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ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 13 (8): 1474-1483, 2014
ISSN 1812-5638 / DOI: 10.3923/itj.2014.1474.1483

A Review on the Energy Storage Technique for Real-time Wind Power Regulation

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Abstract: The energy storage technique is one of the most effective means for the real-time wind power regulation to enhance the stability of wind power. Firstly, this study discussed the operation mode of energy storage system in the course of real-time wind power balance. Also, it was proposed that the energy storage system applied into the real-time wind power regulation should be of the properties of high power density, high energy density and long cycle life. From the standpoint of practical engineering, this study carried out a comparative analysis on the energy storage properties of different energy storage elements. Furthermore, the research status and engineering development of each energy storage element were introduced. In view of the deficiency of single energy storage pattern, the composition of hybrid energy storage system was described. According to the operation requirement for balancing the fluctuant wind power in real-time, a comparative research on the topology of battery-supercapacitor energy storage system was carried out. This study hopes to supply new hints for enhancing the power controllability of wind farm.

Key words: Wind power, energy storage, real-time power regulation, power fluctuation, topology

INTRODUCTION

At the maximum wind energy capture mode, the real-time wind power fluctuates randomly as the real-time wind speed varies violently. The uncontrollable and fluctuant wind power will destroy the energy/power balance of power grid. As a result, the power grid with high wind power penetration levels will confront with several challenges in construction, dispatching and power quality (Wu *et al*., 2011; Yang, 2005; Eriksen *et al*., 2005; Sun *et al*., 2003).

For the purpose of dealing with the random and violent fluctuation of wind power, the abundant spinning reserve capacity is required to balance the wind power fluctuation (Yang, 2005; Eriksen *et al*., 2005). However, that method will lead to the increase in the operation cost of the power grid. Because the fluctuant wind power induces the variation of the active and reactive current injecting into the power grid, the grid voltage will fluctuate (Sun *et al*., 2003). At the same time, the large scale integration of wind power will reduce the rotational inertia of power grid and destroy the frequency stability of power grid. Even more, the fluctuant wind power will lead to the forced power oscillation (Sun *et al*., 2008). In order to reduce the negative effects brought by the wind power, the power fluctuation range and power regulation ability have been stated clearly in the technique rule for wind power integration all over the world (Wang *et al*., 2007).

At present, the common methods for wind power regulation are dealing with the power variation passively, such as the wind abandoning (Liu *et al*., 2012), suppressing the fluctuant wind power by rotating reserve units (Han and Chen, 2010) and the load switching (Tuan and Bhattacharya, 2003). As for the active regulation on the fluctuant wind power, the combined operation of wind power with hydropower or photovoltaic and the thermal-generated power bundled with wind power are considered as one of the most effective methods (Karki and Billinton, 2001; Ullah *et al*., 2008; Xiao *et al*., 2010). Nevertheless, the real-time wind power balance can not be achieved by any of the above mentioned methods.

As the charging-discharging power of the energy storage system can be controlled precisely, rapidly and flexibly, the energy storage system can be employed to suppress the fluctuant wind power in real-time (Barton and Infield, 2004). The development of energy storage technique successfully reduces the investment cost. Therefore, the application of energy storage system can be regarded as an effective way to enhance the controllability of the wind farm. This study focuses on

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summarizing the researches on the energy storage technique which can be applied into the real-time wind power regulation. This research lays foundation for exploring the efficient methods for enhancing the stability of wind power. In the meanwhile, this study is intended to supply new hints for making the wind farm obtain the ability of participating in the frequency regulation of power grid.

OPERATION MODE OF ENERGY STORAGE SYSTEM IN THE REAL-TIME WIND POWER REGULATION

In order to regulate the output power of the wind farm, the energy storage system can be located at the low voltage side of the transformer of wind farm to exchange the power/energy with the wind farm (Barton and Infield, 2004; Cardenas *et al*., 2001). When the real-time wind power P_{real} is bigger than the reference power value P_{ref}, the energy storage system should be controlled to absorb the excessive energy generated by the wind farm as the power value $P_{energy} = P_{real}-P_{ref}$. On the contrary, the energy storage system should be regulated to release the energy as the power value $P_{energy} = P_{ref}-P_{real}$ to compensate for the shortage of wind power when P_{real} is smaller than P_{ref}. Through that operation mode, the wind power can be controlled stably and therefore, the wind farm is able to operate as the power curve established by the dispatching center of the power grid. The combined operation of the wind farm with energy storage system can be illustrated by Fig. 1.

When the energy storage system is utilized to suppress the fluctuation of wind power, the maximum wind energy capture mode of wind turbines will not be interfered. The wind energy can be fully exploited. During the course of the wind power balancing, the energy storage system serves as a power/energy buffer. If the efficiency of energy storage system is high enough, little energy will be wasted.

Influenced by the random variation of wind speed, the wind power fluctuates randomly, violently and rapidly. Hence, the energy storage system applied into the real-time wind power regulation should be able to endure the rapid, frequent and bidirectional charging-discharging process. For the purpose of regulating the long-term wind power fluctuation, the energy storage system should also obtain the abundant energy storage capacity. As a conclusion, the energy storage system participating in the real-time wind power suppression should be of the properties of high energy density, high power density and long cycle life to reduce the investment and maintenance cost (Yu *et al*., 2012).

ENERGY STORAGE PATTERNS APLLIED INTO REAL-TIME WIND POWER REGULATION

As for all kinds of energy storage patterns, the compressed-air energy storage (Swider, 2007) and pumped storage (Chen, 2008) are considered as the most mature energy storage techniques. Although they possess the massive energy storage capacity, the long charging-discharging response time and limited power response ability inhibit their application on the real-time wind power suppression. They are often employed to take on the task of peak shaving of the wind power. The energy storage patterns which are suitable to undertake the task of

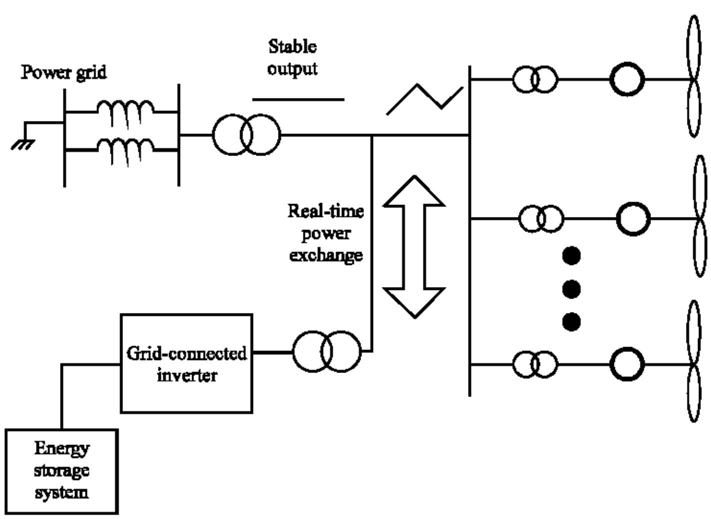

Fig. 1: Combined operation of energy storage system with wind farm

real-time wind power suppression are the flywheel energy storage system, superconducting magnetic energy storage system, supercapacitor energy storage system and battery energy storage system.

Flywheel energy storage system: The Flywheel Energy Storage System (FESS) is a kind of mechanical energy storage mode (Tan and Li, 2012; Wei *et al*., 2002). FESS can convert the electrical energy into the rotation kinetic energy of the flywheel. At the same time, the rotation kinetic energy of flywheel can be converted into the electrical energy rapidly and efficiently. Through the integration of power electronic equipment, the fast and precise power exchange between the FESS and the power grid can be realized. The FESS possesses the following merits: fast charging-discharging response, high energy conversion efficiency (>90%), high power density (>5 kW kg^{-1}), long cycle life (20 years) and excellent power characteristic (Wei *et al*., 2002).

The application of FESS into the wind power regulation has drawn plenty of interest from the researchers. Cimuca *et al*. (2010) proposed that the FESS can be integrated into the DC link of the back-to-back converter of direct-driven permanent magnet wind turbine to smoothen the power fluctuation of wind turbines. Also, the combined control strategy was developed. Suvire and Mercado (2012) discussed the coordinative operation algorithm of the FESS with wind farm to achieve the real-time wind power balance. By that proposed method, the frequency stability of the wind integrated power system can be improved. Cardenas *et al*. (2000) presented that the FESS can be exploited to serve as a power regulator for the isolated wind power system. At the same time, they developed a current feed-forward control mode and verified the feasibility of the regulation scheme for energy balance.

With the advancement in technique, the FESS has been put into engineering application gradually. Visa Company finished the 277 kW h FESS which can be utilized to smoothen the fluctuant power of the 300 kW wind turbine. North China Electric Power University developed a 2 MJ/10 kW quasi suspension FESS. Currently, the deficiency of FESS lies on the security, rotor strength and bearing consumption (Hongxin *et al*., 2010).

Superconducting energy storage system: The Superconducting Energy Storage System (SMES) is composed of the superconducting coil which lies in the low temperature environment supplied by the liquid nitrogen. Under the regulation of the power converter, the SMES can be controlled to exchange power/energy precisely and rapidly with the power grid (Zhou *et al*., 1999). The SMES has the following merits: Fast response, high energy storage efficiency (96%) and high power density (1 kw kg^{-1}).

In recent years, the research on the application of SMES into the wind power system has been carried out gradually. Shi *et al*. (2011) integrated the SMES into the excitation system of wind turbines and studied the validity of wind power suppression by simulation analysis. Chen *et al*. (2009) and Liu *et al*. (2008) proposed the voltage deviation, frequency variation and power fluctuation of power gird can be considered as the control signals for the SMES power regulation system. Nam *et al*. (2012) discussed the power regulation algorithm for the wind integrated HVDC system.

In USA, many companies have put the middle-small SMES into commercial service (Zhou *et al*., 1999). In China, Chinese Academy of Sciences has developed a 1 MJ/0.5 MW high temperature SMES. However, compared to other energy storage techniques, the SMES is expensive. At the same time, the cryogenic environment which is essential for SMES limits the construction and application of the SMES.

Supercapacitor energy storage system: The supercapacitor is developed according to the double layer theory in electrochemistry. It absorbs or releases energy through the transfer of the charge exiting in the surface of the double layer (Conway, 1999). That process is simply a physical process. The supercapacitor possesses the advantages of long cycle life (10^5-10^6), low equivalent internal resistance, fast response (msec) and high power density (several kW kg^{-1}). The supercapacitor can be widely applied into the field where the high charging-discharging power is required.

Because of the superior performance in power characteristic, the research on the application of supercapacitor into the real-time wind power regulation has drawn plenty of interest. Abbey and Joos (2007) and Muyeen *et al*. (2009) studied the method of suppressing fluctuant wind power with supercapacitor. Muyeen *et al*. (2012) proposed the control algorithm to restrict the frequency vibration of wind integrated power system by supercapacitor. Buhan *et al*. (2008) developed a series-parallel supercapacitor system and designed its operation mode to not only balance the wind power fluctuation but also restrain the voltage fluctuation of power grid induced by the fluctuant wind power.

Influenced by its energy storage mechanism and material technology, the supercapacitor is of the disadvantages of low energy density (3-15 W h kg^{-1}) and low withstanding voltage. As a result, the investment cost will be high when the single supercapacitor is employed to undertake the task of wind power balance. Consequently, the large-scale engineering application of the supercapacitor is limited. In 2005, a 450 kW supercapacitor energy storage system was constructed in California to restrain the power fluctuation from a 950 kW wind turbine.

Battery energy storage system: The Battery Energy Storage System (BESS) stores and releases energy through the redox reaction between the positive electrode and the negative electrode. Because of its advantages of high energy storage capacity and rapid power response (Buhan *et al*., 2008), the BESS is suitable to take on the task of real-time wind power regulation.

Through the simulation analysis, Buhan *et al*. (2008) and Teleke *et al*. (2010) verified the feasibility of improving the power quality of wind integrated power system by the BESS and discussed the control strategy of BESS. For the purpose of reducing the investment cost of BESS and achieving maximum economic benefits from the wind farm, Yang *et al*. (2010) studied the capacity allocation method for the BESS.

According to the chemical substances participating in the redox reaction, the battery can be divided into Ni-MH battery, lead-acid battery, lithium battery, sodium sulfur battery, ni-cd battery and vanadium redox flow battery. The properties of different batteries are given in Table 1.

It can be concluded by Table 1 that the lithium battery, sodium sulfur battery and vanadium redox flow battery obtain the superior performance in energy capacity, power response and cycle life. Consequently, those three batteries have been put into the large-scale engineering application of wind power regulation. In Japan, a sodium sulfur battery energy storage system was constructed in Hachijojima to regulate the power of local wind farm (Wen, 2007). In 2008, a 100 kW vanadium redox flow battery energy storage system was developed by China Electric Power Research Institute to achieve the real-time wind power suppression (Hongxin *et al*., 2010). In Zhangbei area of China, a wind power regulation demonstration project was constructed which contained the lithium battery, sodium sulfur battery as well as vanadium redox flow battery. The cumulative generated energy of that project has exceeded 2 billion kW h.

Compared with the supercapacitor energy storage system, FESS and SMES, the power density and cycle life of battery energy storage system is relatively limited. At the same time, the battery energy storage system often requires the precise management on the charging-discharging process. As a result, the investment and maintenance cost will be high if the single battery energy storage system is utilized to regulate the fluctuant wind power in real-time.

Table 1: Performance comparison among different types of batteries

Parameters	Lead-acid battery	Ni-Cd battery	Ni-MH battery	Lithium battery	Sodium sulfur battery	Vanadium redox flow battery
Cycle life	500~700	2000	600~1200	1000~3000	2200	10000
Power densiy (W kg^{-1})	75~200	150~300	160~230	200~330	90~230	50~140
Energy density (W h kg^{-1})	30~55	70	70~80	120~200	150~240	80~130
Advantages	Mature technology and lower investment cost	Rapid charging-discharging and prominent over-rated charging-discharging abillity	Prominent over-rated charging-discharging abillity	High energy density, high efficiency, long cycle life and low self-discharge	Prominent performance in both power and energy properties	High energy storage efficiency, large capacity
Disadvantages	Low power and energy density and short cycle	Polluting the environment and memory effect	High self-discharge	Poor performance in high temperature, slow charging-discharging process and poor homogeneity	Operating at the temperature of 300~350°C	Poor performance in power property
Application region	Backup source	Electric vehicle and power system	Electric vehicle	Electric vehicle, mobile communication equipment	Power regulation for renewable energy	Power regulation for renewable energy

APPLICATION OF HYBRID ENERGY STORAGE SYSTEM INTO REAL-TIME WIND POWER REGULATION

According to the above discussion, the quantitative comparison on the energy storage performance of flywheel energy storage system, superconducting energy storage system, supercapacitor energy storage system and lithium battery energy storage system is shown in Table 2. In the course of real-time wind power suppression, the promiment energy storage performance for energy storage system is essential which is high power density, high energy and long cycle life. Through Table 2, we can conclude that the single energy storage pattern can not fully meet the above performance requirement. By combining different energy storage patterns together to constitute the hybrid energy storage system, the performance of energy storage system can be significantly improved. Accordingly, the investment and and maintenance cost will be reduced. In recent years, the application of hybrid energy storage system into the real-time wind power regulaion has become a new research focus.

Composition of hybrid energy storage system

Battery-supercapacitor hybrid system: The battery possesses the properties of high energy density, low power density and limited cycle life. At the same time, the supercapacitor obtains the performance of low energy density, high power density and long cycle. Obviously, the energy storage performance of battery and supercapacitor can be well complemented (Tang and Qi, 2006; Yu *et al*., 2012). Therefore, they are suitable to constitute the hybrid energy storage system to achieve the improved energy storage performance. The battery-supercapacitor hybrid system can not only fully meet the performance requirement for energy storage system in the course of wind power balance but also reduce the investment and maintenance cost (Tang and Qi, 2006; Yu *et al*., 2012).

Battery-flywheel hybrid system: As for the battery-flywheel hybrid system, the integration of the flywheel makes up for the shortage of the limited cycle life of battery. Furthermore, the energy capacity of flywheel can be supplemented by the battery.

Battery-superconducting hybrid system: The initial design intension of battery-superconducting hybrid system is the same as that of the battery-flywheel hybrid system. Ise *et al*. (2005) discussed the performance of that hybrid system.

Fuel cell-battery, superconducting or supercapacitor hybrid system: The fuel cell contains high energy density. At the same time, its terminal voltage will descend sharply when the fuel cell discharges as the high power value. Therefore, the battery, superconducting or supercapacitor can be integrated into the hybrid system to compensate for the power shortage of fuel cell. Out of question, that hybrid system will obtain a superior performance in both energy capacity and power characteristic (Thounthong *et al*., 2008).

As for the above discussed hybrid energy storage system, the battery-supercapacitor hybrid system has come into commercial service in the field of electric vehicle because of the merits of mature technology, wide operation range and relatively low investment cost. In the field of real-time wind power regulation, the battery-supercapacitor hybrid system also has a bright prospect in engineering application.

Topology of battery-supercapacitor hybrid system: The effectiveness of wind power regulation and the development of the merits of battery and supercapacitor rely on the reasonable design on the topology of battery-supercapacitor energy storage system. According to the relative position of the battery, supercapacitor and the power controller in the hybrid system, the topology of battery-supercapacitor hybrid system has several categories as follows.

Topology 1: The composition of topology 1 is shown in Fig. 2. In this topology, the battery is connected to the supercapacitor in parallel by the power controller. Under the control of grid-connected inverter, the battery-supercpacitor hybrid system exchanges power/energy precisely and rapidly with the wind farm to smooth the fluctuant wind power. The power controller is resoponsible for regulating the magnitude and direction of the charging-discharging power of the battery. The difference between the whole charging-discharing power of hybrid system and the charging-discharging

Table 2: Performance comparison among flywheel, superconducting, supercapacitor and lithium battery

Parameters	Flywheel energy storage system	Superconducting energy storage system	Supercapacitor energy storage system	Lithium battery energy storage system
Cycle life (Year)	20	10^6	10^5~10^6	1000~3000
Power density (kW kg^{-1})	>5	1	Several	200~330
Energy density (W h kg^{-1})	>20	<1	3~15	120~200
Efficiency (%)	>90	90	>95	85

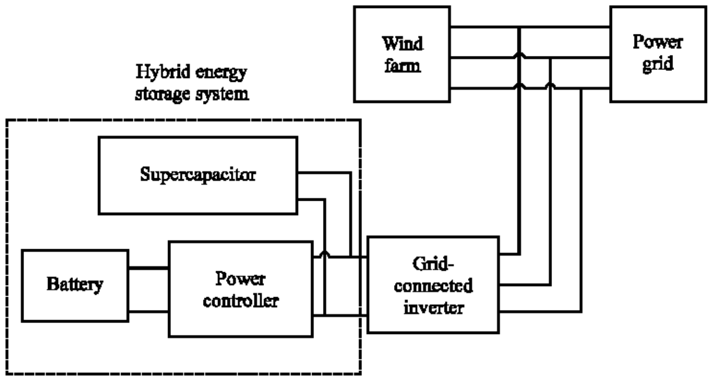

Fig. 2: Topology 1 of battery-supercapacitor hybrid energy storage system

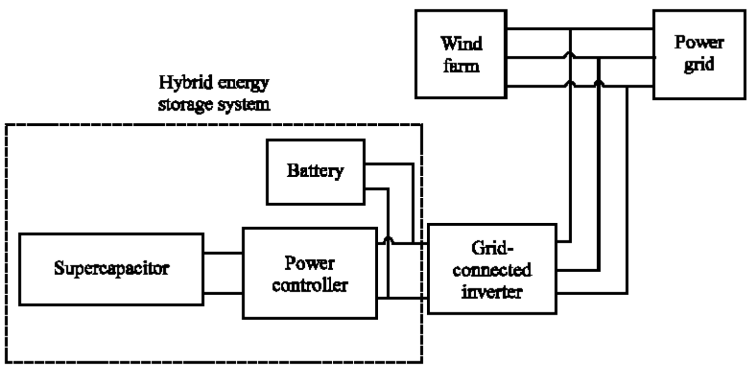

Fig. 3: Topology 2 of battery-supercapacitor hybrid energy storage system

power of battery is compensated by the supercapacitor. Gao *et al.* (2005) discussed the properties of that topology.

As for that topology, the charging-discharging process of the battery can be managed by the power controller. The battery is able to avoid charging and being discharging by the over rated power value. Consequently, that topology helps to prolong the service life of the battery.

In topology 1, the whole charging-discharging power of the hybrid system should be controlled by the grid-connected inverter. As the voltage of supercapacitor varies violently during the charging-discharging process, the measures to keep the dc link voltage of grid-connected inverter stable will be essential.

Topology 2: As shown in Fig. 3, the supercapacitor is connected with the battery by the power controller which controlls the charging-discharing power of supercapacitor. The battery compensates for the difference of the whole charging-discharging power of hybrid system and the charging-discharging power of supercapacitor. That topology has been widely applied into the field of electric vehicle (Pay and Baghzouz, 2003). Hongxin *et al.* (2010) carried out a research on the effectiveness of balancing fluctuant wind power by that hybrid system topology. According to the characteristics of the battery and supercapacitor, the authors proposed a proper control algorithm to make the battery and supercapacitor balance the power fluctuation under different frequency respectively.

As for topology 2, the dc-link voltage of grid-connected inverter will be relatively stable compared to topology 1 as the battery is connected to the dc-link of inverter. Hence, the operation stability of inverter can be improved.

The same as topology 1, the whole charging-discharging power of hybird system relies on the control of the grid-connected inverter. At the same time, in topology 2, the battery should endure frequent charging-discharging process as the battery undertakes the task of compensating for the power difference between the whole charging-discharging power of hybrid system and the charging-discharging power of supercapacitor.

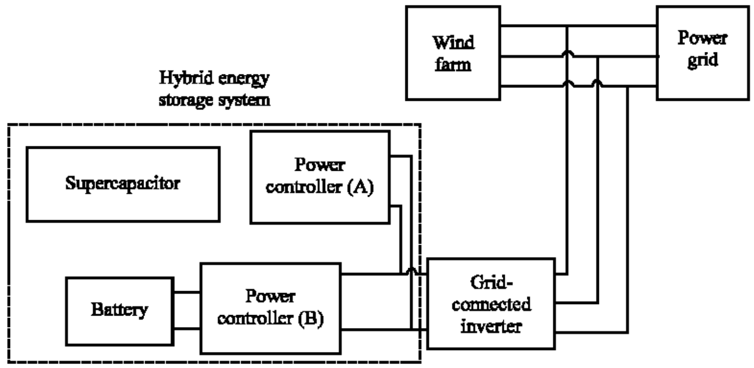

Fig. 4: Topology 3 of battery-supercapacitor hybrid energy storage system

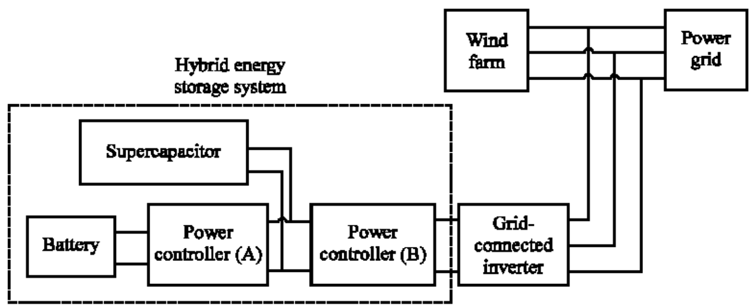

Fig. 5: Topology 4 of battery-supercapacitor hybrid energy storage system

Topology 3: The composition of topology 3 is shown in Fig. 4. In topology 3, the battery and supercapacitor are connected to the dc-link of grid-connected inverter via power controller (A) and power controller (B) separately. By controller (A) and (B), the charging-discharging power of battery and supercapacitor can be managed independently and moreover, the whole charging-discharing power of hybrid energy storage system can be handled actively. Abbey *et al.* (2009) and Antonishen *et al.* (2012) discussed the operation mode and the energy management algorithm of that topology for real-time wind power regulation.

In that topology, the service life of battery and supercapacitor can be prolonged as the battery and supercapacitor can receive the precise charigng-discharging management from controller (A) and (B).

As for topology 3, the method on how to fully develop the merits of battery and supercapcitor in the course of wind power regulation to reduce the investment and maintenance cost has drawn plenty of interests.

Topology 4: Figure 5 describes the composition of topology 4. By power controller (A), the battery is connected to the supercapacitor. The hybrid system is connected to the dc-link of grid-connected inverter via power controller (B). Under the control of power controller (A), the charging-discharging power of the battery can be managed precisely. As a result, the service life of the battery can be prolonged. The whole charging-discharging power of the hybrid system is controlled by the power controller (B) to meet the requirment of balancing fluctuant wind power. In that topology, the supercapacitor serves as a power buffer to compensate for the difference between the whole charging-discharging power of hybrid system and the charging-discharging power of battery. As a result, the decoupling control on power controller (A) and power controller (B) can be achieved. Yu *et al.* (2011) discussed the operation mode of that hybrid topology by modeling analysis. At the same time, the authors developed a double layer control model according to the energy storage characteristics of the battery, the supercapacitor and the fluctuation characteristics of the wind power. By that method, the investment and operation cost of energy storag system can be greatly reduced.

Because of the reasonable design on the location of the power controllers, the whole charging-discharging power of the hybrid system can be allocated flexibly between the supercapacitor and the battery. Through that topology, the battery and supercapacitor can be designed to suppress different kinds of wind power fluctuation respectively to fully develop their own energy storage merits. Furthermore, the power controller (B) can be controlled to keep the dc-link voltage of inverter stable when necessary.

Nevertheless, the independent operation of controller (A) and (B) depends on the power/energy buffering of supercapacitor. Therefore, how to keep the supercapacitor at a proper capacity status becomes important for the stable operation of topology 4. At the same time, when the control algorithm for topology 4 is designed, the method on reducing the charging-discharging frequency of battery must be taken into great consideration.

CONCLUSION

This study described the operation mode of the energy storage system which participated in the real-time wind power regulation. For the purpose of reducing the investment and maintenance cost, this study proposed that the energy storage system should be of the performance of high power density, high energy density and long cycle life. As for the energy storage technique which can be applied into the real-time wind power suppression, the energy storage mechanisms and performance of each technique were introduced. At the same time, the technical bottlenecks of each energy storage technique in practical engineering were summarized. In view of the deficiencies of single energy storage pattern, the constitution of hybrid energy storage system was introduced. As a conclusion, the battery-supercapacitor hybrid system was regarded as the relatively mature hybrid energy storage technique. Finally, this study carried out a comparative analysis on the topologies of battery-supercapacitor hybrid system which can be applied into the real-time wind power regulation.

ACKNOWLEDGMENTS

This study was financially supported by the National High Technology Research and Development of China (863 Programme) (Grant No. 2012AA050206).

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