reactive power participating in DSM on bus j.
Q_j^C	Reactive power injected from capacitor on bus j.
r_{ij}, x_{ij}	Resistance and reactance of the branch (i, j).
P_{ij}, Q_{ij}	Active and reactive power on the front end of branch (i, j).
P_j^{DG}, Q_j^{DG}	Actual active and reactive power from DG on jth bus.
$P_j^{DG,\min}$, $P_j^{DG,\max}$	Lower and upper limit of DG active power on bus j, based on the DG rated power.
$P_{j,\max}^{DG}$	The maximum active power output of

Manuscript received May 5, 2016; revised February 27, 2017; accepted April 1, 2017.

H. Xing (corresponding author, e-mail:xinghj_601@126.com), X. Sun and Y. Fu are with School of Electric Power Engineering, Shanghai University of Electric Power, Shanghai 200090, China.

H. Cheng is with Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.

DOI: 10.17775/CSEEJPES.2016.00480

	DG on bus j based on the wind speed.
φ_j^{DG} , φ_j^{L}	Separately power factor angle of load and DG on bus j.
V_l, V_{ss}	The voltage before and after on-load tape changer (OLTC) adjustment.
k_t, $k_{\min}$, $k_{\max}$	Separately current tap position, the lower and upper permitted tap positions of OLTC.
(i, j)	Branch from bus i to bus j.
D_{sc}	Total number of days in scenario sc.
r	Annual interest rate of investment.
δ_y	The present value factor.

I. INTRODUCTION

THE distributed generation (DG) becomes much more important under the background of global energy crisis and serious environment problems. DG is flexible and usually environment-friendly, and can decrease the distribution network active power loss, improve the voltage profile and system reliability. Every coin has two sides, DG also brings a lot of problems, such as voltage rising at public connecting point, short current increasing, three-phase imbalance and voltage fluctuation [1], [2]. These problems will also restrict the DG integration. The visible side of coin depend closely on the siting and sizing of DGs in the distribution system. The improper siting and sizing will not only cause idle assets, but also bring negative effects to the system operation. With the continuously increasing of DG penetration, DG integration plays an important role in alleviating the shortage of power supply and ameliorating energy structure. At the same time, DG integration brings new challenges to power system optimization problems. Therefore, it is significant to use scientific research method for DG siting and sizing.

There are many research achievements in siting and sizing of DGs. Reference [3] presents an analytical approach to minimize the real and reactive power losses with DG proper siting and sizing; the method bases on the sensitivity analysis method. Reference [4] proposes a multi-objective model for DG siting and sizing, considering the interests of DG owners and distribution company; the model is solved with Particle Swarm Optimization algorithm. Reference [5] takes into account the profits of both DG investors and utility, proposes a differential evolution algorithm to confirm the best sites, sizes, and optimal payment incentives of DGs. Reference [6] compares three Mixed-Integer Programming approaches for DG locating and sizing; a linear DC power flow approximation, a nonlinear DC power flow approximation with quadratic terms, and an AC power flow approach are considered. Reference [7] considers the uncertainties of load growth, wind generation, photovoltaics output, fuel cost and electricity price, uses probabilistic power flow-embedded generic algorithm to solve the optimization problem. Reference [8] proposes chance constrained programming mathematical formulation for DG locating and sizing. The Monte Carlo Simulation embedded genetic algorithm is selected to solve the problem. Reference [9] introduces the ordinal optimization approach for DG siting and sizing to achieve a trade-off between DG capacity maximization and loss minimization.

Most of the above-mentioned DG siting and sizing methods are well suited to allocate in traditional distribution network (TDN). However, TDN planning uses the utmost capacity margin to cope with the most serious operation condition aiming at the forecasted peak load. Thus, TDN planning can find the optimal solution for all the operation problems encountered in the planning period. Therefore, the planning methodology of TDN is relatively simple, the assets cannot be fully excavated, the network lacks of the flexible controllable characteristic. The booming Active Distribution Network (ADN) is a system with controllable mechanism and diversified energies [10]. With active management of the controllable equipment, ADN can improve the DG penetration, enhance the asset utilization, and postpone the network upgrading. In the planning stage, ADN focuses on the detailed system operation, instead of the most serious operation condition. There are some research progresses about DG siting and sizing in ADN.

Reference [11] proposed the bi-level model of distributed wind generation (DWG) siting and sizing based on the real-time control and active management of DGs. The upper level model maximizes the expectation of net benefit of DWG; the lower level model minimizes the expectation of DWG curtailment. Reference [12] uses convex formulation of ac optimal power flow to define the Mixed-Integer Second-Order Cone Programming (MISOCP) problem; then the method and formulation to site and size the Energy Storage System (ESS) optimally in distribution system is proposed. Reference [13] proposes a battery operation strategy for better utilization of ESS and mitigation operation risk from price uncertainty. The siting and sizing of ESS is obtained through cost-benefit analysis method, the fuzzy Particle Swarm Optimization algorithm is used to solve the optimization problem. From above, the global optimal method SOCP has not been used in siting and sizing research in ADN, and some of the important key points like scenario amount for the uncertainties and environment benefits for the better objective function in the above researches are not identified.

The main contributions of this paper include: 1) proposing the Mixed-Integer Second-Order Cone Programming (MISOCP) model of DG siting and sizing in ADN, SOCP can find the global optimal solution properly; 2) different amount of operation scenarios are considered to analyze the effect of active management to the final planning result and total investment; 3) comparing the planning results with and without considering active management, with and without considering the environment benefits to show the effectiveness and cost reduction of the proposed method.

This paper is organized as follows, after the introduction section, the SOCP and ADN planning is presented; and then the mathematics model of the problem is proposed, including the method to transfer the original model to a SOCP model. The proposed model and solving method are verified on a modified IEEE 33-bus distribution system in section V. Conclusions are drawn in the last section.

II. ADN PLANNING

The difference between active distribution system planning and traditional distribution system planning can be explained with Fig.1, where the yearly load profile is assumed with only a step changing. For traditional distribution system planning, normally there is a margin between the peak load and maximum substation capacity; the margin ensures the load successfully transferring when fault happens. There is a macroscopical index capacity-load ratio in China for this margin. The capacity-load ratio has some relations with the load growth rate. As for median voltage (MV) network, capacity-load ratio is set around two. But peak load is only an operation point, the majorities much lower that the peak load. So the annual utilization time of the facilities is lower.

The ADN has many diversified energies and controllable mechanisms, like the demand response, DG, ESS, OLTC, etc. In addition, ADN has advanced metering infrastructure (AMI) and information communication technology (ICT). All the above enables the planners to take into consideration the active management in the network planning stage, so as to enhance the asset utilization, and decrease the total planning cost. In Fig. 1 b), as the maximum substation capacity decreases, the peak loads are supported by DGs/ESS installation and active management of the network. Then the substation capacity decreasing, the newly installed DGs/ESS and active management should have a synthetically optimization to decrease the total cost with all the system constraints fulfilled. When the practical profile is considered, large number of decision variables and constraints, superposing on uncertainties, lead to much complex operation states, which affect feasible solution space. In this paper, the cluster method is used to simplify the problem, which will be explained in the next section.

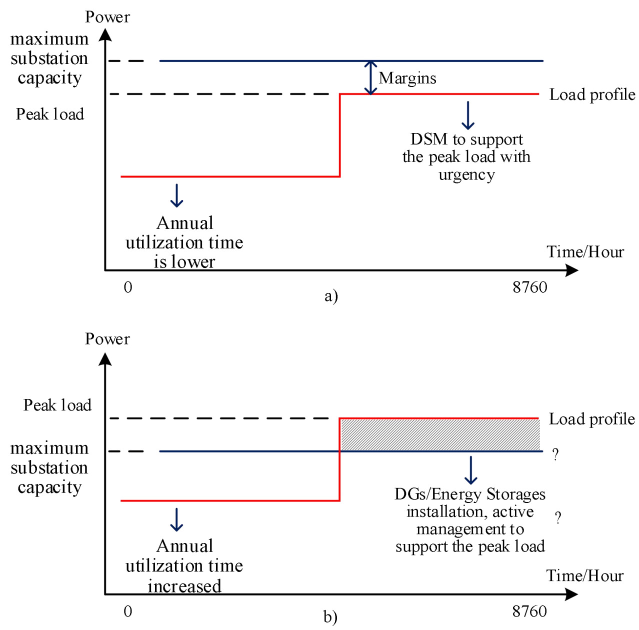

Fig.1. Distribution system planning explanation.(a) Traditional distribution network planning. (b) Active distribution network planning.

III. Second-Order Cone Programming

SOCP problems are nonlinear convex ones, which can be solved by efficient primal-dual interior point method (PDIPM). Many engineering problems can be formulated as SOCP such as filter design, truss design, and so on [12]. The researches considering SOCP within the power system domain include the optimal allocation of Dispersed ESS [12], optimal power flow [14], distribution network reconfiguration [15], [16], etc.

The proposed formulation in this paper is a MISOCP problem. We can solve it using the Mixed-Integer Programming solving method. Firstly, solve the SOCP without considering the integer constraints using PDIPM, then solve the MISOCP integrating the integer constraints with Branch and Bound method or Branch and Cut method.

IV. DG Siting and Sizing Model in ADN

There are lots of uncertainties in the distribution network. In ADN, the planners need to follow the uncertainties closely in order to take measures for the controllable facilities. In this paper, the uncertainties of WTG (Wind Turbine Generation), PVG (Photovoltaic Generation) and load are considered. The risks caused by the uncertainties will be managed and controlled with DG active power adjustment, OLTC control and demand side management (DSM). Uncertainties are normally obtained with probabilistic model, interval model, and historical data. In this paper, the uncertainties are revealed with historical data. The scenario analysis method in [17] is adopted for the uncertainties. The detailed procedures are as follows:

1) Hour level historical data of DGs and load over a year is selected to generate a matrix $\boldsymbol{A}_{m\times n}$, where m represents the number of days over a year and n represents the number of WTG, PVG and load data per day. With the historical data calculated by the hour in (1), m equals 365, n equals 72.

$$\begin{array}{c} day \\ 1 \\ 2 \\ \vdots \\ 365 \end{array} \begin{bmatrix} \overbrace{a_{1,1} \ \cdots \ a_{1,24}}^{WTG} & \overbrace{a_{1,25} \ \cdots \ a_{1,48}}^{PVG} & \overbrace{a_{1,49} \ \cdots \ a_{1,72}}^{LOAD} \\ a_{2,1} \ \cdots \ a_{2,24} & a_{2,25} \ \cdots \ a_{2,48} & a_{2,49} \ \cdots \ a_{2,72} \\ \vdots & \vdots & \vdots \\ a_{365,1} \ \cdots \ a_{365,24} & a_{365,25} \ \cdots \ a_{365,48} & a_{365,49} \ \cdots \ a_{365,72} \end{bmatrix}$$

* MERGEFORMAT (1)

2) K-means cluster method is used to categorize the historical data for the problem simplification. The Matlab cluster function *IDX=kmeans(A, K)* is used, where K is the number of the clusters. The final centroid of each cluster K is selected to represent all the samples in it.

A. Problem Definition

The proposed objective function of DG siting and sizing includes: 1) the initial investment cost and 2) the system operation and maintenance cost.

$$\min f = \mathrm{C}^{inv} + \mathrm{C}^{om}$$

$$\mathrm{C}^{inv} = \sum_{j\in\Psi_D} \sum_{k\in\Psi_j} Z_k^{DG} P_{k,rated}^{DG} C_k^{DG}$$

$$\mathrm{C}^{om} = \sum_{y} \delta_y \left(\sum_{sc} D_{sc} \cdot \left(\sum_{t} \left(P_t^{loss} C_t^P + \sum_{j\in\Psi_D} \sum_{k\in\Psi_j} f_k^{DG}\left(P_{k,t}^{DG}\right) + \sum_{n\in\Psi_n} P_{n,t}^{DSM} C_t^{DSM} - \sum_{j\in\Psi_D} \sum_{k\in\Psi_j} C_k^{env} \cdot P_{k,t}^{DG} \right)\right) + \sum_{j\in\Psi_D} \sum_{k\in\Psi j} Z_k^{DG} P_{k,rated}^{DG} C_{k,m}^{DG} \right)$$

* MERGEFORMAT (2)

$$\delta_y = 1 \big/ (1+\mathrm{r})^{y-1}$$

* MERGEFORMAT (3)

The operation and maintenance part of the objective aims at minimizing a total cost associated to the different system operation scenarios *sc*. The C^{om} consists of 1) total power losses cost; 2) DG operation cost; 3) cost paid to the customers for the DSM participation; 4) environmental benefit of DG power generation in substitution of the traditional coal-fired power plant; 5) DG maintenance cost. All the operation and maintenance cost is brought to the investment year for the cost-benefit analysis.

B. Constraints

The constraints of the proposed model includes equipment investment constraints, network security constraints and active management constraints:

1) Equipment Investment Constraints

$$0 \le Z_k^{DG} \le Z_k^{DG,\max} \quad k \in \Psi_j$$

* MERGEFORMAT (4)

$$\sum_{j\in\Psi_D}\sum_{k\in\Psi_j} Z_k^{DG} P_{k,rated}^{DG} + \sum_{j\in\Psi_D}\sum_{g\in\Phi_j} P_{g,rated}^{DG} \le \beta \cdot \sum_{n\in\Psi_n} P_{n,rated}^{L}$$

* MERGEFORMAT (5)

The constraint defines the maximum capacity of DGs which can be installed on bus *k*.

The constraint defines the DG penetration constraint; the permitted maximum DG penetration rate is *β*.

2) Network Security Constraints

The SOCP formulation proposed in [18], [19] has been adapted to define the network security constraints. Only the square of voltages and current flows appear in the both objective function and constraints. Therefore, the new variables are introduced in order to transfer the mathematics model to MISCOP model. υ_i is to represent the square of V_i, $\upsilon_i = V_i^2$; ℓ_{ij} is to represent the square of I_{ij}, $\ell_{ij} = \left(P_{ij}^2 + Q_{ij}^2\right)/V_i^2$.

The following constraints account, respectively, for the balance of active and reactive power flows on each line with distribution network forward backward-sweep power flow equation [20]:

$$\sum_{k:(j,k)\in\psi_b} P_{jk} = \sum_{i:(i,j)\in\psi_b} \left(P_{ij} - r_{ij}\ell_{ij}\right) - P_j^L + P_j^{DG}$$

* MERGEFORMAT (6)

$$\sum_{k:(j,k)\in\psi_b} Q_{jk} = \sum_{i:(i,j)\in\psi_b} \left(P_{ij} - x_{ij}\ell_{ij}\right) - Q_j^L + Q_j^{DG} + Q_j^C$$

* MERGEFORMAT (7)

$$\upsilon_j = \upsilon_i - 2\left(r_{ij}P_{ij} + x_{ij}Q_{ij}\right) + \ell_{ij}\left(r_{ij}^2 + x_{ij}^2\right)$$

* MERGEFORMAT (8)

The following constraint has been added to the problem to ensure that the nodal voltages are in the feasible region with the introduced variable.

$$\left(V_n^{\min}\right)^2 \le \upsilon_n \le \left(V_n^{\max}\right)^2 \quad n \in \psi_n$$

* MERGEFORMAT (9)

Equation (10) defines the line flow constraints with the introduced variable:

$$0 < \ell_{ij} \le \left(I_{ij}^{\max}\right)^2$$

* MERGEFORMAT (10)

$$\ell_{ij} = \left(P_{ij}^2 + Q_{ij}^2\right)/\upsilon_i$$

* MERGEFORMAT (11)

Equation is the constraint brought by the introduced variables, which dcan be relaxed to the following SOCP formulation:

$$\left\| \begin{matrix} 2P_{ij} \\ 2Q_{ij} \\ \ell_{ij} - v_i \end{matrix} \right\|_2 \le \ell_{ij} + \upsilon_i$$

* MERGEFORMAT (12)

where $\|\cdot\|_2$ is the 2-norm, the relaxation equation (12) is proved to be equivalent with , as the optimization solution will fall into the boundary of (12) [18], [19].

Equation (13) defines the upper and lower limits of active power that can be produced by DGs.

$$P_j^{DG,\min} \le P_j^{DG} \le P_j^{DG,\max} \quad j \in \psi_D$$

* MERGEFORMAT (13)

The following constraints define the relationship between active and reactive power of DGs and Loads, respectively.

$$Q_j^{DG} = P_j^{DG} \cdot \tan\left(\varphi_j^{DG}\right) \quad j \in \psi_D$$

* MERGEFORMAT (14)

$$Q_j^L = P_j^L \cdot \tan\left(\varphi_j^L\right)$$ * MERGEFORMAT (15)

The total power losses in can be defined as

$$P^{loss} = \sum_{(i,j)\in\psi_b} \ell_{ij} r_{ij}$$ * MERGEFORMAT (16)

3) Active Management Constraints

Active management schemes applied in this paper include DG active power adjustment, DSM and OLTC control.

The DG active power adjustment is to adjust the active power of DGs with the technical method, e.g. adjusting the blade angle of WTG. The following constraint defines the upper limits that the DG power can be curtailed.

$$P_j^{DG,cur} \le P_{j,\max}^{DG} \quad j \in \psi_D$$

* MERGEFORMAT (17)

As for WTG, $P_{j,\max}^{DG}$ is associated with the wind speed. The wind power curtailment $P_j^{DG,cur}$ on bus *j* equals $P_{j,\max}^{DG} - P_j^{DG}$.

DSM is to actively manage the load demand with the electricity price incentive or the aforehand contract. The following constraint defines the upper limits that the customers can participate in the DSM.

$$P_j^{DSM} \le P_{j,\max}^{L} \quad j \in \psi_n$$

* MERGEFORMAT (18)

$P_{j,\max}^{L}$ is associated with the load profile. The load active power that can participate in the DSM P_j^{DSM} on bus *j* equals $P_{j,\max}^{L} - P_j^L$.

OLTC control is to adjust the OLTC tap position for the voltage adjustment. The following constraints define the OLTC adjustment limits.

$$V_h = V_H \cdot \left(1 + \alpha k_t\right)$$ * MERGEFORMAT (19)

$$k_{\min} \le k_t \le k_{\max}$$ * MERGEFORMAT (20)

$$\sum_{t=1}^{24} \left| sign\left(k_t - k_{t\text{-}1}\right) \right| \le \lambda$$ * MERGEFORMAT (21)

V_H is the primary voltage of substation; V_h is the bus voltage after tap adjusting. k_t is the OLTC tap position at time t. α is the voltage adjustment of each tap distance.

Constraint is the upper and lower limits the OLTC tap positon can be adjusted.

Constraint is the OLTC operation constraint; the tap adjusting times per day is limited to λ for the operation security in accordance with the substation operation code. k_0 for every scenario is assumed to be 0.

In order to convert the constraint to Second-Order Cone formulation, the binary variable b_t is introduced. b_t takes the value 1 if the tap changes at time t and 0 otherwise. Then the constraint can be derived as below.

$$-\left(k_{\max} - k_{\min}\right)\cdot b_t \le k_t - k_{t\text{-}1} \le \left(k_{\max} - k_{\min}\right)\cdot b_t \quad t = 1 \sim 24$$ * MERGEFORMAT (22)

$$\sum_{t=1}^{24} b_t \le \lambda$$ * MERGEFORMAT (23)

b_t =0 leads $k_t = k_{t\text{-}1}$, which means the tap is not adjusting at time t. b_t =1 constrains the tap position adjusting range at the adjacent time. The sum of b_t during 24 hours artfully reveals the total numbers of the tap position changing times. With and the tap adjusting frequency per day is constrained within the permitted value λ.

The procedure of DG siting and sizing is shown in Fig. 2.

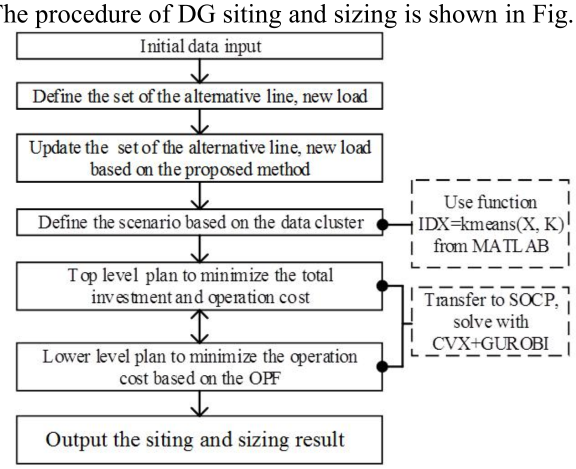

Fig.2. The solving procedure.

V. Application Example and Result

The modified application example from [20] is selected for the verification, the initial structure of the example is shown in Fig. 3. This test system is a single substation radial distribution network, the original load parameter can be found in [20]. In this paper, we assume there is 20% increases of the load to show the system support from the DG installation. The load profile is from the historical data of East China Grid. Table I shows the parameters used in the application example, including the DG type, DG unit capacity, maximum DSM participation of every load bus, DG penetration rate, etc.; Table II shows the DG installation cost, operation cost and maintenance cost.

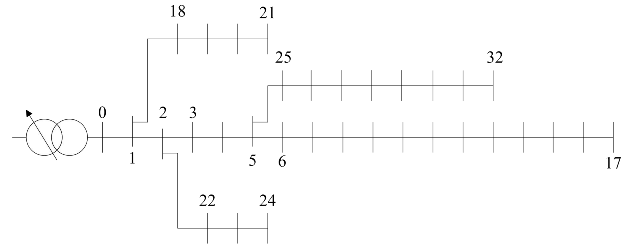

Fig.3. Modified network structure of IEEE 33-bus system.

The DGs include WTG, PVG and Micro Turbine Generator (MTG). The wind speed and illumination intensity refer to the practical data from wind farm and photovoltaic plant. The generated power from WTG and PVG can refer to [8].

The example is verified with CVX [21] on MATLAB platform, the GUROBI 6.5 [22] solver is selected for the solving. The tests are conducted on a 2.5GHz PC with 4200M CPU.

TABLE I
Parameters of the Application Example

DG type	WTG, PVG and MTG
DG unit capacity(kW)	50
DG maximum installation number on buses	10
DG penetration rate(%)	35
Electricity price(RMB/kWh)	0.337 (6:00~22:00); 0.677 (other time)
DSM incentive cost(RMB/ MWh)	1.2×10^4
Maximum DSM participation of every load bus(%)	30
environmental benefit of DG(RMB /MWh)	0.004×10^4
OLTC	50 MVA, 110± 8×1.25% kV, YNd11 three phase 2-winding transformer
Bus voltage limit(p.u.)	0.95 ~ 1.05
Branch capacity limit(MVA)	10
Scenario quantity	8
Voltage reference(kV)	12.66
Discount rate(%)	10
Planning period(years)	5

TABLE II
Parameters of DG Cost

DG	Alternative installation site	Investment cost (10^4 RMB /100 kW)	Operation Cost (RMB/ kWh)	Maintenance Cost (10^4RMB /100 kW.y)
WTG	5, 17, 32	30	0	1
PVG	21, 24	50	0	0.5
MTG	11, 18	20	0.5	2

1) With and Without Considering Active Management

Table III is the DG installation result with and without considering active management schemes. With active management, the total WTG is 400 kW, MTG is 500 kW; without active management, the total WTG is 1250 kW, MTG is 250 kW. Additional 600 kW DG is installed when the active management is not considered. As the high maintenance cost and the existing operation cost, the MTG installation capacity has been lowered down when the active management is not considered (the active management of MTG is disabled). As the environment profits and lower maintenance cost in substitution of the traditional coal-fired power plant, WTG installation capacity increases largely. The DG installation positions are mainly on the two heavy loaded feeder 5~17 and 5~32.

TABLE III
DG INSTALLATION RESULT

DG	With AM	Without AM
WTG	5(0), 17(3), 32(5)	5(10), 17(5), 32(10)
PVG	21(0), 24(0)	21(0), 24(0)
MTG	11(10), 18(0)	11(5), 18(0)

Note: The left number is the DG installation bus; the right number in the brackets is the quantity of DG the unit capacity.

Fig. 4 is the operation curve of 500 kW MTG installed on bus 11. We can see in the peak load time, MTGs are fully participated in the operation to support the system peak load; in the valley time, MTGs are not dispatched. As the total planning period is 5 years, we need to have a systematically dispatch scheme for the MTG to lower down the operation cost, then the total planning scheme.

Table IV is the costs of the planning result. We can conclude that the total cost without active management increases 58.11% comparing with the result considering active management. Within all the cost items, the main parts which is higher without active management are investment cost, operation and maintenance cost. The investment cost without active management increases 93.18% comparing with the one considering active management. The large capacity of WTG installation without active management leads to lower power loss and higher environment profit.

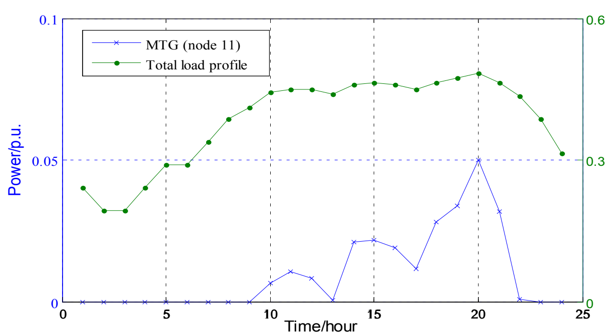

Fig.4. The active management of MTG on bus 11.

TABLE IV
THE DG INVESTMENT AND OPERATION COST OF ADN (10^4RMB)

Scenario	Total cost	Invest. cost	O&M cost	Ploss cost	DSM cost	Env. profit
With AM	1000.3	440	301.9	281.5	1.6	24.7
Without AM	1581.6	850	602.6	206.2	0	77.2

2) With and Without Considering Environment Profit

Table V is the DG installation result with and without considering environment profit. The WTG installation capacity is 100 kW without considering environment profit, which is 300 kW smaller than the one considering environment profit. MTG installation capacity is 600 kW without considering environment profit, which is 100 kW larger than the one considering environment profit. From above we can see, with the present situation of high intermittent DG investment cost, the environment profit needs to be synthetically integrated to reveal the environment-friendly characteristic of intermittent DG and increase the intermittent DG penetration.

TABLE V
DG INSTALLATION RESULT

DG	With Env. profit	Without Env. profit
WTG	5(0), 17(3), 32(5)	5(0), 17(0), 32(2)
PVG	21(0), 24(0)	21(0), 24(0)
MTG	11(10), 18(0)	11(10), 18(2)

Table VI is the costs of the planning result with and without considering environment profit. As less MTGs are installed, the investment cost without considering environment profit is 140 × 10^4 RMB lower than considering the environment profit. The operation and maintenance cost increases with more MTG installation when the environment profit is not considered. The total cost considering environment profit is a little lower.

TABLE VI
THE DG INVESTMENT AND OPERATION COST OF ADN (10^4RMB)

Scenario	Total cost	Invest. cost	O&M cost	Ploss cost	DSM cost	Env. profit
With Env. profit	1000.3	440	301.9	281.5	1.6	24.7
Without Env. profit	1028.6	300	413.8	309.0	5.8	0

3) Different Number of Scenarios

The difference between active distribution system planning and traditional distribution system planning is that, traditional distribution network planning uses the utmost capacity margin to cope with the most serious operation condition aiming at the forecasted peak load, whereas the active distribution network planning needs the precise management of the network. The final planning result of active distribution network includes the traditional network solution and non-network solution, which is the detailed network operation schemes. In order to analyze the effect of the detailed network operation schemes to the planning result, the different operation scenarios are considered.

Table VII and VIII are the DG installation results and costs for scenario quantity 4, 8 and 16. Comparing with scenario quantity 8, the DG installation capacity of scenario quantity 16 decreases from 900 kW to 800 kW. The DG installation capacity of scenario quantity 4 is the same as the scenario quantity 8; the operation and maintenance cost increases comparing with scenario quantity 8.

The active management can decrease the total planning cost. With the scenario quantity decreasing, the operation scheme becomes simple and operable; on the contrary, the operation scheme becomes complex and inoperable. The scenarios should be fully designed and compromised during the practical distribution network planning.

TABLE VII

DG INSTALLATION RESULT

DG	scenario=4	scenario=8	scenario=16
WTG	5(0), 17(3), 32(5)	5(0), 17(3), 32(5)	5(0), 17(2), 32(4)
PVG	21(0), 24(0)	21(0), 24(0)	21(0), 24(0)
MTG	11(10), 18(0)	11(10), 18(0)	11(10), 18(0)

TABLE VIII
THE DG INVESTMENT AND OPERATION COST OF ADN (10^4RMB)

Scenario quantity	Total cost	Invest. cost	O&M cost	Ploss cost	DSM cost	Env. profit
4	1036.1	440	320.5	300.1	1.6	26.1
8	1000.3	440	301.9	281.5	1.6	24.7
16	955.8	380	288.0	306.8	1.4	20.4

4) Effectiveness of SOCP

Below gives out the gap of $\left|\ell_{ij} - \left(P_{ij}^2 + Q_{ij}^2\right) / V_i^2\right|$ for 32 branches with 24 hours. The gap is very small with the 10^{-6} level. The branches in the beginning of the network have bigger gaps because of the current accumulation. The result shows that the relaxation of (12) in this paper is precise.

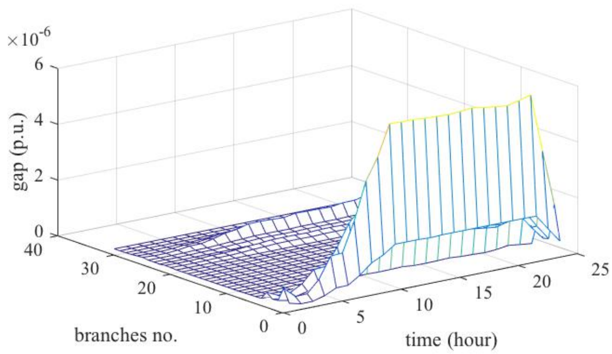

Fig. 5. The gap distribution of the relaxation.

In this paper, the iteration of the interior point method costs 0.05s in average, the Branch and Bound method costs 4.49s in average with total 16839 iterations. The total time consuming is 4.54s in average. Fig. 5 is the convergence process using Branch and Bound for MISOCP. We can see that the solving strategy with SOCP is effective.

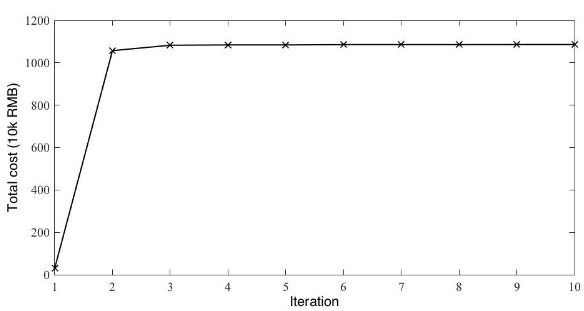

Fig. 6. The convergence process using Branch and Bound for MISOCP.

VI. CONCLUSION

This paper proposes the MISOCP model of DG siting and sizing in ADN, the planning result are compared with and without considering active management, with and without considering the environment benefits. The different amount of operation scenarios is considered to analyze the effect of active management to the final planning result and total investment. From the application example verification, we can see the MISOCP model of DG siting and sizing can be easily solved with the current mature solver. Proper DG siting and sizing can support the system expansion. With multiple active management schemes, the planning cost can be largely decreased. The conclusion are as follows:

When considering the integration of intermittent DG, the environment profit needs to be synthetically integrated to reveal the environment-friendly characteristic of intermittent DG and increase the intermittent DG penetration.

The scenario quantity can affect the result of the ADN planning. With the scenario quantity increasing, the total cost of the planning decreases. With the scenario quantity decreasing, the operation scheme becomes simple and operable; on the contrary, the operation scheme becomes complex and inoperable. The scenarios should be fully designed and compromised during the practical distribution system planning.

In this paper, the cost of active management scheme has not been taken into consideration. In the practical operation, the active management of the network will cause some expense like the operation cost and asset depreciation cost. This will be quantified and considered in the future research of the author.

REFERENCES

[1] C. Po-Chen, R. Salcedo, Z. Qingcheng, F. de Leon, D. Czarkowski, J. Zhong-Ping, et al., "Analysis of Voltage Profile Problems Due to the Penetration of Distributed Generation in Low-Voltage Secondary Distribution Networks," IEEE Transactions on Power Delivery, vol. 27, no. 4, pp. 2020-2028, 2012.

[2] A. Ipakchi and F. Albuyeh, "Grid of the future," IEEE Power and Energy Magazine, vol. 7, no. 2, pp. 52-62, 2009.

[3] S. N. Gopiya Naik, D. K. Khatod, and M. P. Sharma, "Analytical approach for optimal siting and sizing of distributed generation in radial distribution networks," IET Generation, Transmission & Distribution, vol. 9, no. 3, pp. 209-220, 2015.

[4] A. Ameli, S. Bahrami, F. Khazaeli, and M. R. Haghifam, "A Multiobjective Particle Swarm Optimization for Sizing and Placement of DGs from DG Owner's and Distribution Company's Viewpoints," IEEE Transactions on Power Delivery, vol. 29, no. 4, pp. 1831-1840, 2014.

[5] H. A. Hejazi, A. R. Araghi, B. Vahidi, S. H. Hosseinian, M. Abedi, and H. Mohsenian-Rad, "Independent distributed generation planning to profit both utility and DG investors," IEEE Transactions on Power Systems, vol. 28, no. 2, pp. 1170-1178, 2013.

[6] J. D. Foster, A. M. Berry, N. Boland, and H. Waterer, "Comparison of Mixed-Integer Programming and Genetic Algorithm Methods for Distributed Generation Planning," IEEE Transactions on Power Systems, vol. 29, no. 2, pp. 833-843, 2014.

[7] V. A. Evangelopoulos and P. S. Georgilakis, "Optimal distributed generation placement under uncertainties based on point estimate method embedded genetic algorithm," IET Generation, Transmission & Distribution, vol. 8, no. 3, pp. 389-400, 2014.

[8] Z. Liu, F. Wen, and G. Ledwich, "Optimal siting and sizing of distributed generators in distribution systems considering uncertainties," Power Delivery, IEEE Transactions on, vol. 26, pp. 2541-2551, 2011.

[9] R. Jabr and B. Pal, "Ordinal optimisation approach for locating and sizing of distributed generation," IET Generation, Transmission & Distribution, vol. 3, no. 8, pp. 713-723, 2009.

[10] C. D'Adamo, S. Jupe, and C. Abbey, "Global survey on planning and operation of active distribution networks - Update of CIGRE C6.11 working group activities," in Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on, 2009, pp. 1-4.

[11] Z. Jietan, P. Shun, T. Haiqing, and W. Maochun, "Siting and sizing of distributed wind generation under active management mode," in Power System Technology (POWERCON), 2010 International Conference on, 2010, pp. 1-8.

[12] M. Nick, R. Cherkaoui, and M. Paolone, "Optimal Allocation of Dispersed Energy Storage Systems in Active Distribution Networks for Energy Balance and Grid Support," IEEE Transactions on Power Systems, vol. 29, no. 5, pp. 2300-2310, 2014.
[13] Z. Yu, D. Zhao Yang, L. Feng Ji, M. Ke, Q. Jing, and W. Kit Po, "Optimal Allocation of Energy Storage System for Risk Mitigation of DISCOs With High Renewable Penetrations," IEEE Transactions on Power Systems, vol. 29, no. 1, pp. 212-220, 2014.
[14] L. Na, C. Lijun, and S. H. Low, "Exact convex relaxation of OPF for radial networks using branch flow model," in Smart Grid Communications (SmartGridComm), 2012 IEEE Third International Conference on, 2012, pp. 7-12.
[15] J. A. Taylor and F. S. Hover, "Convex Models of Distribution System Reconfiguration," IEEE Transactions on Power Systems, vol. 27, no. 3, pp. 1407-1413, 2012.
[16] E. Dall'Anese and G. B. Giannakis, "Convex distribution system reconfiguration using group sparsity," in Power and Energy Society General Meeting (PES), 2013 IEEE, 2013, pp. 1-5.
[17] S. S. Al Kaabi, H. Zeineldin, and V. Khadkikar, "Planning Active Distribution Networks Considering Multi-DG Configurations," IEEE Transactions on Power Systems, vol. 29, no. 2, pp. 785-793, 2014.
[18] M. Farivar and S. Low, "Branch flow model: Relaxations and convexification," in T&D Conference and Exposition, 2014 IEEE PES, 2014, pp. 1-1.
[19] H. Xing, H. Cheng, Y. Zhang, and P. Zeng, "Active distribution network expansion planning integrating dispersed energy storage systems," IET Generation, Transmission & Distribution, vol. 10, no. 3, pp. 638-644, 2016.
[20] M. E. Baran and F. F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," IEEE Transactions on Power Delivery, vol. 4, no. 2, pp. 1401-1407, 1989.
[21] M. Grant and S. Boyd, "CVX: Matlab software for disciplined convex programming, version 2.0 beta," [Online]. Available: http://cvxr.com/cvx, 2013.
[22] Gutobi Optimization, Inc, "Gurobi Optimizer Reference Manual," [Online]. Available: http://www.gurobi.com, 2012.

Haijun Xing received his B.Eng. and M.Eng. degrees in department of electrical engineering from Harbin Institute of Technology in 2002 and 2004 respectively. He received his Ph.D. degrees in Department of electrical engineering from Shanghai Jiao Tong University in 2016. He is now a lecturer of Shanghai University of Electric Power. His special fields of interest cover distribution network operation and planning, integrated energy and smart grid.

Xin Sun received her B.S. and M.S. degrees in department of electrical engineering from Harbin Institute of Technology in 2002 and 2004 respectively. She received her Ph.D. degrees in department of electrical engineering from Tsinghua University in 2009. She is now an associate professor of Shanghai University of Electric Power. His special fields of interest cover power system operation and optimal power flow.

Yang Fu received his M.S. degree from Southeast University, and the Ph.D. degree from Shanghai University. His employment experience has included the department of electrical engineering, Shanghai University of Electric Power. Currently, he is a professor and the dean of the college of electrical engineering, Shanghai University of Electric Power. His special fields of interest include simulation of power systems, transformer fault diagnosis, planning of electric networks, and renewable energy.

Haozhong Cheng received the B.S., M.S., and Ph.D. degrees in power systems from Shanghai Jiao Tong University in 1983, 1985, and 1998, respectively. He is now a professor of Shanghai Jiao Tong University. His special fields of interest cover power system planning, voltage stability, harmonics, operation, and deregulation.