Optimization Method of Hybrid Energy Storage Capacity of Wind Farm

Zhu Kedong[1, a], Mei Fei[2, b], Zhang Chenyu[3, c]

[1] School of Electrical Engineering, Southeast University, Nanjing, Jiangsu Province 210096, China

[2] College of Energy and Electrical Engineering, Hohai University, Nanjing, Jiangsu Province 211100, China

[3]Electric Power Research Institute, Nanjing, Jiangsu Province 211103, China

[a]hhuzkd@sina.com, [b]mario82@163.com, [c]zcy530@sina.com

Keywords: DC micro network, frequency spectrum analysis, chance constrained programming, genetic algorithm

Abstract. The hybrid energy storage is used to stabilize the wind fluctuations for intermittent generation and random of distributed generation system in DC micro network. The power of wind farm is analyzed by Fast Fourier transform (FFT) while the minimum hybrid energy storage compensation capacity is obtained by using anti Fourier transform. According to the characteristics of different energy storage devices, adopting battery and supercapacitor hybrid energy storage, with mixed storage cost as the objective function and hybrid energy storage's state of charge and the maximum output power system performance as the constraint, the chance constrained programming is used to make the fluctuation of output power under a certain confidence level, which also meet the electrical quality and economy. The optimal solution of hybrid energy storage capacity is carried out by using genetic algorithm based on stochastic simulation. Finally, the simulation results show that the method is effective.

Introduction

In order to balance the volatility of the output power of renewable energy and improve power quality and stability of the system operation, energy storage devices must be equipped. According to the different characteristics, long-term storage energy storage device is divided into superconductor storage, flywheel energy storage, super capacitor and battery energy by a variety of ways. Battery has several advantages: high specific energy, low price, good reliability for electric energy, which can be used to increase the energy adjustment range in the whole scenery load of the power generation system. However, battery power ratio is relatively low. Super capacitor can has the advantages of high specific power, long cycle life and fast response. Super capacitor is very suitable for high output power in short time, which can effectively suppress the short-time energy fluctuations in the system and smooth the instantaneous energy [1-2]. In addition, super capacitor can reduce the configuration capacity of energy storage unit and the cost of investment. As a result, this paper uses battery and super capacitor hybrid energy storage device.

According to different control targets, energy storage device and DC micro renewable energy network mode can be divided into two categories: 1) smooth output fluctuations with renewable energy; 2) intermittent renewable sources of energy changes into energy scheduling, such as load shifting and power generation plans [3]. In this paper, we mainly solve the smoothing output power by using FFT algorithm to obtain the minimum hybrid energy storage compensation capacity. Establishing the hybrid energy storage multi-objective optimization function and the constraint function based on chance constrained programming, stochastic simulation is solved by genetic algorithm.

System Model

The system composition model is shown in Fig. 1. The distributed power supply includes photovoltaic power generation and wind power generation, providing energy for the entire system. Energy storage includes battery and super capacitor, connecting DC bus by the power electronic converter interface DC / DC and AC / DC while DC load is connected to DC bus by DC / DC.

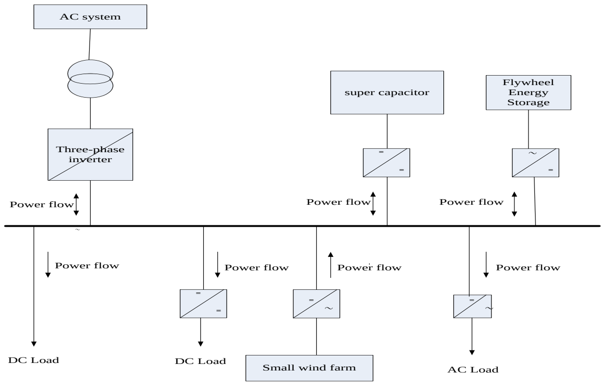


Fig. 1 Structure of DC micro grid

Hybrid energy storage model

In this paper, a hybrid energy storage model is shown in Fig. 2:

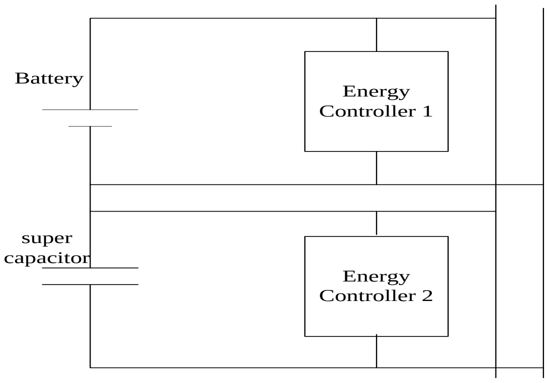


Fig. 2 Hybrid energy storage model

This structure can handle storage medium and energy management for flexible configuration, which not only can make their terminal voltage control in the reasonable range for prolonging the service life, but also guarantee a good stable DC bus voltage.

Wind power generation model

A large number of experimental data show that the wind power generation power has a linear relationship with wind speed, which is shown in Eq. (1):

$$\begin{cases} p = 0, v \le v_{ei}, v \ge v_{eo} \\ p = p_r \dfrac{v - v_{ei}}{v_r - v_{ei}}, v_{ei} \le v \le v_r \\ p = p_r, v_r \le v \le v_{e0} \end{cases} \tag{1}$$

In Eq. (1), v represents wind speed at the turbine height; v_{ei} represents cut-in wind speed; v_{eo} represents cut-out wind speed; v_r represents the rated wind speed, p_r represents the rated output power.

Operation strategy and configuration scheme of energy storage system

Due to the intermittent and random fluctuation of wind power and the random load fluctuation, energy storage system must realize the power balance between power supply and load, and maintain the balance of DC bus voltage. At the same time, it can smooth the output power of distributed power and get the target of cutting peak and filling valley. The hybrid energy storage device is used to absorb the low frequency band power in the compensation power while super capacitor is used to compensate the power of the high frequency segment. The control strategy about hybrid energy storage stabilizing wind power and its operation flow diagram are shown in Fig. 3, Fig. 4 [4-5], respectively.

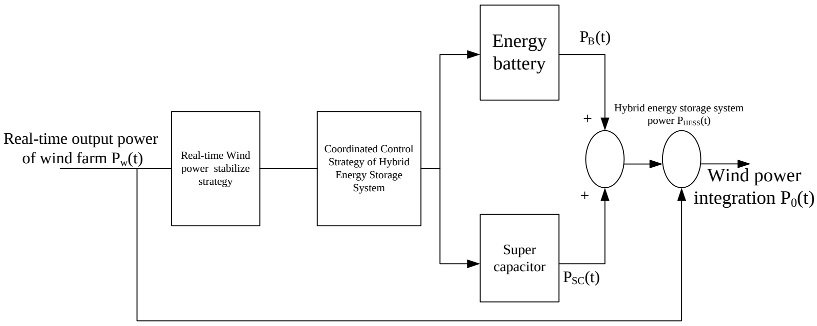
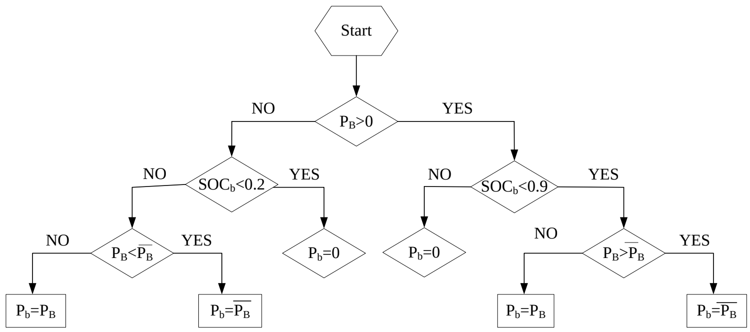
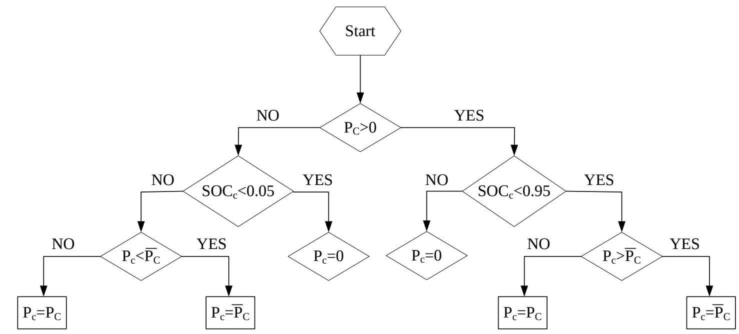


Fig. 3 Wind power fluctuation stabilizing control strategy



(a) Battery charging/discharging management strategy



(b) Management strategy of super capacitor charging/discharging

Fig. 4 Hybrid energy storage charging/discharging management strategy

In Fig. 4, P_C, P_B represent power compensated for battery and super capacitor respectively; $\overline{P_B}$, $\overline{P_C}$ are the rated compensation power of battery and super capacitor, respectively; P_c, P_b are actual compensation power of battery and super capacitor; SOC_b, SOC_c are power state of charge (SOC). In addition, battery compensates the low frequency part of power while super capacitor compensates the high frequency part of power.

Relationship between the state of charge and the charging/discharging power in energy storage equipment is as Eq. (2):

$$S_x = \frac{E_x^{ini} + \int_0^t \left(\eta_{ch}^x P_{ch} - \frac{1}{\eta_{dis}^x} P_{dis} \right) dt}{\overline{E_x}} \tag{2}$$

Where E_x^{ini}, S_x are energy storage equipments' initial capacity, SOC respectively; P_{ch}, η_{ch} are charging power and efficiency respectively; P_{dis}, η_{dis} are discharging power and efficiency respectively.

The constraint functions of battery and energy storage battery are as Eq. (3) and Eq. (4):

$$s.t.\begin{cases} -\overline{P_{bat}} \le P_{bat} \le \overline{P_{bat}} \\ S_{bat}^{low} \le S_{bat} \le S_{bat}^{up} \\ E_{cmin} \le E_b \le E_{cmax} \end{cases} \tag{3}$$

$$s.t.\begin{cases} -\overline{P_c} \le P_{bat} \le \overline{P_c} \\ S_c^{low} \le S_c \le S_c^{up} \\ E_{cmin} \le E_c \le E_{cmax} \end{cases} \tag{4}$$

Where: E_b, E_c are the rated capacity of battery and super capacitor respectively; $\overline{P_{bat}}$, $\overline{P_c}$ are the rated power of battery and super capacitor respectively; S_x^{up}, S_x^{low} respectively the lower and upper bounds of the SOC.

Genetic algorithm

Genetic algorithm is a stochastic optimization search method referencing biology evolutionary rule. Its main features contain probabilistic optimization, adaptive adjustment of search direction, fast convergence, and better global optimization ability. The specific flow chart of genetic algorithm is shown in Fig. 5.

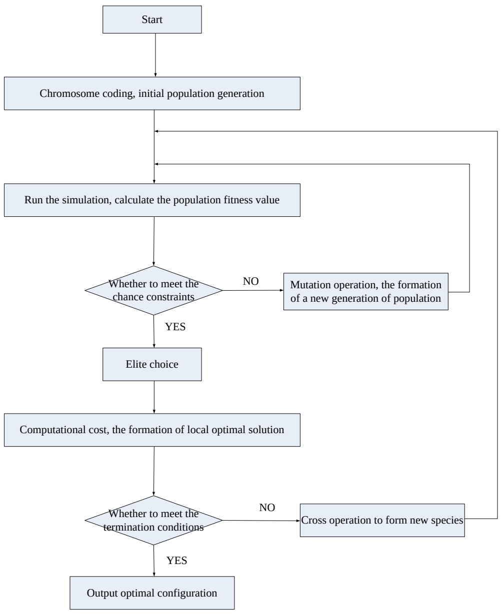


Fig. 5 Genetic algorithm flow chart

Directed at making decisions under adverse circumstances, chance constrained programming occurs, which may not meet the constraints sometimes. So such a principle is adopted: allow the decision satisfying the constraint conditions in a certain extent, which can ensure that the probability of constraint conditions establishment is not less than a given confidence level for getting moderate compromise between meeting the constraint condition and objective function. The common form is shown in Eq. 5:

$$\begin{cases} \min\ f(x,\varepsilon) \\ s.t. \begin{cases} P_r\{g_j(x,\varepsilon) \le 0\} \ge \alpha \\ G(x,\varepsilon) \le 0 \end{cases} \end{cases} \tag{5}$$

Where: ε is random vector; x is decision vector; $f(x,\varepsilon)$ is objective function; $Pr\{g_j(x,\varepsilon)\le 0\}$ is the probability of satisfying the constraint conditions; $g_j(x,\varepsilon)$ is chance constraint; α is the confidence level of chance constraints; $G(x,\varepsilon)\le 0$ is rigid constraints, with meeting 100% requirement [8].

From the characteristics of the wind power fluctuation, the cost will be increased rapidly when completely satisfying the constraint conditions for hybrid energy storage device configuration while Setting a certain confidence level for satisfying the constraints will have practical value. Therefore, chance constrained programming is adopted for optimizing storage capacity configuration, which can control the output power of wind power in the limit of interval δ under the formulation of the target value.

In order to test the smooth effect of wind power output by energy storage system, smooth ratio η_{eer} is the selected as evaluation index.

$$\eta_{eer} = \frac{P_{WT} + P_B + P_U - P_{WT}^*}{P_{WT}^*} \tag{6}$$

Where: P_{WT} is wind power output; P_B, P_U is the power output of battery and super capacitor respectively; P_{WT}^* is the rated wind power output; the low frequency part of wind power output P_{WT} is selected as target P_{WT}^*.

A series of criterion about wind power grid connection is established. This paper adopts references [6-7] for taking example, which is shown in Eq. (7):

$$F_{kt} = \frac{p_{kt}^{\max} - p_{kt}^{\min}}{P_N} \times 100\% \tag{7}$$

Where: k represents the k-th period; F_{kt} represents the power changing rate in k-th period; $F_{kt}\le 10\%$; P_{kt}^{max} and P_{kt}^{min} are maximum and minimum power in k-th period respectively.

The actual analysis results show that compensation capacity of energy storage device is directly related with compensation frequency band. Under the same frequency band width, the required storage capacity with high compensation frequency band is less than that of low compensation frequency band. The FFT spectrum of wind power output is analyzed in this paper. After determining system compensation frequency band, the trial and error method is adopted: from the beginning of the high frequency, gradually extend band to the low-frequency; thorough using inverse FFT transform and comparing different frequency comparison, guarantee the minimum cost and meet the volatility requirement. The output power spectrum analysis of wind turbine and the maximum fluctuation of the target output power in different compensation frequency bands are shown in Fig. 6, 7 respectively.

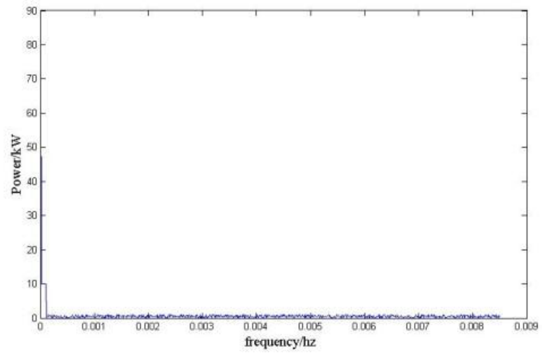


Fig. 6 Output power spectrum analysis of wind turbine

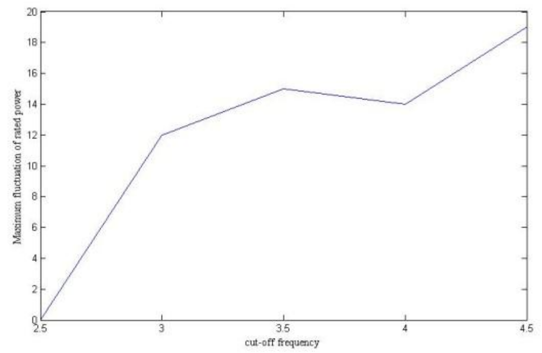


Fig. 7 Maximum fluctuation of target output power at different cut-off frequency

From the above shows that when the cut-off frequency is 0.003hz, the output power fluctuation in 1min is just 10% of the rated power, which meets the grid requirements, and guarantees the minimum compensation of hybrid energy storage. So the low frequency part of the wind power output power P_{WT} when cut-off frequency is 0.003hz is selected as the output target value P_{WT}^{*}.

Example analysis

With Matlab/Simulink simulation environment analysis, the cut-off frequency of the high pass filter is 0.02 Hz based on the operating characteristics of DC power distribution network and hybrid energy storage while wind smooth rate interval S is $\pm 2\%$. The SOC initial value of super capacitor and energy storage battery was 0.5. The parameters of battery and super capacitor are shown in Table. 1.

Table.1 The parameters of Hybrid energy storage system

Type	Rated power cost/(USD/kWh)	Rated capacity cost/(USD/kW)	Lifetime	SOC range	Cycle times	Equipment type/%
battery	488	325	15~30	0.20~0.80	3000	75~85
Super capacitor	366	37000	50	0.05~0.95	50000	95

Confidence a is simulated in the interval [80%, 100%], whose results are shown in Fig. 8. The analysis of Fig. 8 shows that with the increase of confidence degree, the total cost of the hybrid energy storage system will be increased. In addition, there are two turning points in 90% and 96%, which can be selected as the optimal confidence level.

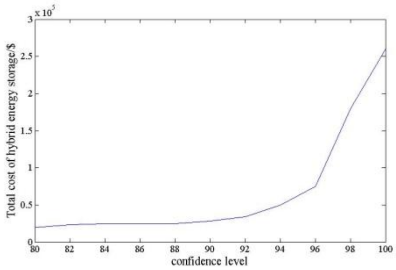


Fig. 8 Total cost of hybrid energy storage under different confidence level

Optimal capacity configuration of hybrid energy storage system under confidence 90%: the rated capacity and power of super capacitor are 0.0127 kW, 19.9005l kWh, respectively; the rated capacity and power of storage battery are 23.2944kW, 20.2518 kWh, respectively. Hybrid energy storage simulation results are shown in Fig. 9:

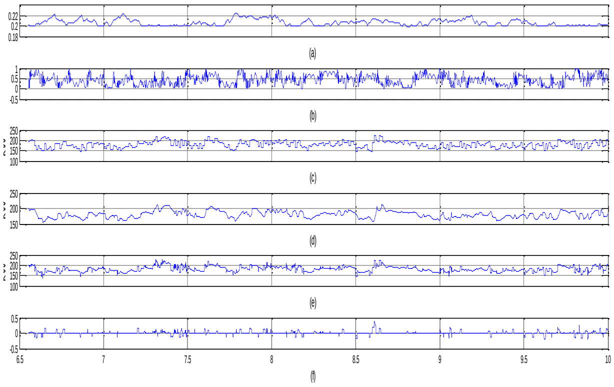


Fig. 9 Simulation results of hybrid energy storage under 90% confidence level

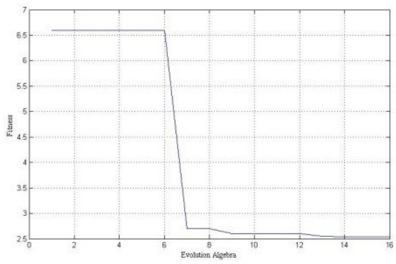


Fig. 10 Genetic algorithm optimization process

In Fig. 9, (a) is battery SOC; (b) is super capacitor SOC; (c) is wind power output; (d) is the rated wind power output; (e) is wind power output with the compensation energy device; (f) is wind level slip rate. From (a), it can be known that the SOC of battery is kept in the range between 0.2 and 0.8 in order to prevent too charging/discharging. The low frequency part of power is compensated by the characteristic of high energy density, which results in the reduced frequency of power charging. (b) shows that super capacitor SOC is kept in the range of 0.05 and 0.95 in order to prevent too charging/discharging. The high frequency part of power is compensated by the characteristic of fast power compensation, which results in the reduced switching frequency and extending the batter life. (f) can be seen that the hybrid energy storage system has a good smoothing effect on the wind power output, including reducing the volatility of the wind power output and improving the power supply quality of the wind power system. Compared (c), (d), (e) show that hybrid energy storage device performs good in compensating output power so that the output power is close to the rated one, with reducing the volatility of wind power output and cost saving. The fitness curve of Fig. 10 shows that the cost of hybrid energy storage is convergent in the ninth generation.

Conclusion

In this paper, the wind power output is test by FFT spectrum analysis; the minimum compensation energy storage capacity can be get by inverse FFT and video-law method; adopt the minimum cost of hybrid energy storage as objective function; adopt the chance constrained programming for making volatility to meet a certain confidence interval; realize the complementary between economy and power quality; the optimal solution is get by genetic algorithm. Finally, the experiment study is used to verify the effectiveness of the purposed method.

Acknowledgements

This work was supported by the China Postdoctoral Science Foundation under Grant No.2015M571654 and Fundamental Research Funds for the Central Universities under Grant No.2013B15020022.

References

[1] Li Junwei. Research on the optimal plan and control of energy storage system to reduce the effect of wind power on the grid [D]. Beijing: North China Electric Power University, 2012

[2] Yue Yuan, Qiang Li. Optimal Operation Strategy of Energy Storage Applied in Wind Power Integration based on Chance-constrained Programming [J]. 2009 International Conference on Sustainable Power Generation and Supply, 2009

[3] Wang Chengshan, Yu Bo, Xiao Jun, Guo Li. Sizing of Energy Storage Systems for Output Smoothing of Renewable Energy Systems[J]. Proceedings of the CSEE, 2012, 32(16)

[4] Jiang Wei, Zhou Gan，WANG Xiaodong, Yang Yongbiao. Power allocation strategy of hybrid energy storage system for microgrid[J]. Electric Power Automation Equipment, 2015, 35(4)

[5]Shujun Liu , Zaijun Wu. Optimal configuration of hybrid solar-wind distributed generation capacity in a grid-connected microgrid [J]. Innovative Smart Grid Technologies (ISGT), IEEE PES, 2013

[6] Sang Bingyu, Wang Deshun, Yang Bo, Ye Jilei, Tao Yibin. Optimal allocation of energy storage system for smoothing the output fluctuations of new energy [J]. Proceedings of the CSEE, 2014, 34(22)

[7] Li Wenbin. Study on the smooth up wind farm output fluctuation by energy storage system [D]. Chongqin: Chongqing University, 2012

[8] Xie Shixiao, Yang Li, Li Lina. A chance constrained programming based optimal Configuration method of hybrid energy storage system [J]. Power System Technology, 2012, 36(5)