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Configuration Scheme of Battery-Flywheel Hybrid Energy Storage Based on Empirical Mode Decomposition

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Abstract. In recent years, extreme weather occurs frequently, and the energy crisis is becoming more and more serious. The unified scheduling of new energy sources such as scenery can alleviate the problems of primary energy shortage. However, the randomness and fluctuation of new energy lead to its low internet access. Building an energy storage station for new energy generation side can not only solve the fluctuation problem of new energy grid connection, but also increase the grid connection of new energy sources. This article decomposes the output data of wind farm into high, medium and low frequency components through empirical mode decomposition. The low frequency component can be directly connected to the grid, battery could stabilize intermediate frequency component and and flywheel stabilize high frequency component.Combined with the objective function of minimum cost of the energy storage station, minimized capacity is carried out, and the economic optimal scheme is obtained.

Keywords. renewable energy; hybrid energy storage; empirical mode decomposition; whole cycle life cost.

1. Introduction

In the future, economy will be developed faster and faster, energy sources become a hot problem. China's energy consumption structure needs to be changed urgently. However, coal and fossil fuels cannot be in line with the concept of sustainable development because of their resource reserves and adverse impact on the environment. Therefore, making renewable energy generate more electricity has become a research hotspot. However, new energy has its volatility and randomness[1-2], resulting in its inability to smoothly connect to the grid. Configuring building energy storage with the wind power generation can effectively solve renewable energy's randomness.

According to its physical characteristics, energy storage systems has two kinds of categories: energy storage and power energy storage[3]. Energy-based energy storage such as batteries has high energy density, but frequent charging and discharging will affect its service life; Power-type energy storage such as flywheels and supercapacitors has high power density, short start-stop response time and little impact on life. At present, single energy storage technology cannot cope with the complex power situation, so consider the different energy storage combined. Hybrid energy storage can smooth the

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fluctuation, such as battery-supercapacitor[4-5], flywheel-battery[6-7] and other hybrid energy storage systems.

So far, the common discuss on energy storage mainly concentrate on decomposing the output of new energy and stabilizing the randomness of new energy source. Literature [8] suggests a grid-connected control strategy for wind power in hybrid energy storage system with adaptive sliding average algorithm and genetic algorithm-variational mode (GAV/MD). Literature [9] proposes a stochastic optimization and regulation method for hybrid energy storage to stabilize wind power fluctuations based on probability prediction and decomposes the grid-connected wind power by adaptive VMD method, so as to plan the target pre-dispatch value of hybrid energy storage charge and discharge power. Literature [10] uses a first-order low-pass filtering algorithm to realize power distribution between energy storage batteries and supercapacitors.

In this essay, the wind farm original output is decomposed by empirical mode decomposition, and the critical frequency of medium and high frequency is determined by the decomposed IMF image, so as to pre-plan the capacity allocation strategy of the battery-flywheel. The energy storage scheme is configured in combination with the objective function of the lowest cost and lowest volatility with the construction of battery-flywheel storage stations.

2. Empirical Modal Decomposition

2.1. Empirical Mode Decomposition Determines the Critical Frequency

The new energy power generation power and load power are nonlinear changes, so the EMD and Hilbert transform methods are used to calculate the power distribution between the battery and the flywheel. The unbalanced energy $P_{\mathrm{J}}(t)$ defined as the difference between the generated power and the load data,

$$P_{\mathrm{J}}(t)=P_{w}(t)-P_{\mathrm{L}}(t) \tag{1}$$

Where $P_{W}(t)$ is wind power； $P_{L}(t)$ is the load data.

After selection, $P_{\mathrm{J}}(t)$ is divided into a number of intrinsic modal functions (IMF) $\mathrm{c_i}(t)$. After the Hilbert transforming, the momentary frequency-time curve of all IMFs is got. Select the appropriate IMF curve to determine a demarcation frequency $\mathrm{f_m}$, and the frequency part above $\mathrm{f_m}$ is the high-frequency component $P_{\mathrm{C}}(t)$, which is compensated by the flywheel; The frequency part below $\mathrm{f_m}$ is the low-frequency component $P_{\mathrm{B}}(t)$, which is compensated by the battery.

2.2. Hybrid Energy Storage Power Distribution

After determining the decomposition frequency, the output at the t time of the battery and flywheel would be calculated by the following formula. The part with a frequency higher than $\mathrm{f_m}$ is denoted as a high-frequency component $P_{F}(t)$; The frequency part below f_m is the low-frequency component $P_B(t)$, which is compensated by the battery[11].

$$P_F(t) = c_1(t) + c_2(t) + \ldots + c_g(t) + c_{\text{overlap, } g+1}(t) - c_{\text{overlap, } g}(t) \quad (2)$$

$$P_B(t) = c_{l+1}(t) + c_{l+2}(t) + \ldots + c_m(t) + c_r(t) + c_{\text{overlap, } l}(t) - c_{\text{overlap, } l+1}(t) \quad (3)$$

Where $C_{\text{overlap, } g}(t)$ is the power compensated by the battery instead of the flywheel in $C_g(t)$; $C_{\text{overlap, } l+1}(t)$ is the power in $C_{l+1}(t)$ compensated by the flywheel instead of the battery.

3. Battery-flywheel Hybrid Energy Storage Configuration

3.1. Mathematical Model

3.1.1. New Energy Power Generation System Model

Figure 1 shows the composition of an independent wind farm, which consists of a wind farm, loads, battery-flywheel storage system and the grid. Wind-driven generator supplies energy to power grid through the DC/DC converter, and when the power generation is larger than the prescribed on-grid electricity quantity, the excess quantity is stored by the battery-flywheel device through the DC/DC converter[12]. If the power generated is less than the required energy, the energy storage device transmits the insufficient quantity to the grid through the DC/DC converter.

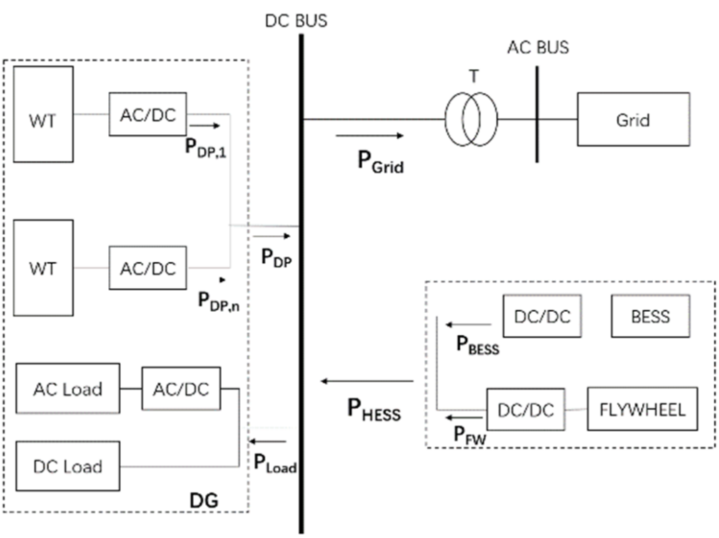

Figure 1. Wind power generation system.

Where $P_{DP,1}, P_{DP,n}$ is the distributed wind farm generation; P_{Load} is the load power of the system; P_{BESS} is the battery's energy with charge and discharge; P_{FW} is flywheel output in t time.

When renewable power generation is larger than the required power of the grid, battery-flywheel storage system is charged. The relationship between remaining electricity and the charging power is shown in (4).

$$\begin{cases} E_{\mathrm{B}}(t) = E_{\mathrm{B}}(t-1) + P_{\mathrm{B}}(t)\Delta t \cdot \eta_{\mathrm{Bc}} \\ E_{\mathrm{F}}(t) = E_{\mathrm{F}}(t-1) + P_{\mathrm{F}}(t)\Delta t \cdot \eta_{\mathrm{Fc}} \end{cases} \tag{4}$$

When the new energy power generation power is smaller than the required quantity of the grid, the battery-flywheel storage system is discharged, and the relationship between the remaining electricity and the discharge power is shown in (5).

$$\begin{cases} E_{\mathrm{B}}(t) = E_{\mathrm{B}}(t-1) + \dfrac{P_{\mathrm{B}}(t)\Delta t}{\eta_{\mathrm{Bd}}} \\ E_{\mathrm{F}}(t) = E_{\mathrm{F}}(t-1) + \dfrac{P_{\mathrm{F}}(t)\Delta t}{\eta_{\mathrm{Fd}}} \end{cases} \tag{5}$$

where $E_B(t)$, $E_F(t)$, $E_B(t-1)$, $E_F(t-1)$ is the remaining power of the battery and flywheel at the *t* time point and *t*-1 time point; $P_{\mathrm{B}}(t)$ and $P_F(t)$ are battery and flywheel output rating at *t* time point.

3.1.2. Lithium Battery Model

Assume that the nominal capacity of the single battery is $C_{ba}(Ah)$, the nominal voltage is $U_{ba}(V)$, m is the cascade number of the battery, and its total energy storage E_{ba} is:

$$E_{\mathrm{ba}} = mC_{\mathrm{ba}}U_{\mathrm{ba}} / 10^6 \tag{6}$$

Discharge rate of storage battery is usually C10, so storage battery's output rating is shown in (7)

$$P_{\mathrm{ba}} = mC_{\mathrm{ba}}U_{\mathrm{ba}} / 10^7 \tag{7}$$

3.1.3. Flywheel Model

The calculation formula for the flywheel output data is shown in (8):

$$SOC = SOC_0 - \frac{\int_0^t N_{\mathrm{f}} dt}{E} \tag{8}$$

Where SOC_0 is the primacy data of flywheel; E represents the flywheel's total storage power; $\mathrm{N_f}$ is real-time output power for flywheel energy storage.

3.2. Objective Function

The objective function is the multi-objective optimization with the least volatility and the lowest total cost of energy storage.

$$\gamma_w(t) = \frac{\Delta P_w(t)}{P_{\mathrm{rate}}} \times 100\% \tag{9}$$

$$\mathrm{C} = \mathrm{C_{own}} + \mathrm{C_{LT}} + \mathrm{C_{ST}} \tag{10}$$

$$\mathrm{F} = \min(\gamma_w(t),\ \mathrm{C}) \tag{11}$$

Where $\gamma_w(t)$ is the volatility of wind power at the t time point; $\Delta P_w(t)$ represents the amount of wind power fluctuation at the t moment; P_{rate} represents the wind farm output rating; $\mathrm{C_{own}}$ represents the total cost of energy storage and operation and maintenance for construction; $\mathrm{C_{LT}}$ represents curtailment costs; $\mathrm{C_{ST}}$ represents the cost of penalties for wind power deviations.

The cost calculation formula for building energy storage and operation and maintenance is[13]:

$$C_{\mathrm{inv}} = \frac{\delta(1+\delta)^y}{(1+\delta)^y - 1}\left(\rho_{\mathrm{pinv}} P_{\mathrm{own}}^{\mathrm{cap}} + \rho_{\mathrm{einv}} E_{\mathrm{own}}^{\mathrm{cap}}\right) \tag{12}$$

$$C_{\mathrm{om}} = \frac{\delta(1+\delta)^y}{(1+\delta)^y - 1}\rho_{\mathrm{eom}} P_{\mathrm{own}}^{\mathrm{cap}} \tag{13}$$

$$C_{\mathrm{own}} = C_{\mathrm{inv}} + C_{\mathrm{om}} \tag{14}$$

Where C_{inv} and C_{om} are construction cost and operating maintenance cost; ρ_{pinv} and ρ_{einv} is construction cost per unit energy storage power capacity and investment cost per unit energy storage energy capacity; ρ_{eom} represents unit energy storage power capacity maintenance costs; δ represents the discount rate; y represents the storage station service life; E_{own}^{cap} represents the energy storage deploy capacity.

The curtailment cost calculation formula is:

$$\mathrm{L_{LT}} = \sum_{t=1}^{T_1}\left(\mathrm{P}(t) - \mathrm{P}_{ref}(t)\right)\Delta t \tag{15}$$

$$\mathrm{C_{LT}} = \rho_L \mathrm{L_{LT}} \tag{16}$$

where L_{LT} is the abandoned wind power in the month after installing energy storage; T_1 is curtailment times; ρ_L is the price of wind farm abandoned wind energy loss corresponds to the unit price.

The maximum forecast error of wind farm generation cannot more than 25%, and if the standard is not met, it will be assessed with the deviation integral capacity of 0.2 points/10,000 kWh. The maximum forecast error of the daily curve is calculated as follows:

$$E_i = \left|\frac{P_i^r - P_i^n}{P_i^n}\right| \times 100\% \tag{17}$$

$$\mathrm{C_{ST}} = 0.2 \times \left|\mathrm{P_i^r} - \mathrm{P_i^n}\right| \tag{18}$$

Where E_i is the error of the daily forecast curve.

3.3. Constraints

(1) Charge and discharge power constraints

$$P_{min} \le P(t) \le P_{max} \tag{19}$$

(2) Capacity constraints

$$SOC_{min} \le SOC(t) \le SOC_{max} \tag{20}$$

4. Example Analysis

Taking a wind power generation system with an installed capacity of 10MW as an example. The peak of the conventional load is 5.2MW, the sampling interval is 1hour, and Figure 2 shows the wind power generation curve from 1:00 to 24:00 on a certain day. The relevant parameters of the battery-flywheel storage system are shown in Table 1.

Among them, the proportion of important loads is set to 0.6, the autonomous operation time period of wind power generation system is 24h, conversion efficiency of the converter is set to 0.95.

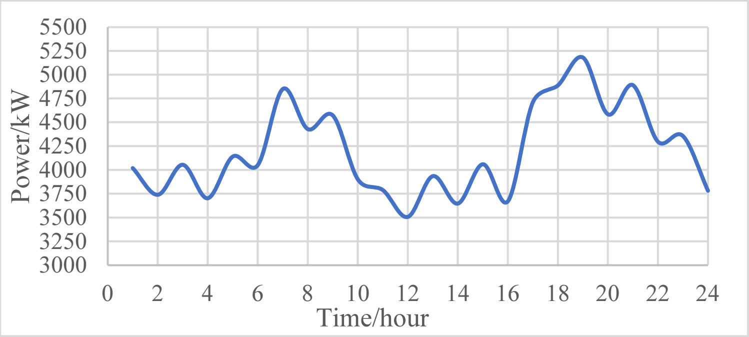

Figure 2. Wind power curve.

Table 1. System-related parameters.

OBJECT	INDEX	PARAMETER
Flywheel	Charge and discharge efficiency /%	92
	Maximum remaining power	$0.9E_r$
	Minimum remaining power	$0.1E_r$
Battery	Charge and discharge efficiency /%	80
	Maximum remaining power	$0.8E_B$
	Minimum remaining power	$0.2E_B$

After decomposing the unbalanced power empirical mode, 7 $c_i(t)$ and one margin $c_r(t)$ are obtained, and Figure 3 shows the instantaneous frequency-time curve of part of the IMF. C_6~ C_7 frequency of high and low frequencies are determined in figure 3. After determining the demarcation frequency, the specific values of the output rating of the battery-flywheel storage devices would be calculated.

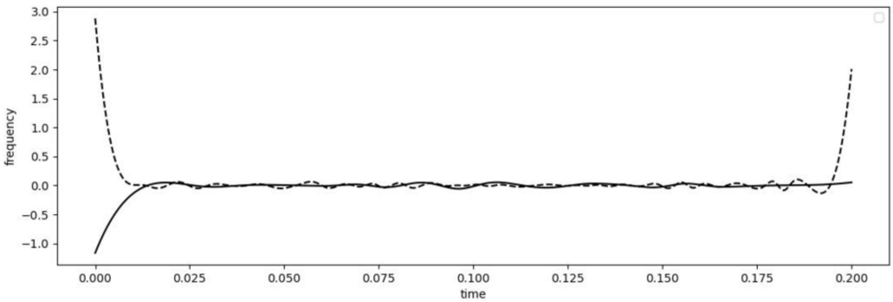

Figure 3. $C_6(t)$~ $C_7(t)$ with instantaneous frequency-time.

After getting the output rating of the hybrid energy storage device, the configuration problem is solved by genetic algorithm. In this paper, the crossover probability is set to 0.5, mutation probability is set as 0.05, the maximum iterations are set as 300, the population size is set as 200.

After the genetic algorithm solves, the final hybrid energy storage configuration results are shown in Table 2. It not only meets the goal of minimum total cost, but also realizes the goal of minimum fluctuation. The wind power curve after increasing energy storage is shown in Figure 4.

Table 2. Hybrid energy storage capacity configuration results.

PARAMETER	RESULT
Nominal power of Flywheel/MW	2
Nominal capacity of Flywheel/MWh	5
Nominal power of Battery/MW	0.25
Nominal capacity of Battery/MWh	1
Annual combined cost/million RMB	18.31

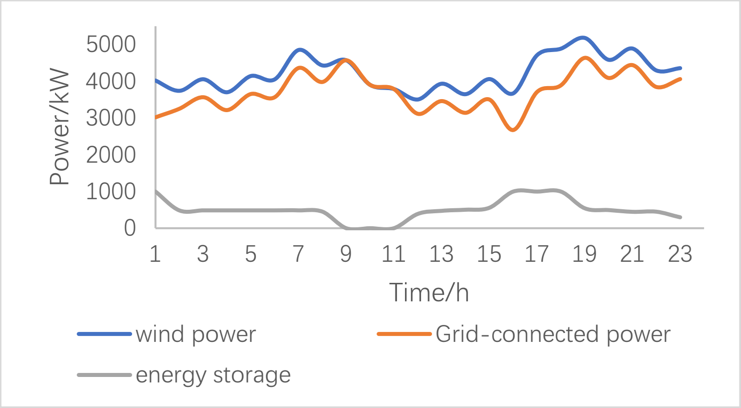

Figure 4. the wind power curve with energy storage.

5. Conclusion

According to fig. 3, an appropriate critical frequency is selected from the IMF image obtained based on empirical mode decomposition. The flywheel to stabilize high frequency components, and the battery stores energy to stabilize intermediate frequency components. The capacity of hybrid energy storage can be effectively pre-allocated. At the same time, by solving the objective function of minimizing the cost of building a hybrid energy storage station, the optimal hybrid energy storage configuration scheme is obtained. From Tab.2, the flywheel energy storage configuration is 2MW, and the battery energy storage configuration is 0.25MW. Annual combined cost is 18.31million. According to Fig.4, the wind power curve after stabilizing by flywheel-battery energy storage is close to the grid-connected power curve, which means it can be directly connected to the grid.

This research presents a method of wind power output decomposed by EMD. It can effectively select the critical frequency and pre-allocate the capacity of flywheel-battery energy storage. It has the advantage that reduce the cost and improve the calculation efficiency. Secondly, the optimal scheme of flywheel-battery energy storage configuration is obtained through model solution, which has the advantage of optimal economy. At the same time, it stabilized the fluctuation of wind power and make it smoothly connected to the grid, which improved the consumption of renewable energy.

References

[1] WOYTE A, VAN THONG V, BELMANS R, et al. IEEE Transactions on Energy Conversion, 21(1):202-209.
[2] ZHANG Guoju, TANG Xisheng, QI Zhiping. Automation of Electric Power Systems, 34(12):85–89
[3] N. Tephiruk, P. Jamjang, A. Taweesap, 2022 19th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), Prachuap Khiri Khan, Thailand, 2022, pp. 1-4.
[4] Lu Hongxin, Tao Fazhan, Fu Zhumu, et al. Electric Power Systems Research ,220.
[5] JIANG Youhua, ZHAO Xiaolin, TANG Jie. Electric Engineering. ,2022(09):26-31.
[6] LIU Yingming, WANG Wei, WANG Xiaodong. Electrical & Energy Management Technology. 2017(13):22-27.
[7] Hou Jun, Song Ziyou, Hofmann Heath, et al. IEEE Transactions on Industrial Informatics, 17(2).
[8] JIANG Feng, XUE Tianliang, ZHANG Lei, et al. Northeast Electric Power Technology. 43(10):49-55.
[9] QIAN Weiting, ZHAO Changfei, WANG Can, et al. Automation of Electric Power Systems. 45(18):18-27.
[10] SUN Yushu, TANG Xisheng, Sun Xiaozhe, et al. Proceedings of the CSEE. 38(09):2580-2588+2826.
[11] LI Xiang, ZHANG jiancheng, WANG Ning. Electric Power. 51(11):117-124.
[12] J. Li et al. 2022 IEEE 5th International Electrical and Energy Conference (CIEEC), Nangjing, China, 2022, pp. 4271-4276.
[13] K. J. Lim, L. W. Chong, S. Morris, 2022 IEEE 5th International Symposium in Robotics and Manufacturing Automation (ROMA), Malacca, Malaysia, 2022, pp. 1-6.