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Optimal allocation of distributed energy storage of distribution network based on equal cost energy ratio

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Abstract. This paper presents a novel algorithm for representing the effects of an optimal configuration of distribution energy storage system (DESS). The method was developed in the context of a framework in power distribution network with DESS, which includes such considerations as: SOC, cost of energy storage device, electricity price, transmission losses. The presented method provides a means for computing an optimal schedule of DESS energy resource allocation for new energy sources and loads power fluctuation, which can synthesize all useful energy storage devices, that is better for system stability and is contributed to the interests of energy storage owners, because energy storage device usually cannot be used adequately. Of particular interest, the method considers the relation between the depth of discharge and the use-cost of different energy storage device and the influences of transmission losses.

1. Introduction

In recent years, the proportion of new energy power generation has gradually increased in China, but the output power of new energy power generation has fluctuations and uncertainties. Power is difficult to absorb electric energy in distribution networks with large-scale new energy power generation devices [1-2]. At the same time, new energy power generation devices such as solar photovoltaic station and wind power station all have their own energy storage devices. Most of these energy storage devices operate independently and lack coordination and interaction. The high penetration rate of new energy brings challenges to the safe and stable of the distribution network. The electric energy which generated by new energy power generation was lack of stability and adjustability. Therefore, a large amount of wind and light source was discarded, which reduces the economic, reliability and environmental protection of the distribution network [3-4]. The energy storage devices in the distribution network lack a coordination mechanism and utilization rate is low, which affects frequency and voltage of the power grid greatly. As a branch of energy storage technology, DESS has the outstanding capability of energy storage device energy storage, and its characteristic of distribution can effectively solve the space problem in the frequency and voltage modulation process [5-6]. However, the cost of energy storage batteries is still high, which greatly limits the commercialization of energy storage technology to participate in frequency and voltage modulation technology. How to properly call each distributed energy storage device to improve economy while maintaining safety and stability is the key to research.

A large number of studies have been conducted to verify the energy storage participation in grid auxiliary services at home and abroad. The feasibility under different scenarios was analyzed considering the characteristics and economy of the energy storage equipment in [7]. The efficiency of energy storage in AGC frequency modulation was verified in [8] by comparing the effect of energy storage with that of hydroelectric, gas and thermal power units, combined with the environmental cost and energy storage construction cost. The cost calculation of energy storage devices were simplified in [9] which taking into account only the investment cost and operation and maintenance cost. An economic evaluation model for the full life of energy storage devices was established in [10], which, combined with the charging and discharging action strategy, verifies the feasibility of energy storage devices as an auxiliary means of frequency modulation.

The above literature verifies the feasibility of energy storage participating in grid auxiliary services [11]. However, none of them is designed into a distributed energy storage system, nor does it reflect the impact of system transmission loss. Although the transmission loss accounts for a small proportion of cost, the heat generated in the power transmission process will lead to the line aging and even the line insulation decline.

A completely distributed algorithm was proposed in [12] that connects the energy storage unit of the dominant node with the control centre to construct a response mechanism. A distributed energy storage regulation strategy was proposed in [13] based on second-order multi-agent system to achieve coordinated control of power and power. Although the above documents propose related algorithms to implement the issuance of control instructions, the energy storage life costs are not considered in the regulation process. In summary, the existing related research on the energy storage participation in the FM problem is rarely considered in the operation of the distributed energy storage system while taking into account the impact of network loss, in the regulation process, the battery cost life is not considered.

To sum up, existing relevant researches on energy storage participation in frequency modulation rarely consider the operation of distributed energy storage system while taking into account the impact of transmission loss. In the process of regulation, battery cost life is also not taken into account.

This paper aims at minimizing the total call cost of the distributed energy storage system. In order to solve the problem of distributed energy storage allocation in the power system, it firstly considers the influence of the transmission loss of the power distribution network on the line and the current state of the energy storage device, and determines the response range of the energy storage battery. The cost of distributed energy storage device to participate in power grid adjustment is obtained by the comprehensive cost of energy storage battery, electricity cost and transmission loss cost. By referring to the principle of equal consumption micro increase rate, the equal cost micro increase rate of each energy storages is calculated in Matlab, and the charging and discharging process of energy storage is adjusted. Finally, an example is given to illustrate the rationality and effectiveness of the model and algorithm.

2. Cost analysis of distributed energy storage system

2.1. Distributed energy storage device cost

Battery is one of the equipment with short life in power distribution network. Frequent charging and discharging will greatly shorten its service life and affect the overall economy of the system. Therefore, it is necessary to establish the corresponding life quantification evaluation model so that the results of energy storage planning can make a reasonable compromise between system operation economy and energy storage service life. There are many factors influencing the service life of energy storage battery, including discharge depth, overcharge amount, charging current, voltage and environmental temperature. Based on the analysis of experimental data, it can be found that under normal working conditions, the discharge depth has the greatest influence on the cycle times of energy storage battery. In this paper, three types of energy storage batteries including lead-acid battery, sodium-sulfur battery and li-ion battery are selected, and the corresponding relation between discharge depth and cycle life is given as shown in **Table 1**[14].

Table 1. Relationship between battery discharge depth and cycle life [14].

depth of discharge	cycle life		
	lead-acid battery	sodium-sulfur battery	li-ion battery
0.1	3800	125092	150000
0.2	2850	41265	50000
0.3	2050	21569	30000
0.4	1300	13612	14000
0.5	1050	9525	10000
0.6	900	7115	8000
0.7	750	5560	7500
0.8	650	4490	6000
0.9	600	3719	5000
1	550	3142	4000

It can be seen from the table that the relationship between cycle life and discharge depth can be represented by the power function model. The lifetime equation of energy storage system is obtained by power function fitting.

$$cyc = a \cdot D_t^{-b} \tag{1}$$

Where a and b are battery coefficients which can be fitted in Matlab, Cyc is the maximum number of charge-discharge cycles in the system life cycle, D_t is battery discharge depth.

According to the total cycle life and total system cost, the relative loss cost of energy storage battery life is defined as

$$C_{loss} = \frac{m \cdot Q_i}{cyc} \tag{2}$$

Where: Q_i is the capacity of energy storage system (MWh), m is the unit investment cost of energy storage system.3

Based on the above equation, the cost function of life loss is obtained as follows:

$$C_{loss} = \frac{m \cdot Q_i}{a \cdot D_t^{-b}} \tag{3}$$

2.2. *The operating cost of distribution network*

The operating cost of distribution network is considered on the basis of the rated capacity and rated power

$$f_2 = \sum_{t=1}^{T_a} \sum_{i=1}^{N_D} (Q_i (\eta_{in} \eta_{out})^{-1} f_{(P_{Git})}) \tag{4}$$

Where: T_a is the number of annual running time periods and this paper takes it as 8760, N_D is the total number of distributed power sources in distribution network, P_{Git} is the output of the *ith* distributed power supply in time period t, $f_{(P_{Git})}$ is the burnup cost function corresponding to the *ith* distributed power supply, η_{in} is charging efficiency and η_{out} is discharge efficiency.

2.3. *The cost of active power loss*

In the optimal configuration of distributed energy storage devices, the distance factor should be fully considered and transmission loss should be included in the configuration cost. This paper only considers the active loss. The objective function of the cost of active power loss as:

$$f_3 = \sum_{i=1}^{n} I_i^2 R_i \cdot T \tag{5}$$

Where: I_i is the rated transmission current of energy storage device *ith*, R_i is the resistance value of energy storage device *ith* transmission line, T is the system configuration cycle.

3. Optimization model

3.1. Objective function

Based on Cost analysis of distributed energy storage system in section 2, the security and economy of the entire system should be considered. The cost model of distributed energy storage is established, which includes battery life, operating cost and the cost of active power loss.

In summary, the total cost of energy storage adjustment F as:

$$F = C_{loss} + f_2 + f_3 \tag{6}$$

In terms of stored energy output power:

$$F = \frac{m \cdot Q_i}{a \cdot (D_{t\text{-}1} + {(P_{Gi} \cdot T)}/{Q_i})^{-b}} + \frac{P_{Gi} \cdot T \cdot f_{dj}}{\eta} + (\frac{P_{Gi}}{U})^2 R \cdot T \tag{7}$$

Where: U is voltage rating of lines.

3.2. Constraint condition

Power balance constraint,

$$\sum_{j=1}^{N_D} P_{\text{Git}} U_j^t + U_{dis}^t P_{dis,t} - U_{ch}^t P_{ch,t} + P_{\text{grid},t} = P_{\text{D},t} \tag{8}$$

Where: $P_{dis,t}$ and $P_{ch,t}$ are the discharge and charging power of energy storage at time t, $P_{\text{grid},t}$ is the power exchange between the distribution network and the large power network in time period t; U_{dis}^t and U_{ch}^t are the discharge and charging states of energy storage at time t. $P_{\text{D},t}$ are system load power demand in time period t, U_j^t is the state in service of energy storage device *j,* 0 means power off and 1means power on.

Line transmission power capacity limit,

$$P_{grid}^{\min} \le P_{grid,t} \le P_{grid}^{\max} \tag{9}$$

Where: $P_{grid}^{\min}$ and $P_{grid}^{\max}$ are respectively the minimum and maximum power allowed by the contract.

Distributed energy storage output power constraint,

$$U_i^t P_{Gi}^{\min} \le P_{\text{Gi},t} \le U_i^t P_{Gi}^{\max} \tag{10}$$

Where: $P_{Gi}^{\min}$ and $P_{Gi}^{\max}$ are the minimum output power of the *i*th distributed power supply.

Distributed storage operation constraints,

$$SOC_i^{\min} \le SOC_i \le SOC_i^{\max} \tag{11}$$

$$\begin{cases} 0 \le P_{ch,\text{i}} \le P_{ch,i}^{\max} \\ 0 \le P_{\text{dis,i}} \le P_{ch,i}^{\max} \end{cases} \tag{12}$$

Where $SOC_i^{\min}$ and $SOC_i^{\max}$ are the SOC upper and lower limit of the *ith* energy storage device, $P_{ch,i}^{\max}$ and $P_{ch,i}^{\max}$ are the upper limits of energy storage charge and discharge power respectively, When the SOC of the energy storage battery *ith* reaches the limit, switch to the next energy storage to continue the power transmission until the scheduling is completed [15].

4. The principal of equal cost energy ratio

4.1. The law of equal consumed energy ratio

In practice, the optimal allocation problem of active power load with unlimited energy consumption can be considered as the optimal distribution problem of active power load between thermal power generation equipment and thermal power plants. In order to simplify the preliminary analysis, the load distribution is limited to two sets of power generation equipment or two power plants, and network loss is omitted. In mathematics, the method of Lagrangian multipliers is often used to solve such problems. According to the given objective function and equal constraint conditions, a new unconstrained objective function, Lagrangian function, can be established.

$$C^* = F_1(P_{G1}) + F_2(P_{G2}) - \lambda(P_{G1} + P_{G2} - P_{L1} - P_{L2}) \quad (13)$$

Where: $F_i(P_{Gi})$ is the energy consumed per unit of time when power generating equipment *ith* provides active power, P_{Gi} is the active power provided by power generating equipment *ith*, P_{Li} is the line loss from power generating equipment *ith*, λ is Lagrange's multiplier.

When computing the minimum of C^*, it can be obtained from the above three conditions as:

$$\frac{\partial F_1(P_{G1})}{\partial P_{G1}} - \lambda = 0 \quad (14)$$

$$\frac{\partial F_2(P_{G2})}{\partial P_{G2}} - \lambda = 0 \quad (15)$$

$$f(P_{G1}, P_{G2}) = P_{G1} + P_{G2} - P_{L1} - P_{L2} = 0 \quad (16)$$

In addition, since $\frac{\partial F_1(P_{G1})}{\partial P_{G1}}$ and $\frac{\partial F_2(P_{G2})}{\partial P_{G2}}$ are respectively the micro increase rate of consumption when the power generation equipment 1 and 2 bear the active power load respectively,

$$\lambda_1 = \lambda_2 = \lambda \quad (17)$$

In order to minimize the total consumption, the load should be distributed between the generating equipment or the power plant at the same rate of micro increase. This is equal consumed energy ratio.

4.2. The principal of equal Cost Energy Ratio

This paper refers to the preparation of equivalent consumption micro-increment mentioned above. First, the system network loss cost is weighted, and the weight coefficient A is applied to the original network loss foundation, and then the consumption coefficient of distributed energy storage device I_F is calculated and prioritized.

$$I_F = \frac{\partial (C_{loss} + f_2 + A \cdot f_3)}{\partial P_G} \quad (18)$$

Where: P_G is the transmission power.

I_F can be calculated in simulation software Matlab, which can be obtained in the following steps:

Step1: DESS receives call instruction, including node, mark of charge and discharge, power, energy requirement and impedance.

Step 2: identify the function of energy storage in this call，1 means charge and 2 means discharge.

Step 3: Select energy storage device according to power.

Step 4: Select energy storage device according to SOC (The remaining power supply meets the demand of one cycle T. In this paper, T is 30 min).

Step 5: Energy storage devices are sorted and used according to I_F.

Step 6: When a cycle finished, Update DESS status and restart until the call end.

5. Simulation

The IEEE33 node system was selected as the example in this paper. Its topology is shown in Figure 1. Distributed energy storage power supplies are arranged at nodes 2, 11, 17, 20 and 27 respectively. Those devices are established by grid or new energy company. According to the corresponding relation between discharge depth and cycle life of three energy storage batteries, the corresponding function is as follows.

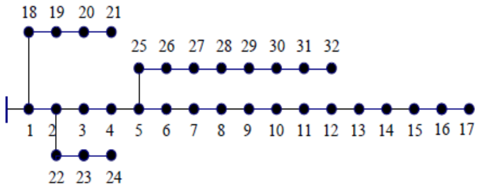

Figure 1. System of IEEE33.

Table 2. The Technical Parameters of Energy storage power.

Node	type of battery	capacity	charge efficiency
2	sodium-sulfur battery	1 MWh	90%
11	lead-acid battery	1 MWh	80%
17	li-ion battery	1 MWh	**95%**
20	li-ion battery	1 MWh	**95%**
27	lead-acid battery	1 MWh	80%

The data of type discharge depth of energy storage battery and number of battery cycle in Table 2 were respectively fitted, and the fitting curve was shown in Figure 2, Figure 3 and Figure 4. In this paper, the relationship between battery discharge depth and battery cycle number is expressed by power function. The life equation of energy storage system obtained by power function fitting is,

$$cyc_{la} = 674.5D^{-0.7775} \tag{19}$$

$$cyc_{ss} = 3142D^{-1.6} \tag{20}$$

$$cyc_{li} = 3946D^{-1.58} \tag{21}$$

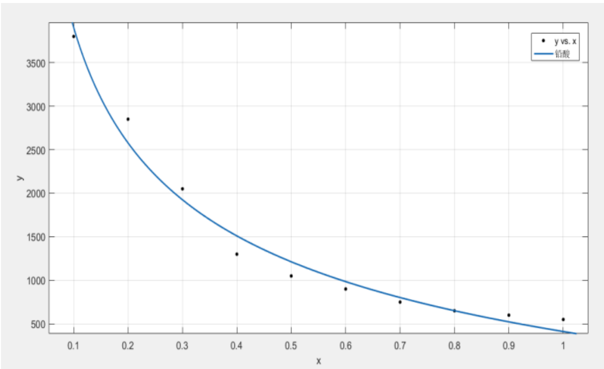

Figure 2. Lead-acid battery cycle life and depth of discharge relationship.

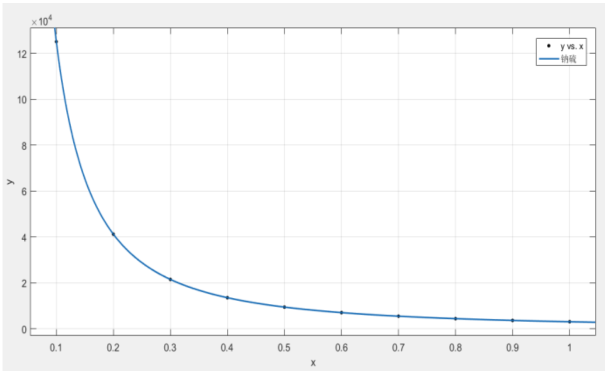

Figure 3. Sodium-sulfur battery cycle life and depth of discharge relationship.

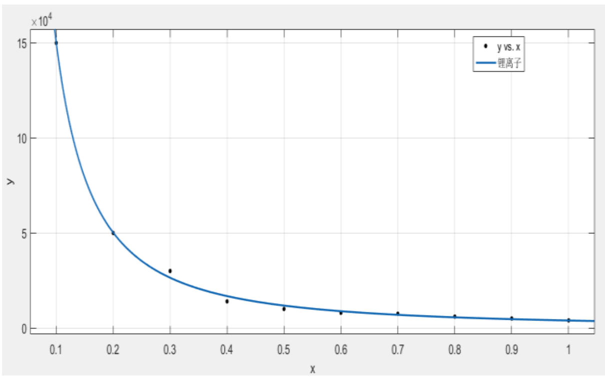

Figure 4. Lithium-ion battery cycle life and depth of discharge relationship.

In this example, in view of the power deficiency at node 16 in the distribution network system, a call instruction is issued to the distributed energy storage system, requiring the distributed energy storage system to provide the power of 2 MWh to the system. The output power of the energy storage power source is 100KW, the update cycle of the optimized configuration instruction is 1h, and the discharge depth at the initial state is 0.In the transmission process, if the battery SOC limit is encountered, the transmission battery shall be replaced according to priority sequence. In this example, the lower limit of SOC of energy storage is set as 0.2. The cost of sodium-sulfur battery/lead-acid battery/li-ion battery are 2000/500/2500 RMB/KWh. Firstly, the energy storage device involved in the adjustment is selected. According to the calculation example, the capacity of the adjustment is large, and multiple energy storage devices need to be involved in the adjustment.

To further illustrate the rationality of the optimized configuration method proposed in this paper, three scenarios are selected for comparative testing.

Scenario 1: the principle of proximity gives priority to selecting the nearest energy storage power source for power transmission. In this example, distance is reflected by impedance.

Scenario 2: according to the SOC principle, the required power is distributed equally according to the SOC size of the battery.

Scenario 3: the energy distribution is carried out by comparing the consumption characteristics of the distributed energy storage power source.

The constant cost consumption coefficient of each node is shown in the following Figure 5.

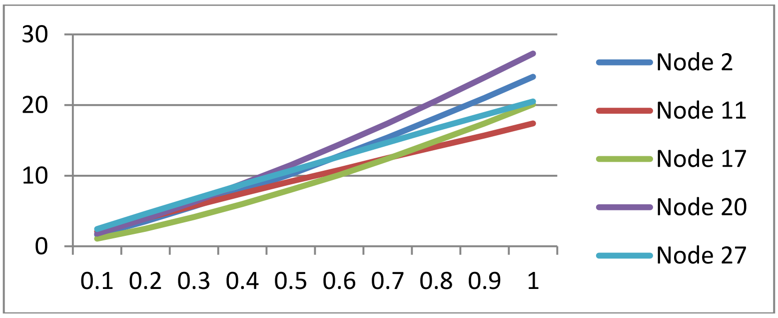

Figure 5. The constant cost consumption coefficient of each node.

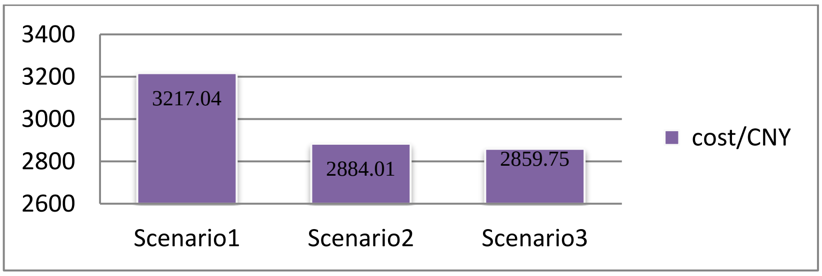

Figure 6. Costs of the battery in different scenarios.

Each cost comparison from Figure 6, it can be seen only from the distance factor distributed energy storage call cost is best, this is because that the energy storage battery life are greatly influenced by the depth of discharge, single consider distance can aggravate the adjacent energy storage unit to charge and discharge load, reduce the efficiency, scenario 2 follow the principle of SOC, such as, this is also the commonly used ones are currently distributed energy storage method is called, but this method ignore the influence of network loss of power distribution network system. In scenario 3, the energy storage resources are rationally allocated by the method of equal cost micro-increment, and the network loss costs are weighted. The method can effectively reduce the cost of energy storage.

6. Conclusions

This paper studies the optimization allocation of distributed energy storage of Distribution Network, which based on Equal Cost Energy Ratio. The cost model of distributed energy storage system is firstly expressed, which includes battery use cost, power cost and line network loss cost and so on. Equal cost energy ratio is applied to solve the optimization allocation to achieve cost minimization of the system. The numerical simulation results show that Scenario 3 can reduce the use cost of DESS. The proposed method could effectively reduce the DESS total cost while increase the lifetime of DESS.

References

[1] Atwa Y M, El-Saadany E F 2010 Optimal Allocation of ESS in Distribution Systems With a High Penetration of Wind Energy[J] *IEEE Transactions on Power Systems* **25(4)** 1815-1822
[2] Linna N I, et al. 2017 Congestion management with demand response considering uncertainties of distributed generation outputs and market prices *Journal of Modern Power Systems & Clean Energy* **5(1)** 66-78
[3] Duval J and Meyer B 2009 Frequency behavior of grid with high penetration rate of wind generation *Powertech, IEEE Bucharest IEEE*
[4] Yihang Song, et al. 2014 An Optimization Model Combining Generation Side and Energy Storage System With Demand Side to Promote Accommodation of Wind Power *Power System Technology* **38(3)** 610-615
[5] Aghamohammadi Mohammad Reza and H Abdolahinia 2014 A new approach for optimal sizing of battery energy storage system for primary frequency control of islanded Microgrid *International Journal of Electrical Power & Energy Systems* **54(1)** 325-333
[6] Delille Gauthier, François Bruno and G Malarange 2012 Dynamic Frequency Control Support by Energy Storage to Reduce the Impact of Wind and Solar Generation on Isolated Power System ' s Inertia *IEEE Transactions on Sustainable Energy* **3(4)** 931-939
[7] Swierczynski, Maciej , et al. 2013 Primary frequency regulation with Li-ion battery energy storage system: A case study for Denmark." Ecce Asia Downunder IEEE
[8] Barnhart Charles 1998 The energetic costs and carbon emissions of grid flexibility technologies: comparing natural gas combustion turbines to renewables paired with storage *Oncogene* **16(5)** 575-86
[9] Mercier Pascal, R Cherkaoui and A Oudalov 2009 Optimizing a Battery Energy Storage System for Frequency Control Application in an Isolated Power System IEEE Transactions on Power Systems **24(3)** 1469-1477
[10] Jiyuan, Huang, et al. 2017 Economic Analysis of Energy Storage Participating in Fast Frequency Regulation *Electrical & Energy Management Technology*
[11] Eyer J M, Corey G P 2010 Energy storage for the electricity grid : benefits and market potential assessment guide : a study for the DOE Energy Storage Systems Program [J] *Geburtshilfe Und Frauenheilkunde* **45(5)** 322-5
[12] Xin H, Zhang M, Seuss J, et al. 2013 A Real-Time Power Allocation Algorithm and its Communication Optimization for Geographically Dispersed Energy Storage Systems[J] *IEEE Transactions on Power Systems* **28(4)** 4732-4741
[13] Morstyn T, Savkin A, Hredzak B, et al. 2017 Multi-Agent Sliding Mode Control for State of Charge Balancing Between Battery Energy Storage Systems Distributed in a DC Microgrid[J] *IEEE Transactions on Smart Grid* **1(1)** 99
[14] Makarov, Yuri V , et al. 2008 Assessing the Value of Regulation Resources Based on Their Time Response Characteristics." *Pacific Northwest National Laboratory, Rep.#PNNL*-17632
[15] Hao Xiao, et al. 2015 Energy Storage Capacity Optimization for Microgrid Considering Battery Life and Economic Operation *High Voltage Engineering* **41(10)** 3256-3265