Review of Grid Codes and Implementation for Wind Farm Frequency Regulation

Xianwen Bao * and Lirong Zhang

Beijing Polytechnic, Beijing, China

Abstract. With the increase of wind power and the construction of UHVDC transmission, the wind turbines must actively participate in the system frequency regulation through inertia response and primary frequency regulation to ensure the safe and stable operation of the power system. However, the wind power penetration rate and the grid structure of each regional power grid are different, so that the corresponding power grid codes are also slightly different. Firstly, this paper introduces the specific requirements of wind power grid guidelines in typical countries and regions, and with reference to the experience of international frequency regulation codes, it puts forward the proposed implementation mode of active support new energy frequency regulation suitable for domestic power grid, and the recommended parameter for wind farm frequency regulation. Secondly, this paper summarizes the frequency modulation implementation schemes of the main wind turbine manufacturers in the world, and demonstrates the potential frequency modulation capability of the wind turbine. Finally, the challenges and realizable solutions of virtual inertia and primary frequency regulation of wind farms are prospected, and some suggestions are given.

1. Introduction

In recent years, there have been several power grid frequency safety accidents all over the world, among which the typical frequency events, such as the "2019.8.9" blackout in Britain [1], accounted for 30% of wind power before the accident, and lightning strike led to short circuit and trip, thus inducing a series of power grid chain reaction is the direct cause of this blackout. This event triggered the domestic power grid and scholars on the replacement of many new energy sources of traditional thermal power system inertia decline, insufficient frequency modulation ability and other issues of deep thinking, so the power industry frequency modulation transformation is imperative.

With the continuous development of new energy technology, the proportion of new energy output of power grid in some regions of China has exceeded 50% [2][3]. In traditional power grid operation, thermal power unit moment of inertia and primary frequency control process is spontaneous response, but the variable speed wind turbine under the inverter control scheme, the speed of the wind turbine and power grid frequency, there is no direct coupling relationship between its rotational kinetic energy was "hidden" rise, caused the lack of wind turbines on the system power oscillation inhibition, It does not have the primary frequency modulation function and inertia response function of conventional units, thus affecting the dynamic frequency response of the system and greatly reducing the stability of the power grid[4][5]. Due to the reverse distribution of domestic energy load, more than 80% of the energy is distributed in the west and north, and 75% of the power load is concentrated in the central and eastern regions. In 2015, an UHV DC bipolar lock fed into East China suffered an instantaneous power loss of 5400MW, and the extreme frequency of East China dropped to 49.56Hz, falling below 49.8Hz for the first time in nearly 10 years, and lasted for hundreds of seconds. According to the accident analysis, only 20% of the units met the primary frequency modulation response performance index during the period, while the remaining 80% were unqualified, and 16% of the units even showed the reverse modulation characteristics, which directly led to the occurrence of large frequency drop of East China Power Grid and could not be recovered for a long time [6]. If the wind farm has energy schedulable and the ability to participate in partial frequency modulation of the power system, it will greatly improve the permeability of wind turbine in the power grid, increase the stability of the system, and improve the grid-connection "friendliness" of wind power [7].

In view of the different wind power grid permeability and grid structure in each region, the grid guidelines are slightly different. This paper introduces the guidelines of wind power grid connection in typical countries and regions in detail, and compares the specific requirements of frequency modulation. According to the requirements of international power grid guidelines, the proposed implementation mode of active supporting new energy frequency modulation adapted to domestic power grid and the recommended parameters of new energy participation frequency modulation are put forward. This paper summarizes the frequency modulation implementation schemes of the main wind turbine manufacturers in the

* Corresponding author: baoxianwen0407@126.com

 https://doi.org/10.1051/e3sconf/202235202012

world, compares and analyses the potential frequency modulation capabilities of wind turbines, further analyses the challenges faced by the inertia of wind farms and primary frequency modulation technology and the possible solutions, and gives the opinions and suggestions on frequency modulation of four wind farms.

2. Power network frequency modulation requirements

2.1 Guidelines for Quebec Power Grid, Canada

Quebec Power Grid in Canada has put forward specific regulations on frequency [8], which are relatively complete in the current power grid guidelines for the inertial control and primary frequency modulation function requirements of wind turbines. It is stipulated in the guidelines that wind farms with rated capacity over 10MW should have frequency control systems and frequency regulation functions. There is no limited power operation state in Canadian power grid, that is, the unit is always in the maximum power tracking state. When low-frequency faults occur in the power grid, wind turbines are required to provide dynamic power support by using the rotor kinetic energy of the unit. Power grid guidelines require different control methods for over frequency and underfrequency. During low-frequency power grid failure, the wind turbine adopts inertia control, while during over frequency power grid failure, the wind turbine adopts droop control to assist the power grid to complete frequency fault crossing.

2.2 European Grid Guidelines

ESB Grid in Ireland requires wind farms to control the active power output in the same way as thermal power plants [9][10], with 2-5% primary frequency modulation capability, and should be able to participate in secondary frequency modulation of the system. The active-frequency curve required by ESB Grid for wind farm operations is shown in Figure 1. Danish Grid Company's requirements for frequency response curve are like those of Irish grid [11][12]. In the state of unlimited power, the output power is only reduced when the grid is over frequency to achieve the reduction of grid frequency. The working process under limited power is like Figure 1, and the power control coefficients corresponding to different frequency points are given in the guidelines. In actual operation, the specific working state is specified by TSO, which requires that the wind farm can complete the switch between limited power control and unlimited power control within 1min. Danish power grid requires that the frequency modulation of wind farm can be realized through wind turbines, or the output characteristics of the whole wind farm can be adjusted through centralized control system [13].

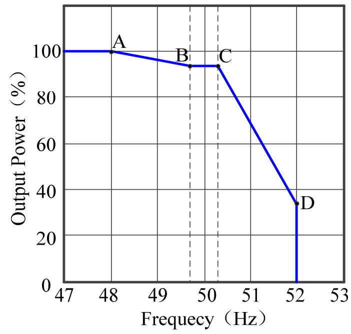

Figure 1. The primary frequency control curve in Ireland

German E. ON Power Grid Company [14][15] stipulates that the new energy generator set must have the ability to limit the active power output. When the grid frequency is greater than 50.2Hz, the new energy generator set should reduce the current actual power by 40% within the unit frequency. When the grid frequency is less than 49.5Hz, the new energy generator set should increase the current power by 10% within the unit frequency. When the grid frequency is greater than 51.5Hz or less than 47.5Hz, the new energy generator set is cut off from the grid. Switzerland and Hungary also adopt the same frequency regulation scheme [16].

The grid requirements of the UK and Germany are slightly different. When the frequency drops to 47Hz, the active power output is 95% of the rated value [17]. The UK CCGT (combined cycle gas turbine) power plant indicates that the unit should output 15% of the maximum power for 10s during a low frequency failure. The British power system requires 160MW reserve capacity to be added for every 10GW of wind power [18]. According to the Regulations of Spanish power grid [19][20], when the grid frequency deviates from the rated value, the wind turbine should have the function of coordinated control of active power in proportion. The frequency control process is like droop control, requiring the system to output 10% of the rated power within 250ms.

Greek power grid has strict requirements on performance indexes of new energy frequency modulation [21], with different requirements for over frequency and underfrequency. Over frequency response: According to different frequency ranges, the wind farm starts the segmentation frequency modulation control strategy. The recommended over frequency modulation dead zone is 200mHz, and the slope is 2%-12%. Under small frequency disturbance, the over frequency response time is required to adjust 20%Pn within 5s and 50%Pn within 10s. Over frequency response time under large frequency disturbance requires 50%Pn to be adjusted within 2s. Underfrequency response: the rotor kinetic energy of the wind turbine is required to provide short time active power support, which can be adjusted by equal proportion or step according to demand, corresponding to different underfrequency dead zone.

2.3 Guidelines for North American Power Grids

There are nine independent System operators (ISO) in North America, serving two-thirds of U.S. electricity customers and more than half of the Canadian population.

Different regional power grids have different requirements for primary frequency modulation. Several representative power grid guidelines are introduced [22][23]:
Mexico power grid requires a frequency dead zone of 0.2Hz, active power regulation capacity of 3%-8% of real power, and response time of less than 2s. The primary frequency modulation requirement of Saskatchewan power grid in Canada is to control and combine points. Inertia control is adopted to simulate the droop control characteristics of traditional thermal power sets. The droop coefficient is adjustable between 0% and 10%, and the recommended value is 5%. The frequency dead zone is adjustable from 0.036Hz to 0.1Hz, and the recommended value is ±0.036Hz. The guidelines for the Quebec Grid in Canada have been described in detail in the previous section and will not be repeated.

2.4 Guidelines for China Power Grid

Mandatory GB 38755-2019 "Guidelines for Safety and Stability of Power System" 3.5 part of network source coordination, requires that wind farms with voltage levels of 35kV and above access to power system should be equipped with primary frequency modulation, rapid voltage regulation and peak regulation capabilities. In centralized access areas, they should be equipped with the ability to support the capacity of moments and short circuit. Electric power industry standard DL/T 1870-2018 Technical Specification for Coordination of Power System Network Source requires that wind farms and photovoltaic power stations with access to 110 (66) kV and above voltage levels must have the function of primary frequency modulation. When the output of wind farms is greater than 10%Pn, the start-up time of primary frequency modulation is not more than 3s, and the response time is not more than 12s. Adjustment time is not more than 15s, active power accuracy is not more than 1%Pn.

2.5 Guidelines for Power Grids in Other Countries

Summarized the primary frequency modulation requirements of other regions [24], focusing on the dead zone, droop coefficient and response speed of primary frequency modulation, as shown in Table 1:

Table 1. The demand for frequency control in other countries.

Region	Deadband (Hz)	Droop
Australia[25]	0.15	2%～10%
Chile	0.2	2%～10%
Finland[26]	--	2%～12%
Italy[27]	0～0.2	2%～5%
Saudi Arabia [28]	0.05	2%～8%

Summarizes the current foreign grid guideline, the various countries and regions changed demand for short-term wind energy reserves, permeability is lower than 10% of the wind power grid requires 1-15% of the spare capacity of wind power, wind power penetration requirements for 20% of the power grid 4-18% of the wind power reserve capacity, if consider wind volatility and prediction error, spare capacity still need to adjust.

2.6 Summary of Power Grid Guidelines

Throughout the domestic and foreign requirements for wind farm frequency modulation network, there are the following characteristics:
(1) All regional power grids at home and abroad have similar requirements for primary frequency modulation curve, with slightly different performance indicators. According to the different proportions of new energy in regional power grids, the active power adjustment amplitude is basically around 10%Pn, and the active power adjustment amplitude can be adjusted according to the actual demand.
(2) According to the requirements of Greek power grid, segmented frequency modulation is more conducive to the coordination and cooperation of new energy stations during major power grid accidents to maintain the consistency of system action. Greece power grid and Quebec power grid in Canada both provide two ways to invoke the rotor kinetic energy of the unit, that is, to provide all the rotor kinetic energy power or to output the rotor kinetic energy power in proportion to the frequency deviation. The two ways correspond to different frequency dead zones.
(3) Referring to the technical indicators of primary frequency regulation of thermal power sets, the recommended primary frequency regulation indicators of wind farms are as follows: the amplitude of under-frequency active power regulation is 10% of rated power, the over-frequency active power regulation value can be appropriately square wide, the response time to reach 90% of the target load value is recommended to be no more than 5s, and the active power control error is no more than ±2%Pn.

3. Frequency modulation technical scheme

3.1 GE Wind Turbine Frequency Modulation Technical Scheme

GE's patent Wind INERTIA™ proposes an inertial response control scheme for wind turbines, like the primary frequency modulation action of conventional synchronous generators during low-frequency grid failures [29]-[31]. The Wind INERTIA™ control method enables the wind field to meet the inertial characteristics required by the power grid. When the power grid is in a short-term low-frequency failure, the speed of the power electronic converter and the mechanical inertia of the rotor can be utilized to provide 5% to 10% of the active power during the low-frequency disturbance for several seconds, effectively reducing the minimum value of the instantaneous frequency drop. It is beneficial to the rapid recovery of the system and gain time for the traditional generator set to improve the active power output. Figure 2 provides the frequency anti-jamming capability corresponding to different energy situations and control strategies in 100MW power grid. The simplified Wind

 https://doi.org/10.1051/e3sconf/202235202012

INERTIA™ control block diagram is shown in Figure 3, and the corresponding control parameters are shown in Table 2. It is worth noting that the control scheme responds only during the low-frequency faults of the power grid, while the traditional limited active power control scheme is still used when the power grid is in the high-frequency faults.

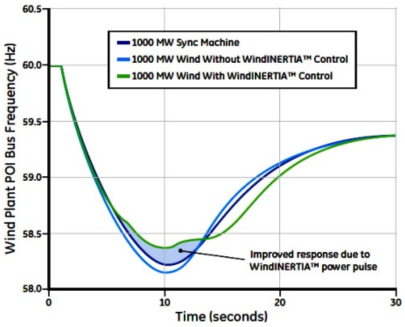

Figure 2. The output frequency response comparison by WindINERTIA™

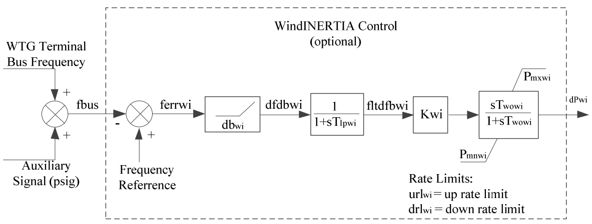

Figure 3. The control block of WindINERTIA™

Table 2. Wind INERTIA Control Parameters

Variable	Recommended value	Variable	Recommended value
K_{wi}	10	url_{wi}	0.1
db_{wi}	0.0025	drl_{wi}	-0.1
T_{lpwi}	1	P_{mxwi}	0.1
T_{wowi}	5.5	P_{mnwi}	0.0

3.2 VESTAS Wind Turbine Frequency Modulation Technical Scheme

Vestas station adopts VMP6000 to realize the frequency control of wind farm. According to the actual frequency of the junction point, wind farm can adopt 6 control points to realize flexible online regulation of active power, and set the frequency modulation dead zone and error rate according to the requirements of different power grid[32], as shown in the figure below.

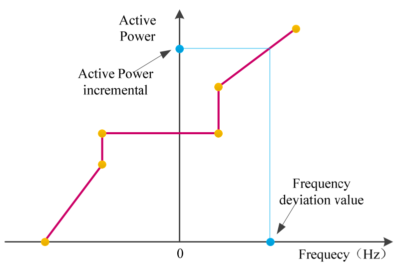

Figure 4 Vestas Frequency response curve

3.3 Frequency Modulation Technical Solutions of Other Wind Turbine Manufacturers

Siemens' proprietary Net Converter® power conversion system enables the generator to operate at variable speed, variable frequency, and variable voltage, and to deliver constant frequency and voltage power to the medium-voltage transformer [33]. The Net Converter® power system can control the wind turbine for active load reduction, slope control, frequency droop control, rotary backup (Delta control) and inertia control [34]. ABB designed a direct torque control system for wind turbine converters, which can spontaneously realize rapid frequency response and damping control [35]. ENERCON also proposed a wind turbine inertia control solution [36].

4. The Research Direction

4.1 Parameter Setting of Frequency Modulation

Literature [37] analyses the influence of primary frequency modulation parameters in regional power grid on power grid frequency, and obtains the parameter setting scheme of power grid's sending and receiving ends. According to the existing literature, the local power grid structure and the load limit of the wind turbine unit should be considered in setting the primary frequency modulation parameters. Therefore, according to the specific situation of the domestic power grid, the setting parameters of primary frequency modulation are studied to ensure that the wind farm can effectively assist the power grid to complete frequency fault crossing, and can ensure the load safety of wind turbines, meet the boundary conditions of control and the stable operation of wind turbines. Coordinate and control the action time and regulation capacity of the new energy station and the traditional thermal power unit by referring to the action time of the thermal power unit. In the early stage of frequency failure, the active power support of the new energy station is provided to gain time for the thermal power unit to participate in primary frequency modulation, and the action characteristics of the wind power unit with different capacities should be fully considered. Adjust the response time corresponding to 10%Pn according to unit capacity setting.

4.2 Wind Turbine Frequency Modulation Control Strategy

Literature [38]-[40] comparatively studied the influence of different control strategies, such as simulated inertia control, droop control, rotor speed control, pitch Angle control and coordinated control, on primary frequency modulation. Based on the analysis of existing literature, wind farms with high permeability have large wind speed fluctuations and wind turbines are operating at maximum power. Only depending on the kinetic energy of the wind turbine rotor cannot provide effective and lasting power support. From the perspective of energy conservation, the excess active power during primary frequency modulation will cause the reverse recovery of power, resulting in secondary frequency fluctuation of power system.

Therefore, the time-limit power strategy for primary frequency modulation is studied to enable the wind farm to have standby capacity of active power, which is conducive to improving the response speed, duration, and control accuracy of primary frequency modulation, and can effectively avoid secondary frequency drop [41].

4.3 Frequency Modulation Scheme of Wind Farm with Energy Storage System

The utilization of energy storage system to assist wind farm to participate in system frequency adjustment has also been widely concerned [42]. According to the existing research results, energy storage device can effectively make up for the deficiency of wind power and realize the primary frequency modulation function of wind farm. With the rapid decline of energy storage prices and the rapid development of technology, the future of new energy primary frequency modulation and inertia response leaves countless room for expansion. Therefore, research on the coordinated control scheme of primary frequency modulation between energy storage system and wind farm, auxiliary wind power prediction of energy storage system, optimized charge and discharge control strategy and economic evaluation of energy storage system will be the focus of future research.

5. Conclusions

Multiple grid at home and abroad are defined in the guide of the inertia response of wind turbine should be involved in electric power system and a frequency modulation control, but the regional power grid wind power penetration and grid space truss structure is different, the guideline, this paper summarizes the domestic and foreign typical regional grid statistics related to the primary frequency control technology index, and comparative analysis of the domestic power grid frequency control requirements, Some suggestions for reference are given. In this paper, the frequency modulation implementation schemes of mainstream wind turbine manufacturers are analyzed, and the performance indexes of different technical schemes are compared. On this basis, the technical difficulties and key research contents of inertia response and primary frequency modulation technology of wind turbine are presented.

Acknowledgments

This work was financially supported by Beijing Polytechnic Key scientific and technological project (2021Z013-KXZ).

References

1. S. Huandong, X. Tao, etal. Analysis on blackout in Great Britain power grid on August 9th, 2019 and its enlightenment to power grid in China[J]. Proceedings of the CSEE, 2019, 39(21):6183-6192.
2. S. Yinbiao, Z. Zhigang, GUO Jianbo, etal．Study on key factor sand solution of renewable energy accommodation[J]．Proceedings of the CSEE, 2017, 37(1):1-9.
3. C. Guoping, L. Mingjie, etal. Study on technical bottleneck of newenergy development [J]．Proceedings of the CSEE, 2017. 37(1): 20-27.
4. L. Hengxian. Unit commitment of High-proportion of Wind Power System Considering Frequency Safety Constraints[J]. Power System Technology, 2020, Network publishing.
5. L. Xiong; Y. Coordinated Control Schemes of Super-Capacitor and Kinetic Energy of DFIG for System Frequency Support, in Energies, vol.11, no.1, pp.103, January 2018.
6. L. Mingjie. Characteristic Analysis and Operational Control of Large-Scale Hybrid UHV AC/DC Power Grids[J]. Power System Technology, 2020, 40(4): 985-991.
7. Q. Xiaohui, S. Lining, etal. Functional qrientation discrimination of inertia support and primary frequency regulation of virtual synchronous generator in large power grid[J]. Automation of Electric Power System, 2018, 49(2): 36-43.
8. Hydro-Québec TransÉnergie ． Transmission provider technical requirements for the connection of power plants to the Hydro-Québec transmission system [R]．Hydro-Québec, February 2009．
9. ESB National Grid. Grid code provisions for wind generators in Ireland, 2004.12.
10. Dudurych I M, Holly M, Power M. Integration of Wind Power Generation in the Irish Grid[C]. Power Engineering Society General Meeting, 2006.
11. Swidish TSO. The black out in southern Sweden and eastern Denmark [EB/OL]．

    http://www.svk.se/upload/3813/IEEE_engelskpres entation_jul2003_2230.pdf．
12. Technical Regulation TF 3.2.5. Wind turbines connected to grids with voltages above 100 kV[R]. Denmark: Elkraft System and Eltra, 2004.
13. Elkraft system and Eltra．Wind turbines connected to grids with voltages above 100 kV[R]．Errits: Elkraft system and Eltra, 2004.
14. E. ON Netz GmbH．Grid Connection Regulations for High and Extra High voltage[R]．Bayreuth: E. ON Netz GmbH, 1st April 2006．
15. Medium Voltage Directive, German Association of Energy and Water Industries (BDEW). 2008.
16. Network code on load frequency control and reserves[S]. Switzerland: ENTSO-E, 2013.
17. European Network of Transmission System Operators for Electricity. Network Code for Requirements for Grid Connection Application to all Generators[R]. ENTSOE, 212.

18. CHRISTI W. Analysis of requirements in selected grid codes[M]. UK: National Grid, 2006.
19. Boëda D, Teninge A, Roye D, et al．Contribution of Wind Farms to Frequency Control and Network Stability[R]．Paris: CIGRE, 2006．
20. Marcela M R, Andreas S, Oriol G B. Comparison of European Interconnection and Operation Requirements for Wind Farms[C]. ICREPQ: Spain, 2009.
21. The Hellenic Grid Code: Independent Power Transmission Operator. Network Code "Requirements for Generators", 2019.
22. Hannele H. Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration[C]. Transmission Networks of Offshore Wind Farms, 2009 Bremen.
23. National Grid Electricity Transmission Plc. The grid code[R]. UK: National Grid Electricity Transmission Plc. 2012.
24. Müfit A, Ömer G, Remus T. Overview of Recent Grid Codes for Wind Power Integration[C]. OPTIM 2010. p1152-1160.
25. Australian Energy Market Commission. National electricity rules-chapter 5-grid connection[R]. Australian: Australian Energy Market Commission, 2012.
26. Finland Power Grid Corp. Code for connection of wind power plants to finish power system[Z]. Finland: Finland Power Grid Corp. 2009.
27. Italian blackout sparked by insufficient control [EB/OL] . http:// www.swissinfo.org/ sen/ Swissinfo.html? site Sect =111&sid=4485955
28. National Grid SA and Saudi Electricity Company. The technical requirements for connecting new generation to the transmission system. 2016.
29. GE Energy. Modeling of GE wind turbine generators for grid studies[R]. General Electric International, Inc. 2010, USA.
30. Kara Clark, Nicholas W. Miller, Juan J. Sanchez-Gasca. Modeling od GE Wind Turbine Generators for Grid Studies. General Electric International, Inc. 2010. 4
31. Y. Zhang, J. Bank, Y. H. Wan. Synchrophasor Measurement- Based Wind Plant Inertia Estimation. IEEE Green Technologies Conference Denver, Colorado April 4–5, 2013
32. Vestas. Vestas Online Power Plant Controller. Vestas-americas@vestas.com.
33. Richard Springer, Active power control from wind power, http://zh.scribd.com/doc/67045153/ Active power control from wind power.
34. Gao W Z, Wu Z P, Wang J H, etal. A review of inertia and frequency control technologies for variable speed wind turbine[C]. Control and Decision Conference, Guiyang, China, 2013: 2527-2533.
35. Slavormir Seman, Raimo Sakki, Inertial response generators and the power electronics. www.nrel.gov/ electricity/ transmission/ pdfs/ Seman. pdf.
36. Enercon GmbH, Enercon wind energy converters technology science, www.enecon.de/p/downloads/EN_Eng_Tands_0710 .pdf.
37. L. Yang. Analysis of Renewable Energy Participation in Primary Frequency Regulation and Parameter Setting Scheme of Power Grid[J]. Power System Technology, 2020, 44(2): 683-689.
38. W. Zhanying. Analysis of Frequency Modulation Parameter for Regional Closed-loop Speed Control System with Different Load Disturbance Based on PSCAD[J]. Shaanxi Electric Power,2014,42(11):74-76,81.
39. L. Ju, Y. Wei. Prospect of Technology for Large-Scale Wind Farm Participating into Power Grid Frequency Regulation[J]. Power System Technology, 2014, 38（3）: 638-646.
40. B. Yuqing, L. Yang, et al. On demand response participating in the frequency control of the grid under high wind penetration[J]. Power System Protection and Control, 2015, 43(4): 32-37.
41. Fan Guannan, Liu Jizhen, Meng Hongmin, et al. Research on primary frequency control for wind farms under output-restricted condition[J]. Power System Technology, 2016, 40(7): 1-9.
42. Tang Xisheng, Miao Fufeng, Qi Zhiping, et al．A coordination control method of wind power and energy storage cluster: China, 201210477712．3[P]．2013-04-10 (in Chinese)．