Experimental Demonstration and Application Planning of High Temperature Superconducting Energy Storage System for Renewable Power Grids

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Abstract—Since High Temperature Superconducting Magnetic Energy Storage system (HT SMES) has attracted significant attention for their fast response in milliseconds, high efficiency (cyclic efficiency over 95%) and unlimited **times** of charging and discharging cycles, it can be **used** for **system stabilizing** - damping out low frequency power oscillations . A voltage source converter (VSC) based HTS SMES has been **optimal designed for a high efficiency and a HT SMES system had been** constructed by China Electric Power Research Institute (CEPRI). This SMES can store the maximum energy, while for the first time used **two state of art high temperature superconductors,** YBCO and BSCCO tapes. It has been tested in a 110 kV transmission power system in CEPRI by a dynamic power fluctuation compensation experiment using three different controlling strategies. The experimental output powers with these three strategies are compared and **the results** show that the SMES can trace the power variation and provide the required power to restrain the power fluctuation in milliseconds successfully. Finally, the application planning of SMES with the equivalent capacity in a **practical** renewable power system at Zhangbei wind power test base is evaluated by a case study based on the PSCAD/EMTDC simulation. **An** optimal switch time of the SMES in wind power system is presented using the real transmission parameters **of Zhangbei power grid**. This study can provide a reference for the demonstration of large-scale SMES systems in renewable power system.

Index Terms — Application planning; dynamic simulation; high temperature superconducting magnetic energy storage system (HT SMES); power fluctuation; Zhangbei wind power grid.

I. Introduction

High temperature superconducting magnetic energy storage system (HTS SMES) is an emerging energy storage technology for grid application. **It consists of a HTS magnet, a converter, a cooling system, a quench protection circuit and a monitoring system and can exchange its electric energy through the converter with 3-phase power system in a small period of time to supply the required power for load, as can be seen in Fig.1. Compared to other energy storage systems, SMES has a high cyclic efficiency, large power density and quick response time [reference needed].** The significant improvement of HTS materials in the past decade has substantially increased the energy and power densities of SMES, which made it very promising for practical applications [1]. Since SMES has a relatively large power density, faster response than other energy storage devices and small energy density [2], it is suitable for applications where high amounts of power must be available for a short period of time, like power quality applications [3]. In addition, SMES can also supply active and reactive power required for the power load simultaneously and overcome some of the major limitations of renewable power system as well.

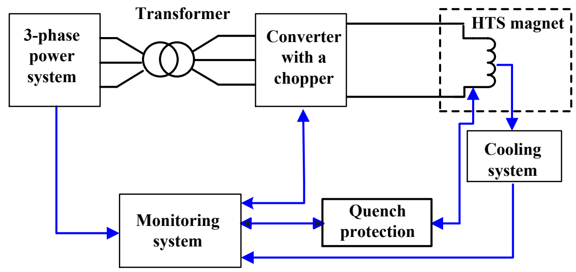


Fig.1. A schematic diagram of HT SMES system with connection of power grid.

*Jiahui Zhu is the corresponding author (Tel: 0086 10 80128056; Fax: 0086 10 81783901-601; E-mail address: zhujiahui@epri.sgcc.com.cn) y are now designing a 2.5MJ and a 5MJ SMES system using REBCO conductors for power quality improvement [5]. NEEL Institute has constructed a twin coil 2 × 200 kJ-1 MW conduction-cooled HTS SMES using BSCCO conductors for pulse power operation and its current output reaches 600 A[6]. There are also researches focused on simulation study of SMES systems for power grid applications. For example, Tohoku University proposed an **Advanced Superconducting Power Conditioning System** (ASPCS) model for compensating the fluctuating renewable energy with SMES [7]. Korea Electro-technology Research Institute (KERI) suggested a novel connection topology model of SMES which can not only smooth the output power flow but improve the performance of **Low Voltage Ride Through (LVRT) of a Permanent Magnet Synchronous Generator** (PMSG) in wind power system [8-10]. Tampere University of Technology studied the environmental benefits of superconducting devices in Distributed Generation (DG) including SMES, flywheels and cable systems using a life-cycle assessment [11].

Other energy storage systems rather than SMES have been studied for wind power generation. University of Salerno (UNISA) investigated a management method for a hybrid power plant with wind turbines, photovoltaic panels and **Compressed Air Energy Storage** (CAES). They presented an example kind of plant can meet the requirement for the renewable energy sources [12]. Catalonia Institute for Energy Research (IREC) reviewed several energy storage technologies for wind power application and points that Energy Storage Systems (ESSs) may play an important role in wind power applications with a stochastic nature [13]. They designed an energy control strategy for a flywheel-based energy storage device [14].

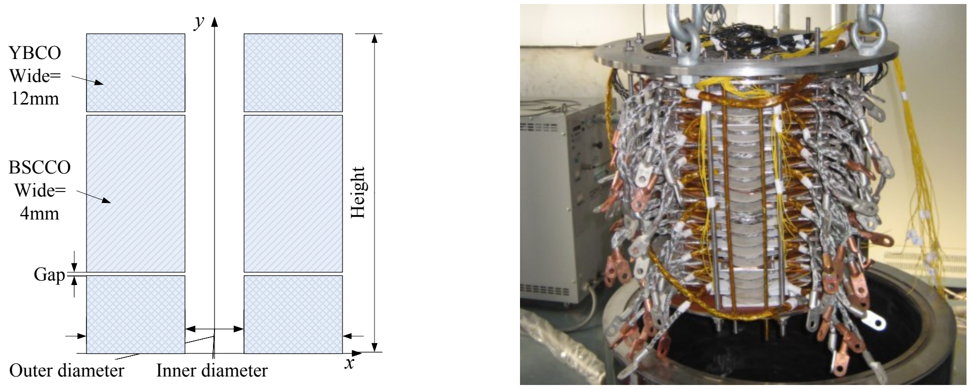
As can be seen, most of the work on SMES is either focused on building superconducting magnet or simulation of using SMES in power systems. There is little study involving both constructing SMES magnets and experimentally using SMES in a power grid environment. Further, there is little study using SMES of state-of-art YBCO tapes in a wind farm. Using SMES can not only adjust the power output but also reduce or even eliminate the frequent power oscillation of the grid. The dynamic management of the transmission / distribution systems and renewable power grid with SMES can be improved with SMES systems and help to achieve a good performance of the power grid transient stability and quality.

This paper has brought together our **original research in building the HTS SMES system, using it in a real dynamic experiment and investigating the application potential in a wind power system for the first time in China Electric Power Research Institute (CEPRI), which has practically demonstrated the applications of SMES in the power system** and validated the design concept. A kJ-class, 20kW HTS SMES has been designed and developed by us [15]. We have used the state-of-art YBCO tapes to build the superconducting magnet which has been rarely demonstrated before due to lack of conductors available. Secondly, the experiments applying HTS SMES for the power fluctuation compensation with three various appropriate control strategies are achieved by constructing an 110kV dynamic simulation power transmission system in CEPRI. The experimental results are compared and analyzed to give the best control strategy of SMES for the power stability regulation. This is the first time that a SMES system is tested in a dynamic power simulation laboratory in order to demonstrate its grid applications. Finally, the future planning for HTS SMES applications in a real renewable power grid is explored for the first time considering the effects of install capacity and switch time of SMES by a case study of Zhangbei wind power grid based on the PSCAD/EMTDC simulation. The experimental and simulation analysis results demonstrate that the SMES can provide required compensation power and restrain power fluctuation within milliseconds very well with optimal allocation in the power grid.

II. Design and Construction of A VSC-based HTS SMES

An optimal design of the HTS SMES using YBCO and BSCCO tapes is achieved in terms of operation current maximization. **The configuration schematic diagram of SMES magnet is shown in Fig. 2a and a photo of the magnet can be seen in Fig.2b. The YBCO coils are located at two ends of the SMES unit and the BSCCO coils are designed to locate at the middle position because YBCO tape has a better critical current property in the perpendicular magnetic field than**

BSCCO tape. Therefore, the SMES unit can have a good critical current performance. Table 1 is the optimal configuration and characteristic parameters of the designed SMES[16-18]. We can find that the SMES has an operational current of 109 Ampere and its energy can increase to 6 kJ when the cooling system operates at the sub-cooled LN2 of 69 K. The SMES unit is settled in a sealed dewar, which is connected with a 600 W GM refrigerator. We can cool the LN2 in the dewar by controlling the GM refrigerator to achieve a range of cooling temperatures from 65 K to 77K conveniently.



(a) **(b)**

Fig.2. Configuration of HTS SMES unit (BSCCO coils are at the middle and YBCO coils are at top and bottom ends):(a) Schematic diagram; (b) magnet photo.

TABLE I
OPTIMAL DESIGN **CONFIGURATION** OF THE HTS SMES

Specification	Quantity
Tape length (m)	2800
YBCO pancake number (12mm tape)	4
BSCCO pancake number (4mm tape)	20
Inner diameter (mm)	68
Outer diameter (mm)	222
Turns per YBCO pancake	450
Turns per BSCCO pancake	220
Total height (mm)	490
Inductance(H)	1.02
Operation current(A@77K/ A@69K)	56/109
Energy(kJ@77K/ kJ@69K)	1.6/6

A LCL filtered **Voltage Source Power Converter** (VSC-based) system, a cryogenic system with sub-cooled LN2, a quench detection and position protection circuit and a host monitoring and controlling system are designed and constructed with the superconducting magnet to develop a kJ-class HTS SMES system. A composition **communication** of the SMES system is shown in Fig.3, which consists of a Nanovolt measurement unit, a PXI data acquisition detection unit, a voltage and current waveform recording unit, a Quench detection & protection unit, a VSC-based power converter unit and a SMES unit with sub-cooled LN2 [19]. The power grid conditions are monitored by the measurement unit, and the responses of SMES are monitored by the acquisition detection unit. The wave recording unit records all the operation information, based on which the control order can be generated by the host system to control the SMES in charge, persistent and discharge modes using the communication protocol of RS232 and LAN. Table 2 shows the operation status correspondence of SMES and its power converter under different control condition.

TABLE II
CORRESPONDING RELATIONSHIP OF THE OPERATING STATE BETWEEN SUPERCONDUCTING MAGNET AND THE POWER CONVERTER

Control command	Converter status				Superconducting magnet status		
	Rectifier	Persistent	Inverter	stop	Charging	Persistent	discharging

Rectification	√				√		
Persistent		√				√	
Inversion			√				√
Stop		√		√		√	

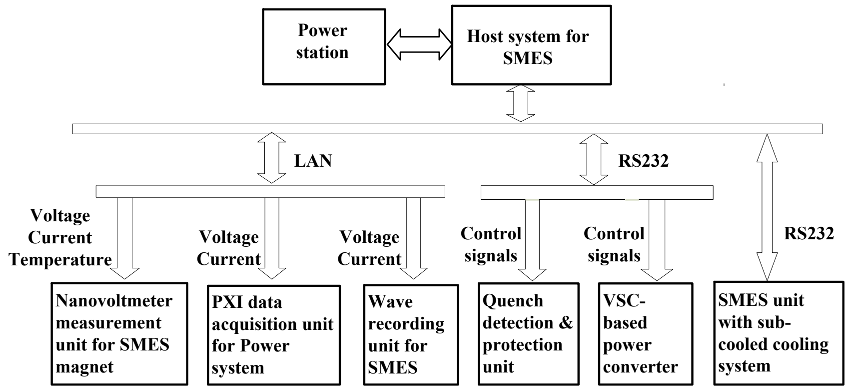


Fig.3. SMES system construction and communication diagram.

III. Dynamic Simulation Experiment with VSC-based HTS SMES

A grid-connected transmission power system using the HTS SMES for power compensation experiment is constructed in a **dynamic simulation laboratory of State Grid Cooperation of China (SGCC).** This experiment power system is built with parameters chosen according to the ratio of actual power system parameters. It consists of a 5kVA generator, 200 km transmission line (Line1), 6kVA transformer, 100kVA transformer and a controllable load with capacity of 3kW. The SMES is in parallel connection with the power system at Bus1, shown in Fig.4. When a fault occurs at the transmission line, the SMES can dynamically track the real-time power waveforms and compensates power fluctuation using control strategies with different combinations of charging, persistent and discharging. To quantitatively demonstrate the contribution of the SMES for power compensation, a power fluctuation fault (at t = 0.41s) is induced by imposing a power drop at Bus1, as shown in Fig. 4. The power drop is achieve by removing a 3 kW load on Bus1 at t = 0.25 s for 160 ms. The SMES is designed to smooth the power fluctuation rather than voltage drop, so the controller takes no action during the power drop, and it begins to operate after the power drop.

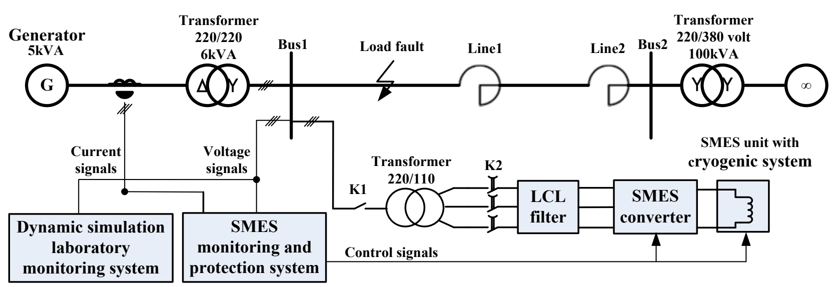


Fig.4. A dynamic transmission system model for power compensation using SMES.

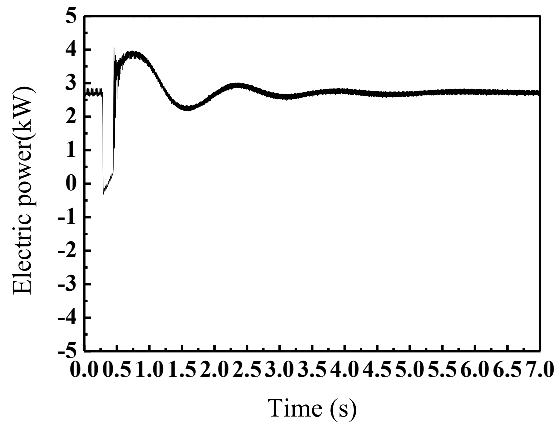


Fig.5. The power fluctuation waveform without SMES.

When the power fault **in Fig.5** is detected at 5 kHz sampling rate, the HTS SMES is driven to produce the power and to compensate the fluctuation by comparing with the referenced power. Three kinds of strategies are proposed for the power compensation by using HTS SMES. In the first strategy, the SMES coils are controlled to charge for 350ms with 100ms delay after the load dump happens and then discharge for 600ms. In the secondly strategy, the SMES coils are controlled to persistent current for 30ms after it is charged for 350ms with 100ms delay and then discharge for 600ms. In the third strategy, the SMES coils have charged for 280ms with 140ms delay after the power drop happens. Then, it has been controlled to persistent for 40ms, and again, the SMES coils continue to charge for 200ms and then discharge for 260ms until the last. Table 3 shows these three different controlling methods for the power fluctuation compensation with SMES.

Based on the power oscillation in Fig.5, SMES traces the power waveforms and smooth it. The electric powers absorbed from the power grid using the above three compensation strategies by SMES are shown in Fig.6. Fig. 7 is the power waveforms of the dynamic experimental power system after using these compensation strategies based on the variable load in Fig.5. From Fig.6 and Fig.7, we can find that when the power deviates from the normal value, SMES can regulate the power waveforms in milliseconds and smooth it. It absorbs the energy from the grid when there is a wave peak in power system and releases its energy to the grid when there is a wave trough. Therefore, SMES can achieve the power smoothing very well. For valuing the compensation effects, a compensation factor k is defined using the rated power P_N as the following:

$$k = \frac{\max\{(P_{\max} - P_N), (P_N - P_{\min})\}}{P_N} \cdot 100\% \tag{1}$$

Wherein, P_{max} and P_{min} are the maximum and minimum power value respectively after the power drop is over.

TABLE III
COMPARISON OF CONTROLLING STRATEGY WITH SMES FOR COMPENSATION THE POWER FLUCTUATION

Item	Power dump duration/ms	Response delay/ms	Charge/ms	Persistent/ms	Charge/ms	Persistent/ms	discharge/ms
1st Strategy	160	100	350	0	0	0	600
2nd Strategy	160	100	350	30	0	0	600
3rd Strategy	160	140	280	40	200	0	260

Table 4 is the comparison of maximum power P_{max}, minimum power P_{min} after the power drop and the compensation factors k for three different compensation scenarios. We can find the power fluctuation factor is 37.8% when SMES does not act, but it will decrease significantly when there is SMES. The smallest power compensation factor is 23.3% when applying the second strategy which is the best. The peak to peak power value of the second strategy is 0.8kW which is 46.2% of the peak to peak power value 1.73kW without SMES. Experimental results achieve a good tracking and real-time compensation for the grid power fluctuations with SMES, and verify the correctness of the SMES design and the validity of the SMES in power system.

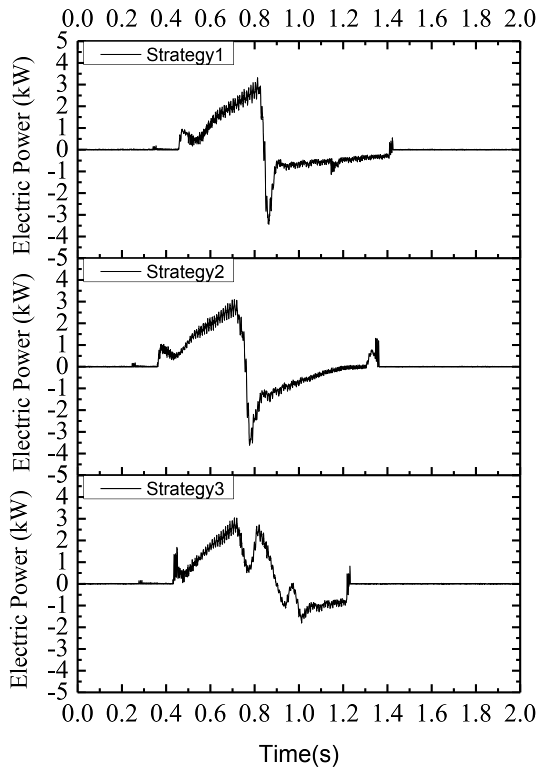


Fig.6. The power absorbed from power grid by SMES using three kinds of strategies.

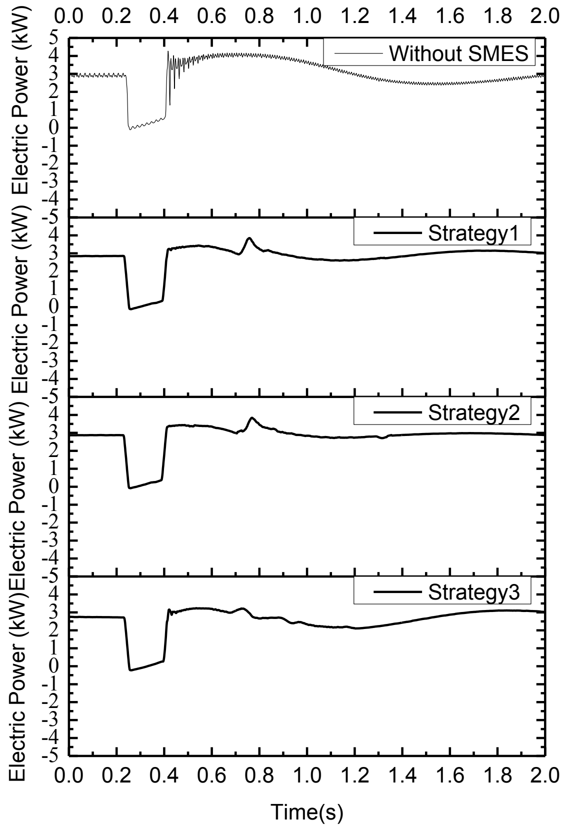


Fig.7. 3-phase power waveforms of power system after compensation with SMES using three kinds of strategies and without SMES

TABLE IV
COMPARISON OF ELECTRICAL POWER BEFORE AND AFTER COMPENSATION WITH SMES IN POWER SYSTEM

SMES operation mode		P_N	Power /kW			
			P_{min}	P_{max}	Peak-Peak value	k
Without SMES		3	2.4	4.13	1.73	37.8%
with SMES	1^{st} Strategy	3	2.7	3.9	1.2	30.0%
	2^{nd} Strategy	3	2.9	3.7	0.8	23.3%
	3^{rd} Strategy	3	2.1	3.2	1.1	30.0%

IV. APPLICATION PLANNING OF SMES IN A RENEWABLE POWER SYSTEM

A. Introduction of SMES Systems in Zhangbei Renewable Power Grid

In recent years, the large penetration of wind power system is considered as an effective means for power production but it can also cause the severe power fluctuation in tie-lines [20]. To alleviate power fluctuation, the superconducting magnetic energy storage can be applied. An application planning in a wind power grid of a SMES constructed by CEPRI is evaluated considering the effects on the stability of power grid based on a PSCAD/EMTDC simulation in this paper.

Based on the above power compensation experiment using the HTS SMES in the dynamic simulation laboratory of SGCC, the grid-connected transmission system is equivalent to a 200km long 110kV transmission line in a real power grid according to the principle of equivalence for the line parameter. The maximum instantaneous output power of the SMES can reach 3.5kW. Since it is a dynamic simulation experiment, this output power is equivalent to 371MW in the simulated double-side transmission line system, and therefore, the SMES energy is equivalent to 100 MJ.

In order to prospect the SMES application planning in a renewable power grid, a 100MJ/ 371MW HTS SMES is applied to a power grid simulation model of Zhangbei wind power test base which is a 100.5 megawatt wind power facility with build-operate-own basis in Zhangbei County, Hebei Province, China. In 2011, **CEPRI**, and also is the research-based subsidiary of SGCC, completed this largest capacity multi-type **wind**, PV and **energy storage demonstration** center (shown in Fig.8). The center includes 500 MW of wind power, 100 MW of solar power, and 110 MW of power storage system and is mainly supported and funded by the National Energy Smart Grid Technology R & D Center and the National Wind Power Integration Research and Test Center of China.

Fig.8. Zhangbei wind power test base in China

B. Application Planning Simulation of SMES Systems

Due to the difference in grid scales, fault types and operation conditions, the performance of SMES for improving transient stability depends greatly on the stored energy, switch time and choice of location. So studying the optimization setting for SMES, such as capability and switch time, can improve not only the performance of system controlling, but also the economic feasibility.

The fundamental principle of SMES is to enable power exchange between SMES and system by controlling the flow of current. So in theory, SMES is equivalent to a controllable current source connected in parallel to the grid, of which the active and reactive current can be controlled respectively. In this paper, a three-phase controllable current source model is used to simulate the dynamic responsive characteristics of SMES. The active and reactive **powers of the SMES are controlled by a Power Converter System (PCS) with** two independent **PI control regulators based on the transient signals of electric power in the wind power system**. When the change of electric power happens in where the SMES is installed, the power is **compared to the normal values for obtaining the output power of the SMES. The output power is used as input singles for the two PI control regulators to control the PCS for power conversion.** The SMES simulation model using active power P_{SMES} and reactive power Q_{SMES} at simulation time step of i are as the following:

$$P_{SMES}(i) = P_{SMES}(i-1) + (k_P + k_I T)\Delta P(i) - k_P \Delta P(i-1) \quad (2)$$

$$Q_{SMES}(i) = Q_{SMES}(i-1) + (k_P + k_I T)\Delta Q(i) - k_P \Delta Q(i-1) \quad (3)$$

Where k_p， k_I is control parameter of PI controllers, T is simulation time step, ΔP， ΔQ are the variation of active power and reactive, respectively.

The planning for SMES installation capacity and switch time is then proposed by system simulation methods considering the two-phase short circuit fault in Zhangbei wind power test base, using the proposed SMES model. By setting installation capacity and switch time of SMES according to the dynamic simulation experiment system parameter, we are looking for the effects of SMES on the renewable power grid, to ensure transient stability of the system.

Figure 8 shows a topology of Zhangbei wind power system installed with SMES. It includes a generator, four transformers T_1-T_4, a wind farm, a Battery Energy Storage System (BESS), a Photovoltaic (PV) power system and two double circuit transmission lines $L_1$and L_2. SMES is in parallel connection to the Bus N_3 via a Power Control System (PCS). The generator sends power to the grid when the power system is in a normal operation. SMES will be controlled to send power to the grid for maintaining power system stability when there is a fault.

To evaluate the effectiveness of SMES, a power angle δ which determines the power the generator has to produce when there is variation in load is proposed to assess the stability of the Zhangbei wind power grid simulation model. When the power angle is above 90 degree or below 0 degree, then the generator falls out of synchronism. It also means the power system is unstable. But, when the power angle is between 0 and 90 degree, the power grid is stable and would become more stable when the waveform of power angle δ closes to a straight line.

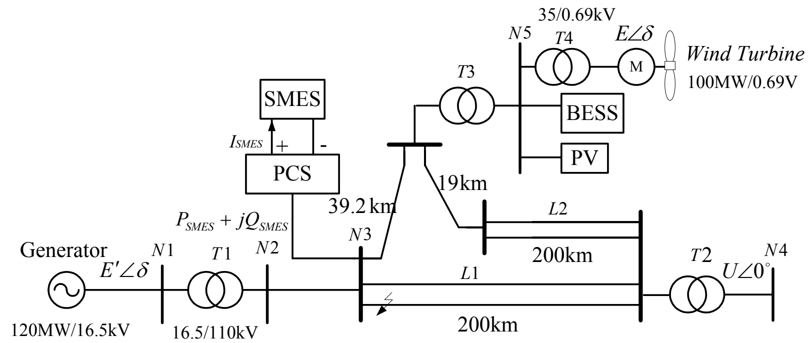


Fig.9. Zhangbei wind power system topology with SMES.

Considering a short-circuit fault of 0.5s in the double circuit transmission line L_1 in Fig.9, we calculate power angle δ considering different switch time of 0, 0.2s, 0.3s, 0.4s, 0.5s, 0.6s, 0.7s, 0.8s of the SMES with a capacity of 371MVA, seen in Fig.10. Curve 1 is without SMES; Curves 2~8 are with SMES. After a short-circuit fault happens, the power angle can no longer stay in the stability region (between 0 and 90 degree) without a SMES. By contrary, when the SMES outputs its energy and provides the required power P_{SMES} and Q_{SMES} to the power system during the short-circuit fault, the power angle waveforms become more smooth with the increase of the switch time of SMES. It suggests that with the installed SMES, the transient stability of the system is well maintained during the fault. But when the switch time of SMES is more than 0.5s, the power angle waveforms will have larger fluctuations. It shows that the system is losing stability.

Moreover, the maximum and minimum value of power angle with different switch times of the SMES are calculated and compared in Table 5. When the switch time of SMES is 0.3s, the Peak-Peak value of power angle is 71.31 degree and is the minimum value in all the conditions considering the effects of different switch times. And it is 26.53% of the Peak-Peak value of power angle without SMES. Therefore, transient stability of the system is well maintained with the installed SMES during the fault with a capacity and switch time combination of (371MVA, 0. 3s) in Zhangbei wind power test base.

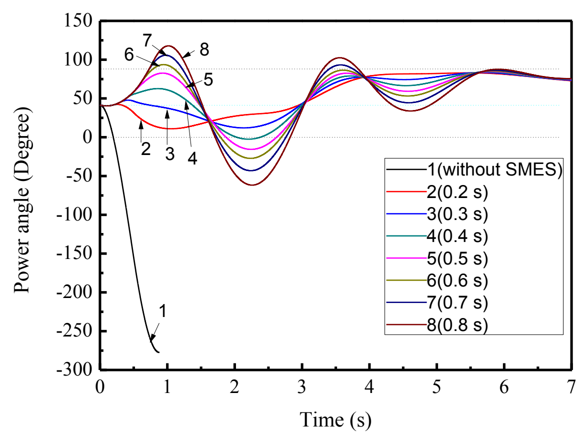


Fig.10. Transient power angle waveforms without and with SMES

TABLE V
COMPARISON OF POWER ANGLE OF THE SIMULATED SYSTEM WITH SMES

Switch time of SMES/s	δ		
	Minimum/Degree	Maximum/Degree	Peak-Peak value/Degree
0	-227.48	41.29	268.77
0.2	10.92	82.94	72.01
0.3	12.08	83.40	71.31
0.4	-2.47	84.02	86.50
0.5	-15.63	84.70	100.33
0.6	-27.199	93.59	120.79
0.7	-43.11	105.72	148.83
0.8	-61.71	117.77	179.49

V. CONCLUSION

A VSC-based SMES consisted of YBCO and BSCCO HTS tapes is constructed successfully for the first time and tested in **CEPRI** for the potential application in a renewable power system. An SMES magnet, a VSC power converter, a sub-cooled LN2 cooling system, quench detection and protection circuit and a host controlling system is integrated in the dynamic power system simulation laboratory of SGCC to stabilize power fluctuations. Three kinds of strategies are proposed and applied to compensate the power fluctuation successfully in milliseconds. An simulation model of this HTS SMES with equivalent capacity in the actual power system are built up and an application planning of the SMES in Zhangbei wind power grid is evaluated by a case study based on the PSCAD/EMTDC simulation. The optimal switch time and capacity of the SMES in the renewable power system is presented. This study can provide a reference for the demonstration of large-scale SMES systems in renewable power system.

ACKNOWLEDGMENT

All the Authors would like to thank the support by NSFC Grant 51207146, EPSRC EP/K01496X/1 and RAEng Research Exchange scheme of UK and acknowledge the dynamic simulation laboratory and Zhangbei wind power test base of **SGCC**.

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