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OPTIMAL DISTRIBUTION SYSTEM PLANNING CONSIDERING REGULATION SERVICES AND DEGRADATION OF ENERGY STORAGE SYSTEMS

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ABSTRACT

An optimal planning method is proposed for power distribution system with energy storage systems (ESS) in this paper, in which the degradation and ancillary service revenue on frequency regulation of ESS are both considered, as well as the network configuration, siting and sizing for ESS and substation expansion. The problem is formulated as a mixed integer programming (MIP) one to optimize the overall planning cost, including investment and operation cost, power transaction cost, revenue from regulation services and degradation of ESS. In addition, the model co-optimizes charging/discharging of ESS to earn money from regulation services and prolong ESS's lifetime simultaneously by adding a penalty term in the objectives, thus further benefiting the economy of the distribution system. A planning problem based on IEEE 33-bus system is tested to demonstrate the effectiveness of the proposed method.

Keywords: frequency regulation, network configuration, energy storage system (ESS), mixed integer programming (MIP), degradation penalty

NONMENCLATURE

Abbreviations	
SUB	Substation
INV	Investment
OPE	Operation
fL	Fixed Lines
cL	Candidate New Lines
PT	Power Transaction
REG	Regulation (Services)
Deg	Degradation
Symbols	
N	Type selections of lines, substations and ESSs
n	Candidate nodes for ESS construction
t	Hour index
s	Typical scenario index
θ_s	Ratio of scenario s to planning period
T	Number of hours in planning period
x	Binary investment decision variables
y	Binary operation decision variables
Y	Linearization degradation term
β	Vector of decision variables on ESS actual operation
g	Power bought from the bulk power system (MW)
c, d	Charge/discharge power of ESS (MW)
r_u, r_d	Committed capacity for regulation up/down (MW)
S	ESS State of charge (MWh)
L	Locational marginal price ($/MW)
$C_{REG,u}$, $C_{REG,d}$	Revenue for committing unit capacity for regulation up/down ($/MW)
P_{max}	Maximum power output of ESS (MW)
σ_u^2, σ_d^2	Variance of regulation up/down signals
p_u^t, p_d^t	Mathematical expectation of regulation up/down signals
Π_u, Π_d	New variables for decision variable relaxation

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1. INTRODUCTION

The recent years have witnessed a dramatic rise in the application of ESS to various scales of power systems, owing a lot to its capability of providing energy arbitrage and ancillary services (AS), as illustrated in Fig 1. Once the ESS is constructed in a distribution system, it can play an important role in load shaving and committing regulation capacity to earn money from bulk power system, which may cut down the expenses in the whole planning process. Nevertheless, the feasibility of this strategy still needs to be further explored, and the degradation of ESS capacity may also cause difficulty in real time operations.

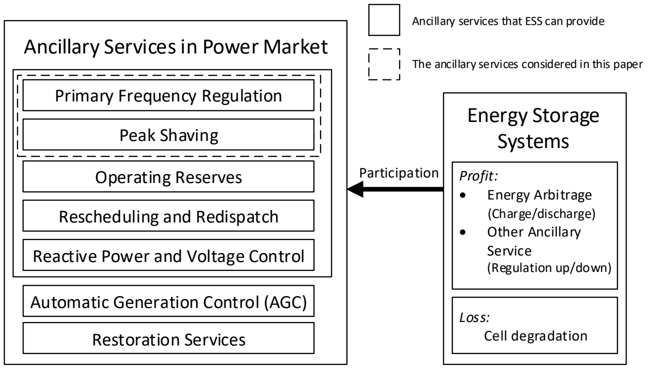

Fig 1 Overview of the relationship between power ancillary service market and ESSs

Gradually, an increasing number of relevant studies appear in the grid planning field. To estimate ESS's lifespan, some semi-empirical battery degradation models [1]-[3] have been proposed and rules of degradation rates are simplified [4] to evaluate ESS profitability. When cell degradation is considered in grid planning problems, more profits can be obtained [4]-[5]. However, some studies only calculate the total revenue of ESSs without applying the degradation model to distribution system, and others ignore the influence of battery's charge-discharge behavior on its operating life.

Besides, the research about ancillary services provided by ESS has become a hot topic. But most of this work has mainly discussed the issues on battery control strategies [6], or has not expended the model to distribution system scale [7]. Therefore, in this paper we proposed a method which combines optimal distribution system planning with ESS regulation services and degradation model.

2. MODEL FORMULATION

The distribution system planning problem considering ESS degradation and regulation services is established as a MIP model, illustrated in Fig 2.

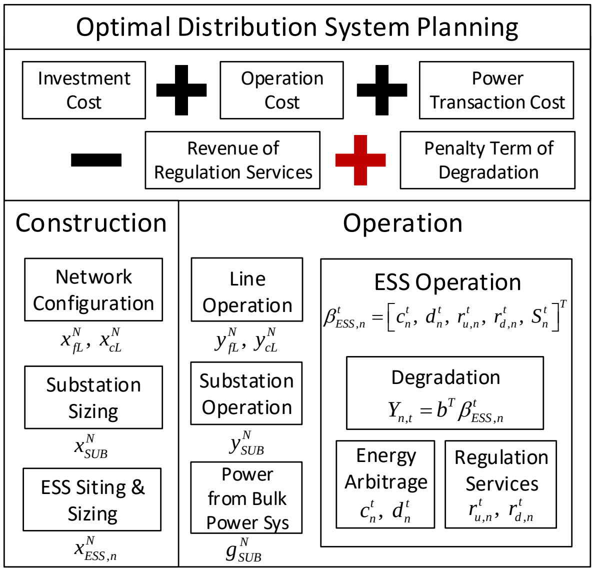

Fig 2 Overview of the MIP model

The objective includes five expenses within the construction and operation period. Network configuration, substation sizing and ESS siting and sizing make up all the missions in the construction stage, where vectors of binary variable x determine whether to invest the facilities or not. As for operation, the decision variables can be divided into y and β. The former are the binary vectors representing the operating lines, substation and ESSs. While the latter is a continuous vector only related to ESS's actions, including the charge/discharge, regulation up/down and state of charge (SOC). By multiply this β with a matrix b^T, the linear degradation model can be obtained.

Noted that some relevant details about distribution system expansion planning [8] and battery degradation [4] are omitted in the following context due to the space limitation.

2.1 Objective

For the planning period, the distribution system will invest in substation, lines and ESSs, whose operation fare will also be covered in overall cost. Besides, electricity needs to be bought from bulk power system as power transaction cost, which will be affected by ESS operation.

Meanwhile, ESSs will provide regulation services to bulk power grid. In this paper, the overall cost of distribution system is minimized, consequently the revenue of regulation services should be subtracted from other expenses mentioned before. To prolong ESS's lifespan, a linear term relevant to degradation model is added to the objective function.

2.1.1 Investment cost

The distribution system needs to bear the investment cost of lines, substation and ESSs, denoted in equation (1). As for line construction, both the investment on fixed lines and candidate new ones should be taken into account.

$$\begin{aligned} C_{INV} = & \sum_{fL} C_{fL}^N \cdot x_{fL}^N + \sum_{cL} C_{cL}^N \cdot x_{cL}^N \\ & + C_{SUB}^N \cdot x_{SUB}^N + \sum_{n} C_{ESS,n}^N \cdot x_{ESS,n}^N \end{aligned} \tag{1}$$

2.1.2 Operation cost

Similarly, the total operation cost needs to involve all the components in the distribution network. Here O represents operation fare of different facilities.

$$C_{OPE} = \sum_{fL} O_{fL}^N \cdot y_{fL}^N + \sum_{cL} O_{cL}^N \cdot y_{cL}^N + O_{SUB}^N \cdot y_{SUB}^N + \sum_{n} O_{ESS,n}^N \cdot y_{ESS,n}^N \tag{2}$$

2.1.3 Power transaction cost

To supply the load demand, power is bought from the bulk power system and denoted as actual power transmitted by the substation. This paper considers four typical scenarios representing different seasons, thus setting θ_s as 0.25. The data sets for locational marginal price named as L_{SUB}^t can be consulted in [9].

$$C_{PT} = \sum_{s} \theta_s \sum_{t=0}^{T} L_{SUB,s}^t g_{SUB,s}^{t,N} \tag{3}$$

In addition, the power transaction cost will be influenced by the regulation up/down and charge/discharge actions of ESSs, known as regulation services and energy arbitrage, respectively.

2.1.4 Revenue of regulation services

In real time operations, for ESS's committing unit capacity to regulation services at hour t, there will be corresponding revenue earned. Variable r_u^t and r_d^t are nonnegative decision variables and the regulation price data sets named as $C_{REG,u}$ and $C_{REG,d}$ can be found in [9].

$$C_{REG} = \sum_{s} \theta_s \sum_{t=0}^{T} \sum_{n} \left(C_{REG,u,s}^t \cdot r_{u,n}^t + C_{REG,d,s}^t \cdot r_{d,n}^t \right) \tag{4}$$

2.1.5 Penalty term of degradation

According to [4], a linear term reflecting degradation rates of ESSs is formulated as following equations so as to mitigate this degradation during operation. Variable a_1, a_2 and p_z are the constants already given, which will affect the degradation rates of different ESS's actions.

$$Y_{n,t} = b^T \beta_{ESS,n}^t \tag{5}$$

$$\beta_{ESS,n}^t = \left[c_n^t,\ d_n^t,\ r_{u,n}^t,\ r_{d,n}^t,\ S_n^t \right]^T \tag{6}$$

$$b = \begin{bmatrix} \frac{a_2}{4}(1-p_z) \\ \frac{a_2}{4}(1-p_z) \\ \frac{a_1^2 p_z}{2a_2} y_{ESS,n}^N P_{\max}^N \left(1.5\sigma_{t,u}^2 - 0.5\sigma_{t,d}^2 - p_u^t p_d^t\right) \\ \frac{a_1^2 p_z}{2a_2} y_{ESS,n}^N P_{\max}^N \left(1.5\sigma_{t,d}^2 - 0.5\sigma_{t,u}^2 - p_u^t p_d^t\right) \\ 0 \end{bmatrix} \tag{7}$$

As illustrated in Fig 2, five expenses are involved in the objective, with both regulation services and degradation of ESSs taken into consideration.

$$\min C_{INV} + C_{OPE} + C_{PT} - C_{REG} + \sum_{t=0}^{T} \sum_{n} M_t^{\deg} \cdot Y_{n,t} \tag{8}$$

2.2 Constraints

This paper considers massive constraints including Kirchhoff's current law (KCL), node voltage limits, feeders' capacity [8], and ESS operation constraints [4]. Furthermore, some extra constraints are supposed to be obeyed in the planning.

2.2.1 Construction logical constraints

The sum of decision variables for construction alternatives of the same facility is no larger than 1, for building redundant project is not allowed. Additionally, the substation and ESSs will only be available after their construction, thus making the operation decision variables no larger than the investment ones.

$$\sum_{n} x_{ESS,n}^N \le 1,\ \sum x_{SUB}^N = 1 \tag{9}$$

$$y_{ESS,n}^N \le x_{ESS,n}^N,\ y_{SUB}^N \le x_{SUB}^N \tag{10}$$

$$\sum_{fL} y_{fL}^N + \sum_{cL} y_{cL}^N = 32 \tag{11}$$

Moreover, no isolated node and loop will exist in the distribution network, so the amount of all the lines constructed must be 32.

2.2.2 Constraints relaxation by big-M method

From equation (5)-(7), it is observed that the binary decision variables $y_{ESS,n}^N$ are multiplied with another continuous ones r_n^t, which leads to nonlinearity. Thus a big-M method is adopted here to relax the product of these two decision variables by introducing new variables $\Pi_{u,n}^{N,t}/\Pi_{d,n}^{N,t}$.

$$\Pi_{u,n}^{N,t} \le r_{u,n}^t,\ \Pi_{d,n}^{N,t} \le r_{d,n}^t \tag{12}$$

$$r_{u,n}^t \le \Pi_{u,n}^{N,t} + M \cdot \left(1 - y_{ESS,n}^N\right) \tag{13}$$

$$0 \le \Pi_{u,n}^{N,t} + M \cdot y_{ESS,n}^N \tag{14}$$

$$r_{d,n}^t \le \Pi_{d,n}^{N,t} + M \cdot \left(1 - y_{ESS,n}^N\right) \tag{15}$$

$$0 \le \Pi_{d,n}^{N,t} + M \cdot y_{ESS,n}^{N} \quad (16)$$

3. CASE STUDIES AND DISCUSSION

3.1 A Modified 33-node System Planning

3.1.1 Network configuration

The planning network is based on IEEE 33-node distribution system in Fig 3. There are 32 solid lines representing fixed branches and 5 dotted ones denoting candidate new lines. In the planning period, the topology can be changed with some new feeders built and other fixed lines abandoned. As mentioned in Section 2.2.1, no isolated node and no loop are allowed in the final network topology, which means only 32 branches will be built. Three types of lines which vary in impedance, power capacity and investment spending are considered in this paper.

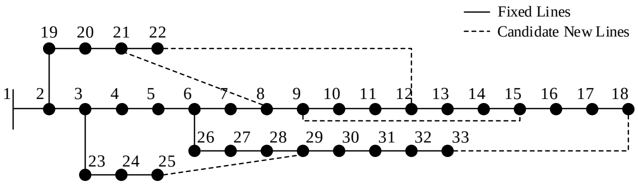

Fig 3 Configuration of the 33-node distribution network

3.1.2 Options of facilities

Apart from line construction, we consider siting and sizing of ESSs, whose candidate locations are the rest 32 nodes except the first one (slack bus). As for substation, it will be built at node 1, with three types different in capacity and cost to select. Options of all the facilities in the system are given in Table I. And the data sets of typical load scenarios corresponding four seasons come from IEEE-RTS [10].

Table I Options for Facilities in the Distribution System

Facilities	**Different Options**		
	Candidate nodes	**Capacity (MW/A)**	**Construction cost (10^4US$)**
SUB	1	5	8
		10	12
		15	15
ESS	2-33	2	30
		4	60
		8	119
Line	1-33	300	Affected by different distances of 32 circuits.
		500	
		800	

3.2 Planning Results

Assume that the planning scheme will last for 15 years and three cases are designed as below, forming two groups of control experiments.

- Case1: Both regulation services and degradation penalty term of ESSs are calculated in the model;
- Case2: Degradation penalty term is ignored;
- Case3: Regulation services of ESSs are ignored.

Case1 adopts the optimal planning method proposed in this paper as the control group, while Case2 and Case3 are two experimental groups. All these cases will be modeled with YALMIP, and CPLEX is used for their calculation. Through pairwise comparison among three cases, the significance of considering regulation services and degradation penalty can be proved separately.

3.2.1 Network topology

The network topologies of three cases are shown as follows, with those small boxes representing ESSs' locations. The network topology of Case2 is the same with that of Case3. However, no ESS will be built in Case3 since the revenue from regulation services is crucial to the investment efficiency of ESSs. Therefore, the boxes in Fig 5 only denote the ESSs built in Case2.

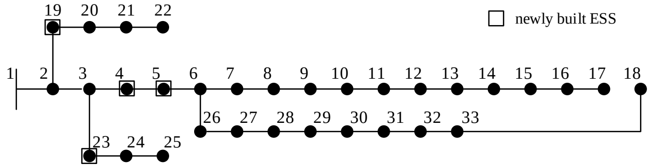

Fig 4 Final topology of the distribution network in Case1

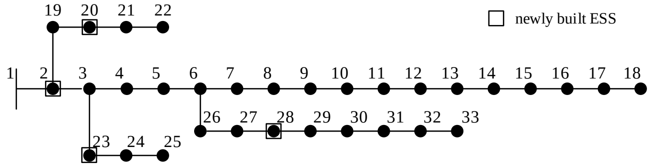

Fig 5 Final topology of the distribution network in Case2(3)

It can be concluded that there are some differences between these two topologies in line construction and ESS siting, indicating that the maximum currents flowing through the lines will be changed with the addition of degradation penalty term.

3.2.2 Economic analysis

In Table II, all the expenses constituting the objective function are listed which serve as economic parameters in each case. Obviously, Case2 is the cheapest because it makes money from ESSs without considering the influence of degradation. While Case3 is the most expensive scheme because of no ESS being built, resulting in no profits in the distribution system.

Table II Economic Parameters in Different Cases

Terms (10^4US$)	Case1	Case2	Case3
Total cost	**4331.08**	**4261.12**	**4513.72**
Investment cost of line & SUB	35.09	35.12	35.12
Investment cost of ESS	476	476	0
Total Investment cost	511.09	511.12	35.12
Total operation cost	39.30	39.30	11.70
Power transaction cost	4341.50	4344.50	4466.90
Regulation services revenue	628.28	633.80	0
Degradation penalty	67.47	0	0

In both Case1 and Case2, the ESSs invested are with the biggest capacity provided in Table I. In other words, once regulation services are considered in the planning period, the valuation of ESS is improved significantly. Subsequently, the least cost spent on purchasing electricity is found in Case1, demonstrating that energy arbitrage and ancillary services of ESSs will reduce the power transaction fare, as mentioned in Section 2.1.3.

Furthermore, several phenomena of trading in power market can be summarized by comparing Case1 and Case2. Sometimes more regulation revenue can be obtained at the expense of more investment fare and power transaction cost (Case2). This normally happens when degradation rates of ESS's actions providing AS decline evidently or the revenue of AS dominates over the locational marginal price.

3.2.3 Comparison of ESS degradation

To further study the influence of degradation term in the objective function, the degradation curves of Case1 and Case2 are compared in Fig 6.

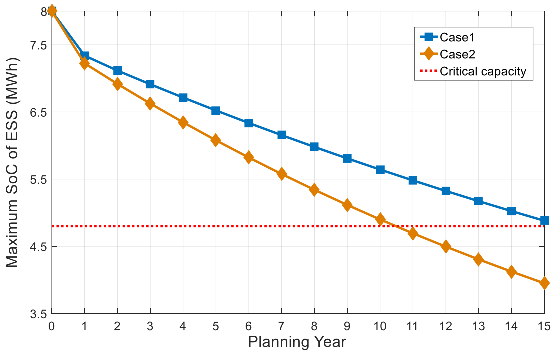

Fig 6 ESS capacity degradation behavior in Case1 & 2

Despite that the curve of Case2 decreases much faster than that of Case1, they have similar rules of degradation behavior. If the ESS can only provide no more than 60% of the rated maximum capacity, we assume that its lifetime is over. Consequently, the ESSs in Case1 can be in operation during the whole planning period while in Case2 ESSs actually work for 10 years. Based on that, the planning results of Case2 are updated in Table III where the ESSs will operate in the first decade and stop for the left five years.

Table III Preliminary and Actual Planning Results of Case2

Terms (10^4US$)	Original	Update
Total cost	**4261.12**	**4490.28**
Investment cost of lines	27.12	27.09
Investment cost of SUB	8	8
Investment cost of ESS	476	238
Total Investment cost	511.12	273.09
Total operation cost	39.30	21.10
Power transaction cost	4344.50	4406.50
Regulation services revenue	633.80	210.41

4. CONCLUSIONS

In this paper, both regulation services and degradation penalty of ESSs are considered with the aim of minimizing the overall cost spent on the distribution system planning. The line configuration, substation sizing, ESS siting and sizing on the IEEE 33-node distribution network in a fixed planning years are optimized via the MIP model.

To prove the significance of regulation services and degradation term, three different cases are performed. The case which does not consider regulation services, reaches the highest overall planning cost on account of no ESS being built. That means revenue from regulation services is a decisive factor for the profitability of ESSs.

Regarding to the degradation penalty, the case ignoring it will weed out ESSs five years earlier than the expected planning period thus being less economical than the optimal case.

The above results demonstrate that both revenue of regulation services and degradation term included in the objective function help to extend ESS's lifetime as well as maximizing economic profits of the distribution system.

ACKNOWLEDGEMENT

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