A DISTRIBUTION SYSTEM EXPANSION PLANNING METHOD CONSIDERING INTEGRATED ENERGY SERVICE PROVIDERS' REVENUE ON ENERGY STORAGE INVESTMENT

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ABSTRACT

In this paper, a planning method for distribution system expansion is proposed, considering distribution feeders upgrading, as well as sizing and siting Energy Storage System (ESS), the investment of which is shared by Integrated Energy Service Provider (IESP) and Distribution System Operator (DSO). The revenue which comes from the ESS arbitrage will attract IESP to invest on ESS, thus achieving a balance between distribution system upgrading and ESS investment. The model is solved by Benders decomposition to obtain the optimal planning results. Case studies based on IEEE 33 nodes and real-world demonstration project prove the effectiveness of the proposed method.

INTRODUCTION

The increasing load which require a certain power supply in a short period, such as massive electric vehicle fast charging loads, is enlarging the gap between the peak and valley value in power system. Energy storage system (ESS) will help address the problem as a flexible distributed power sources, thus delaying the necessity of upgrading a distribution system. Moreover, it can also play an important role in load levelling, power variation damping or transmission, and power quality improvement [1].

Consequently, for the Distribution System Operators (DSO), it is facing difficulties in making decisions about upgrading its power distribution system and possible investment on ESS from users and other companies in order to ensure the reliable and efficient power supply for growing load demand. Some companies named as integrated energy service provider (IESP) are interested in investing on ESS because there is potential revenue coming from the ancillary service and the electricity price difference between peak load hours and valley load hours within a day. As a result, the utility has to consider the possible benefit of ESS on delaying expansion of power distribution system even though they may cover part of fare on ESS construction and operation in their budget. What calls for attention is that though ESS may play an important role in peak load shaving, frequent charge and discharge of ESS may do harm to its original lifespan, which needs to be considered in the distribution system planning model [2].

In fact, the components of traditional distribution system expansion planning (DSEP) generally include network structure planning [3], substation planning [4], coordinated planning [5], etc. Nevertheless, the relevant study has limited content in ESS constructed in distribution network, which may have a significant overall impact on power flow [6], voltage [7] and so on. In [8], a DSEP method considering ESS investment on substations and load side is proposed. However, the ESS investment is all on DSO, and the lifetime cost due to the frequent charging and discharging of ESS is ignored. To further explore the possible benefits of ESS investment in a distribution system, an improved DSEP method is proposed here, which consider investment sharing between IESP and DSO, and IESP's revenue on ESS with detailed ESS lifetime cost formulations.

The rest of this paper is organized as follows: firstly, model formulation is illustrated. Then we present the simplified and solution methods of the proposed model and case studies based on the IEEE 33-nodes distribution system is demonstrated.

MODEL FORMULATIONS

The DSEP method is established as a mixed integer linear programming model (MILP) [8], with constraints denoting the reasonable revenue for IESP and modelling the operation conditions of ESS, as illustrated in Fig. 1.

The proposed model, with massive variables due to the multi-scene analysis for operation, can be solved by Benders decomposition. Where $x^{R,I}$ and $x^{A,J}$ denote vectors of binary variables on replacing and adding lines, x^{ESS} and y^{ESS} are decision variables on ESS investment and operation. k represents the investment proportion on ESS for the utility, and C_{ESS} is the total cost of all ESS in distribution network. P^E, P^R and P^A are the power on fixed, replacing and adding lines, while E^C and E^D are charging and discharging power of ESS in different load scenes. $P(E^C, E^D)$ and $C(E^C, E^D)$ denote selling power income and degradation cost for IESP, $I(x)$ and $M(y)$ are the investement and operation cost of IESP on ESS. α is a certain parameter for IESP revenue, thus the inequality $P(E^C, E^D) - C(E^C, E^D) - I(x) - M(y) \geqslant \alpha$ guarantees the profits for IESP, which can help the utility attract more capitals on ESS. By implementing Benders decomposition, the solving of this model has been accelerated significantly, thus producing an optimal planning result for distribution system planner within acceptable time.

It should be noted that some formulations are already proposed in [8], thus some details are omitted in following context due to the limited space.

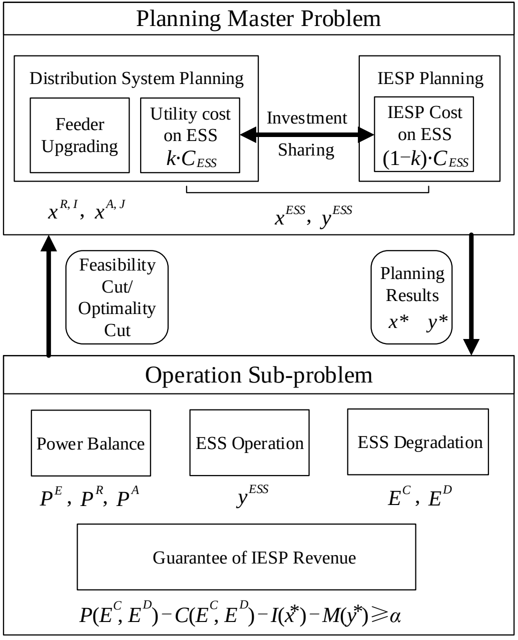

Fig. 1. Mixed integer planning model considering operation problem.

Objective Function

The model is aimed at minimizing the comprehensive cost of construction and operation for the distribution network expansion in typical scenarios, from the perspective of the utility. Consequently, the objective function can be divided into the following five parts based upon past planning experience.

1) Investment and construction cost

The utility's investment costs are mainly for replacing and building new circuits, while may also cover partial fare on ESS, majority of which is normally paid by IESP. The expression combines the investment cost with relevant binary variable x which denotes whether there is a replacing or new line construction.

$$C_{INV} = C_{IL} + k \cdot C_{IE} \tag{1}$$

$$C_{IL} = \sum_{i \in \Psi^{RL}} \sum_{I \in \Omega_i^{CR}} C_{RL,i}^{I} x_i^{R,I} + \sum_{j \in \Psi^{AL}} \sum_{J \in \Omega_j^{CA}} C_{AL,j}^{J} x_j^{A,J} \tag{2}$$

Where C_{INV} represents utility's overall investment and construction cost, C_{IL} and C_{IE} are the cost of circuits and ESS, respectively. k is the investment proportion on ESS for the utility, i and j denote the lines to be replaced and added, Ψ^{RL} and Ψ^{AL} represent the corresponding sets of these lines. I and J are the type selections for replacing and new circuits, Ω^{CR} and Ω^{CA} are the sets of these alternatives. C_{RL} and C_{AL} represent the cost of each replacing and adding line.

2) Operation and maintenance cost

Similarly, this part of cost mainly depends on the operating state of distribution feeders, which is denoted by the binary variable y, and may include part of maintenance cost of ESS.

$$C_M = C_{ML} + k \cdot C_{ME} \tag{3}$$

$$\begin{aligned} C_{ML} = & \sum_{e \in \Psi^{EL}} O_{EL,e} y_e^{E} + \sum_{j \in \Psi^{AL}} \sum_{J \in \Omega_j^{CA}} O_{AL,j}^{J} y_j^{A,J} \\ & + \sum_{i \in \Psi^{RL}} \left(O_{RL,i}^{0} y_i^{R,0} + \sum_{I \in \Omega_i^{CR}} O_{RL,i}^{I} y_i^{R,I} \right) \end{aligned} \tag{4}$$

Where C_M represents utility's total operation and maintenance cost, C_{ML} and C_{ME} are the fare on distribution network and ESS, respectively. e denotes the existing lines which remain unchanged in the planning period, Ψ^{EL} represents the sets of these lines. O_{EL}, O_{RL} and O_{AL} represent the operation fare of each fixed, replacing and adding line.

3) Degradation cost of ESS

In fact, repeated charge and discharge process will wear the battery faster and do harm to its lifespan. Considering the utility may cover partial cost of the ESS built up in the distribution system, the cost referred as C_{CDC} should be illustrated as follow in equation (5).

$$C_{CDC} = k \sum_{s} \rho_s \sum_{h} C_h^{cdc} \left(\sum_{n \in \Pi^{EN}} \left| E_{n,h,s}^{D} \right| + \left| E_{n,h,s}^{C} \right| \right) \tag{5}$$

Where h denotes the hour under typical scenarios, s denotes different load scenario, ρ_s is the ratio of scenario s to planning period. C^{cdc} represents the cost of unit charge/discharge power, E^D and E^C represent charging and discharging power of all the ESS, and Π^{EN} represents the set of nodes to build up ESS.

4) Power transaction cost

For utility, there are two choices to purchase the required electricity: one is from the main grid (MG), the other is from ESS built up by IESP. The peak and valley time price is taken into account in this electricity transaction process, thus accounting for the main sources of IESP's revenues. Note that the purchasing cost from ESS should be multiplied by a coefficient, for the utility bear the partial expenses of ESS investment and operation.

$$C_{PT} = (1-k) \cdot C_{PES} + \sum_{s} \rho_s \sum_{h} P_{R,h}^{BUY} g_{s,h} \tag{6}$$

Where C_{PT} represents utility's cost on purchasing electricity, C_{PES} represents the income from selling power from ESS. P^{BUY} represents the electricity price of main grid, $g_{s,h}$ is the total generated power in the distribution system.

5) Value of lost load (VOLL)

The load which is not supported by each bus can be a valid reliability index for power supply and denoted by r. The cost coefficient of lost load denoted by V_{OLL} should be a relatively high value to avoid the outage in the load nodes.

In conclusion, the objective function is illustrated in equation (7).

$$\min\left(C_{INV}+T\left(C_{M}+C_{CDC}+C_{PT}+V_{OLL}\sum r\right)\right) \tag{7}$$

Where *T* represents the time for the ditribution network expansion planning.

Constraints

The DSEP model proposed in [8], which considers conventional planning constraints based on Kirchhoff's current law, node voltage limits, feeders' capacity, construction logic, load shedding etc., will not be discussed here. Furthermore, there are some expansion constraints illustrated below.

1) Planning and operation constraints for ESS

$$E_{n,h+1,s}^{E}=E_{n,h,s}^{E}+\left(\eta_{n}^{C}E_{n,h,s}^{C}-\frac{1}{\eta_{n}^{D}}E_{n,h,s}^{D}\right) \tag{8}$$
$$h=1,2,\cdots,23$$

$$\sum_{N\in\Omega_{n}^{CES}} y_{n}^{ESS,N}E_{n,\min}^{E,N}\leq E_{n,h,s}^{E}\leq\sum_{N\in\Omega_{n}^{CES}} y_{n}^{ESS,N}E_{n,\max}^{E,N} \tag{9}$$

$$E_{n,h,s}^{E}=E_{n,0}^{E}\qquad h=1,24 \tag{10}$$

$$E_{n,h,s}^{D}\leq\sum_{N\in\Omega_{n}^{CES}} y_{n}^{ESS,N}E_{n,\max}^{D,N} \tag{11}$$

$$E_{n,h,s}^{C}\leq\sum_{N\in\Omega_{n}^{CES}} y_{n}^{ESS,N}E_{n,\max}^{C,N} \tag{12}$$

Where E^C, E^D and E^E represent charging, discharging and storage power, η^C and η^D are the charging and discharging efficiency, $E_{\min}^{E}$, $E_{\max}^{E}$ and E_{0}^{E} are the upper limit, lower limit and initial value of ESS storage capacity, $E_{\max}^{C}$ and $E_{\max}^{D}$ denote the upper limit of ESS charging and discharging power.

2) IESP revenue constraints

In this paper, IESPs cover most of the fare on ESS including investment, operation and maintenance cost, and make money from ancillary service and the electricity price difference during a day. It is assumed that in the planning period, the revenue of IESP is guaranteed to be above a certain threshold, thus facilitating the utility to attract investment.

$$\sum_{T}\frac{1-k}{\left(1+i\right)^{T-1}}\left(T\left(C_{PES}-C_{ME}-C_{CDC}\right)-C_{IE}\right)\geq\alpha \tag{13}$$

Where i denotes the discount rate, α is the guarantee for overall revenue. C_{PES} represents the income from selling power of ESS, while C_{IE} and C_{ME} are the investement and operation cost on ESS. These three variables are illustrated in the following equations.

$$\begin{aligned}C_{PES}&=\sum_{s}\rho_{s}\sum_{h}P_{R,h}^{ESS}\sum_{n\in\Pi^{EN}}E_{n,h,s}^{D}\\&\quad-\sum_{s}\rho_{s}\sum_{h}P_{R,h}^{BUY}\sum_{n\in\Pi^{EN}}E_{n,h,s}^{C}\end{aligned} \tag{14}$$

$$C_{IE}=\sum_{n\in\Pi^{EN}}\sum_{N\in\Omega_{n}^{CES}}C_{ESS,n}^{N}x_{n}^{ESS,N} \tag{15}$$

$$C_{ME}=\sum_{n\in\Pi^{EN}}\sum_{N\in\Omega_{n}^{CES}}O_{ESS,n}^{N}y_{n}^{ESS,N} \tag{16}$$

Where P^{ESS} denotes the electricity price of ESS, C_{ESS} and O_{ESS} represent the investment and operation cost of ESS, respectively.

MODEL SIMPLIFICATION AND SOLUTION METHOD

The problem formulation in this paper is modelled with YALMIP, and CPLEX is used for calculation. To accelerate the convergence speed, and ease the difficulty of solution-searching, the following methods are adopted.

Reducing Unnecessary Constraints

Usually, the voltage constraints are not necessary in every node during all the load scenarios. For IEEE 33-nodes distribution system, the voltage of the first node is fixed to dispense with voltage constraints, and for the rest nodes, we only need to restrict whose voltage is under heavy loading scenarios.

Benders Decomposition

The mixed integer programming model is decomposed into one planning master problem dealing with integer variables and one operation sub-problem dealing with continuous variables, thus simplifying the model and accelerating the solution process to a great degree. Therefore, the first stage goal is to determine the investment and operation decision variable of circuits and ESS, these variables are then transferred to the second stage to figure out the charging and discharging power of those ESS under the guarantee of IESP's revenue. When you solve the first stage problem the ESS operation conditions of the second stage problem is bounded by the optimality cuts. Each iteration of the operation sub-problem adds one cut to the planning master problem, whereas each run of the master problem only replace the old set of decision variables.

CASE STUDY

Case Conditions

The topology based on IEEE 33-nodes distribution system for expansion planning is illustrated in Fig. 2, where double solid lines, single solid lines and dotted lines represent the fixed, replacing and adding circuits, respectively. There are four typical load scenarios corresponding seasons in the planning period, which consults the data in IEEE-RTS [9]. The candidate nodes for ESS construction is the rest 32 nodes except the first one (slack bus) in the topology, and in this planning method, the amount of newly-built ESS is no larger than 6, whose type options are given as Table I. As for the peak and valley electricity price, this paper refers to the data from Guangzhou Power Supply Bureau, and the ratio of peak, flat, and cereal electrovalence is 1.65: 1: 0.5.

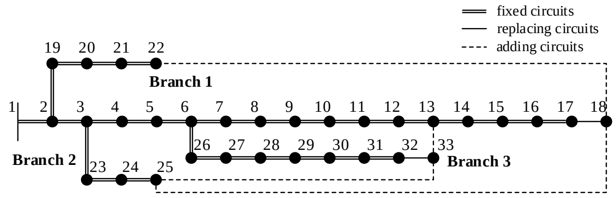

Fig. 2. Topology of the 33-node distribution network.

TABLE I. CANDIDATE TYPE OPTIONS OF ESS

Candidate sites	**Options of ESS**		
	Max output (MW)	**Energy capacity (MW·h)**	**Construction cost (10^4US$)**
Node 2-33	0.2	2	50
	0.4	4	100
	0.8	8	200

Result Analysis

Two different cases are calculated as follows to prove the fact that ESS investment can relieve the pressure from upgrading distribution system.

- Case1: replacing or adding new circuits in the original distribution system with no ESS to be built.
- Case2: considering IESP's building ESS on the basis of Case1 under constraints of IESP revenue guarantee (investment proportion *k* can be set from 1 to 0).

The case results are given in Table II (the proportion *k* in Case2 is 0.2), and daily load curves on the same adding line (node25-33) of this two cases under four scenarios denoted by S1, S2, S3 and S4 is illustrated in Fig. 3. Noted that in IEEE-RTS, spring and fall scenarios have the same daily data, resulting in there being only three curves in Fig. 3 (the curve of S1 is coincided with that of S3).

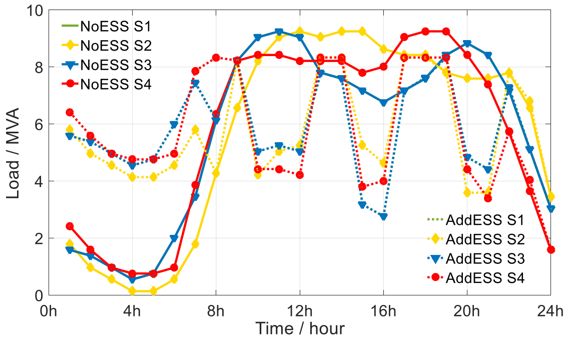

Fig. 3. Daily load curve in case2.

TABLE II. CALCULATION RESULTS OF TWO CASES

	Case	**Case1**	**Case2**
The utility	**Total cost (10^4US$)**	29527	25824
	Construction cost of lines (10^4US$)	689	555
	Construction cost of ESS (10^4US$)	0	240
	Operation cost of ESS (10^4US$)	0	25
	Charge- discharge cost (10^4US$)	0	167
	Purchase fee from MG (10^4US$)	28621	22495
	Purchase fee from ESS (10^4US$)	0	2125
IESP	**Total cost (10^4US$)**	—	1729
	Construction fare of ESS (10^4US$)	—	960
	Operation fare of ESS (10^4US$)	—	101
	Charge- discharge cost (10^4US$)	—	668
	Revenue (10^4US$)	—	396

It can be concluded that because the price of ESS selling power is between the peak load price and the valley price of main grid, ESS can play the role of load shedding and shaving, thus not only decreasing the purchase cost from main grid, but also reducing the maximum current flowing through feeders, which will provide cheaper schemes for line construction. The planning results of case2 are shown in Fig. 4.

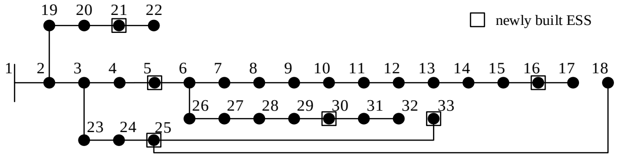

Fig. 4. Topology of distribution network in case2.

By adjusting the investment proportion *k* in case2, the cost of ESS investment, operation and charge- discharge process covered by the utility will also change. The results under different investment proportion including the revenue of IESP and total cost of the utility which are the major concern in the planning problem are shown in Fig. 5. Actually, no matter what value the proportion is, total cost of the utility is less than that of case1, which proves the economic benefit brought by construction of ESS. As *k* becomes larger, the total cost of the utility will reduce while IESP's revenue will increase at first and then decrease. For each situation a certain investment proportion will be determined to keep the utility cost as small as possible under securing enough profits of IESP. To interest more IESPs in investing on ESS, the guarantee of their revenue should be higher, which will restrict the proportion to a certain range.

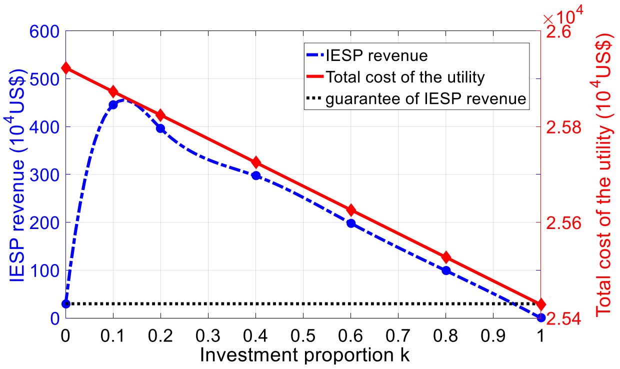

Fig. 5. IESP's revenue and the utility's cost considering different investment sharing propotion on ESS.

In this paper, the model is solved by two methods, one is Branch & Bound and the other is Benders decomposition. Comparing the solver time of these two methods in Table III, it is obvious that Benders strategy will accelerate the solving process.

TABLE III. PERFORMANCE COMPARISON (UNIT: SECOND)

Method	**Case 1**	**Case 2**		
		k=0	*k*=0.2	*k*=0.4
Branch & Bound	3.27	242.02	415.58	205.30
Benders decomposition	0.56	56.36	20.71	85.06

Moreover, what is illustrated above about co-optimizing decisions on adding new and replacing old feeders, and sizing and siting of ESS will help Guangzhou Power Grid Corp.(GPGC) to achieve a balance between expansion of distribution system and ESS investment. Additionally, the method proposed in this paper which considers rationally sharing the investment cost on ESS between the utility and IESP can also provide practical decision-making for both of them. In fact, we have successfully attracted some IESP to invest on ESS after negotiation and making this information public. IESP decided to invest 8MW/40MWh ESS on demand-side which is illustrated in Fig. 6.

Fig. 6. Energy Storage System invested by Integrated Energy System Provider and Guangzhou Power Grid Corp. (8MW/40MWh).

CONCLUSION

In this paper, a distribution system expansion planning method considering IESP's revenue on ESS is proposed and solved by Benders decomposition. As for planning master problem, siting for ESS, replacing and constructing circuits are all taken into account, while in operation sub-problem ESS operation and degradation are discussed to reduce the cost of the utility under the guarantee of IESP's revenue. Note that peak-valley price is considered in this model to ensure the profits of IESP by selling power during peak load time and charging ESS in valley time, thus helping peak shaving.

The calculation results show that ESS may contribute to less cost on upgrading power lines and delay expansion of distribution system. By sharing the investment cost on ESS, the utility will effectively cut expenses as well as obtaining a possible higher revenue to attract IESP investing on ESS.

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