

## Improving the Stability and Reliability of Wind Power Grid-Connected System

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### Abstract

This paper proposes a method for improving the stability and reliability of the wind power grid-connected system. This method comprises of Superconducting Magnetic Energy Storage (SMES) based excitation system for doubly-fed induction generator (DFIG) used in wind power generation. The excitation system is composed of the rotor-side converter, the grid-side converter, the dc chopper and the superconducting magnet. Utilizing the characteristic of high efficient energy storage and quick response of superconducting magnet, the system can be utilized to level the wind power fluctuation, alleviate the influence on power quality, and improve fault ride-through capability for the grid-connected wind farms. Using MATLAB SIMULINK, the model of the SMES based excitation system for DFIG is established, and the simulation tests are performed to evaluate the system performance.

**Key words** — Converters, Doubly-fed induction generator (DFIG), superconducting magnetic energy storage (SMES), wind power generation.

### I. INTRODUCTION

An effective way to solve the global problems such as the environmental pollution and energy shortage is the large scale development of wind power. Wind power has proven to be a potential source for generation of electricity with minimal Environmental impact [1]-[2]. Many large wind turbines operate at variable speed which has improved the efficiency of energy transfer from the wind and optimize the operation of wind turbine Using doubly fed induction generators (DFIGs)[3]-[4]. A variable speed wind turbine with a doubly-fed induction generator is shown in Fig. 1. The DFIG is equipped with a back-to-back power electronic converter, which can adjust the generator speed with the variety of wind speed. The converter is connected to the rotor windings, which acts as AC excitation system.

Although the DFIG have good performance, there are some issues that should be concerned when the wind farms with DFIGs are widely connected to the power grid. The first issue is the power quality induced by the fluctuant power. Especially in the condition of frequent wind speed variation.

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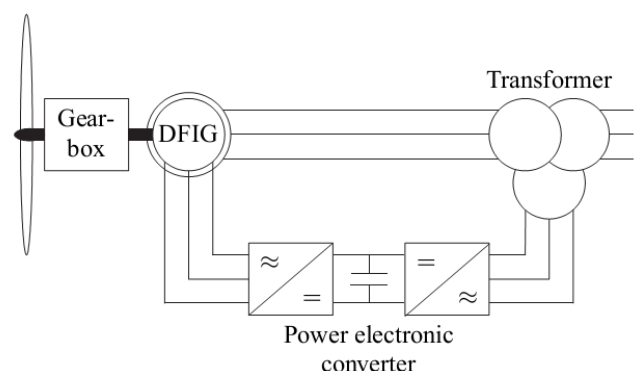
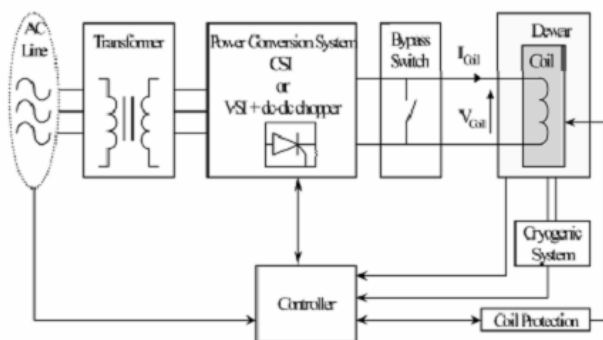


Fig . 1. Variable-speed wind turbine with a doubly-fed Induction generator (DFIG).

The second issue is the operation of DFIG during grid faults. Faults in the power system, even far away from the location of the turbine, can cause a voltage dip at the connection point of the wind turbine. The dip in the grid voltage will result in an increase of the current in the stator windings of the DFIG, which will induce the over current in the rotor circuit and the power electronic converter. To solve the above problems, many devices and control strategies are proposed for wind power smoothing. They can be divided into two categories: One is by regulating the reactive power output of wind turbine generator [5]-[6], which can be categorized as direct control of wind power. This method is poor effect when wind power fluctuations are large. The other is by regulating the power output of additional energy storage devices [7]-[8], which can be categorized as indirect control of wind power. This method can achieve wider regulation of wind power. However, the cost of energy storage devices is relatively high [9], limiting energy storage system application in wind farms. This work is a continuation of research on wind power smoothing. It focuses on the use of small capacity Superconducting Magnetic Energy Storage system (SMES) to improve power quality in wind farms. The energy storage unit is a preferred way to handle the energy transfer caused by power fluctuation or grid fault [10]-[11]. The components of a typical SMES system is shown in Fig. 2.

Fig.2. Components of typical SMES system

An integrated power generation and energy storage system for doubly-fed induction generator based wind turbine systems is proposed. Superconducting magnetic energy storage (SMES), which is characterized by its highly efficient energy storage, quick response, and power controllability, is introduced to the DC link of the back-to-back power converters of the DFIG through a bi-directional DC/DC power electronic converter. The SMES is controlled to level the wind power fluctuation, alleviate the influence on power quality, and improve fault ride-through capability for the grid-connected wind farms. Using



MATLAB SIMULINK, the model of the SMES based excitation system for DFIG is established, and the

simulation tests are performed to evaluate the system performance.

## II SYSTEM CONFIGURATION

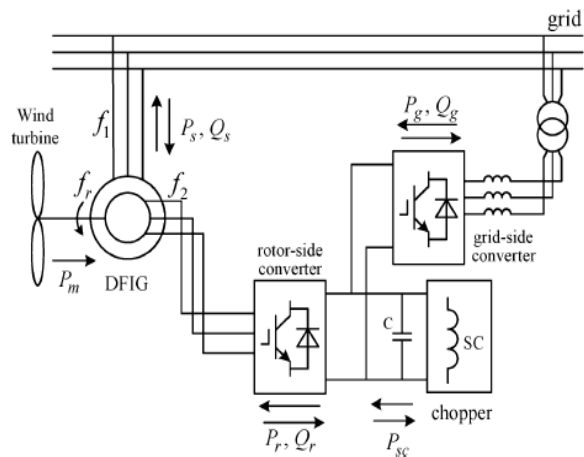


Fig. 3. The main circuit of DFIG wind power system based on

### SMES

The main circuit of the SMES based excitation system for doubly-fed induction generator is shown in Fig. 3. The excitation system is composed of rotor-side converter, grid-side converter, DC chopper, and superconducting magnet. In this excitation system, the energy storage unit must have the characteristic of high energy storage efficiency and quick power response, and the energy storage capacity is not the essential factor. The discharge capabilities of SMES compared to several other energy storage technologies is illustrated in Fig. 4. So, the superconducting magnet is selected as the energy storage unit of the excitation system, it is set at the DC side of the two converters. The DC chopper is utilized to control the charging and discharging of the superconducting magnet. With the coordinate control of converter, the power transfer between the superconducting magnet and the generator rotor or the power grid can be controlled effectively.

The SMES based excitation system for doubly-fed induction generator can fulfill the following functions:

- 1) In the condition that the energy storage capacity of Superconducting magnet is large enough, the power transfer during the operation of variable speed constant frequency (VSCF) can be handled by the superconducting magnet. This operation mode can smooth the power fluctuation of wind farm, and improve the power quality issue induced by the wind power integration.
- 2) During the system operation, the rotor-side converter and the grid-side converter is mutually independent. The system initiatively participate the operation and control of power grid, which can improve the security and

stability of power system.

- 3) In the condition of grid fault, the over current in the rotor can be suppressed using the energy storage of SMES. Moreover, the SMES and the grid-side converter are impervious to the grid fault, which can supply the power compensation to the grid and recover the power coupling point voltage.

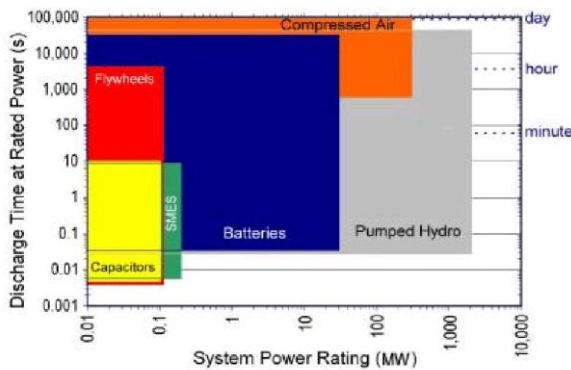


Fig.4. Illustration of power rating and the discharge time of several energy storage technologies.

### III SYSTEM CONTROL

The system control is composed of two levels. Firstly, the operation state of the wind turbine and the grid is monitored. Based on the operation data, the power demand of the rotor-side and grid-side can be analyzed. This function can be regarded as the system level. Then, the other is equipment level, which includes the rotor-side converter control, the grid-side converter control and the DC chopper control. The basic control diagram is shown in 3.1. The System Level

The system level control can be divided into two conditions

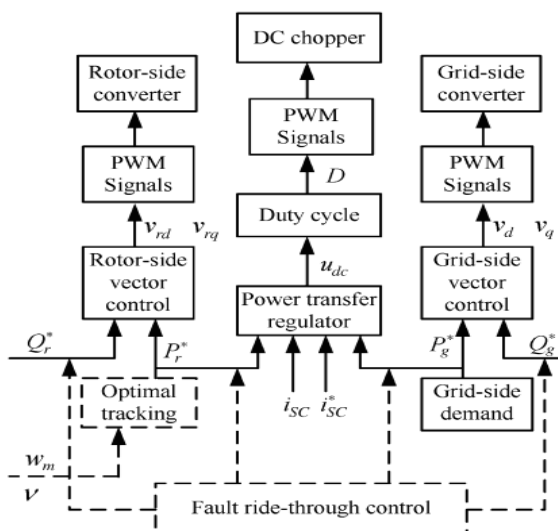


Fig. 5. Control diagram of the SMES based DFIG system

In normal operation state of the grid, the DFIG can realize the operation of VSCF based on tracking the wind speed. In the condition of grid fault, the control objective is to reduce the adverse effect from the grid side and improve the ride-through capability of the DFIG. This control level gives out the power demand for the converters and the SMES, which is represented as the dash line in the Fig. 5.

### 3.2. The Equipment Level

According to the power demand from the system level, the rotor-side converter, the grid-side converter and the DC chopper

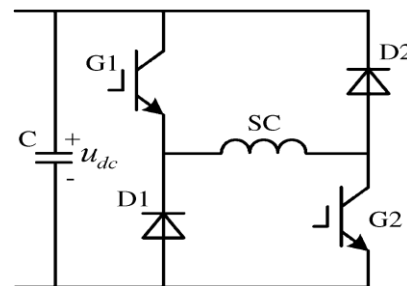


Fig. 6. The topology of DC chopper.

are controlled to regulate the power flow. For the rotor-side and the grid-side converter, the pulse-width modulated (PWM) voltage source converter is adopted. And the vector control method is adopted to improve the dynamic power response [12]. As for the DC chopper, it needs to deal with the active power transfer of the DFIG rotor and the grid, and the integrated energy control should be considered.

The superconducting coil is charged or discharged by adjusting the average (i.e., DC) voltage across the coil to be positive or negative values by means of the DC-DC chopper duty cycle,  $D$ . When the duty cycle is larger than 0.5 or less than 0.5, the coil is either charging or discharging respectively.

The control concept of coil energy charging and discharging is shown in Fig. 7. The DC-DC chopper is controlled to supply positive (IGBT is turned on) or negative (IGBT is turned off) voltage  $V_{dc}$  to SMES coil and then the stored energy can be charged or discharged. When the unit is on standby, the coil current is kept constant, independent of the storage level, by adjusting the chopper duty cycle to 50%, resulting in the net voltage across the superconducting winding to be zero. In order to generate the gate signals for the IGBT's of the

chopper, the PWM reference signal is compared with the saw tooth carrier Signal. The basic typology of the DC chopper is shown in Fig. 6, which consists of two IGBTs and two diodes. The DC chopper can control the magnitude and the polarity of

the voltage across the superconducting magnet (SC) complying with the energy flow of the system. Moreover, the DC chopper can maintain the DC voltage to be essentially constant. Based on the direction of energy transfer, the DC chopper has two operating modes.

Fig. 7. The control concept of SMES charging and Discharging

- a) Charging mode. S1 is ON at all times, and S2 is alternately ON and OFF during each chopper cycle.
- b) Discharging mode. S1 keeps OFF at all times, and S2 is alternately ON and OFF during each chopper cycle. Considering the operation life of the switching device, the switch motion of S1 and S2 can be reciprocated. Based on

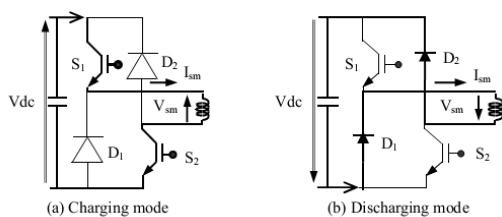


Fig. 7. The control concept of SMES charging and Discharging

**DESIGN PARAMETERS**

	Item	Parameters
	Rating power	75 kW
	Rating voltage	380 V
DFIG	Stator leakage reactance	4 mH
	Rotor leakage reactance	2 mH
	mutual inductance	69.31 mH
Rotor-side converter	rating power	25 kVA
	Switching frequency	5 kHz
Grid-side converter	rating power	45 kVA
	Filter inductor L	6 mH
	Switching frequency	5 kHz
DC chopper	rating power	80 kVA
	Switching frequency	10 kHz
	DC link capacitor	9400 μF
	DC rating voltage	600 V

switching function, the mathematical model of the DC chopper can be arranged as follows:

$$\begin{cases} C \frac{du_{dc}}{dt} = D i_{sc} & + i_{dc} \\ C \frac{du_{dc}}{dt} = (1 - D) i_{sc} & \end{cases} \begin{matrix} \text{charging state} \\ \text{discharging state} \end{matrix} \quad (1)$$

Then, adopting discretization-based state-feedback method

[12], the control equation of the DC chopper can be deduced,

$$\begin{cases} D = C \frac{u_{dc}(k+1) - u_{dc}(k)}{T_{s2}} + \frac{i_{dc}(k)}{i_{sc}(k)} (k) \\ D = 1 - C \frac{u_{dc}(k+1) - u_{dc}(k)}{T_{s2}} + \frac{i_{dc}(k)}{i_{sc}(k)} (k) \end{cases} \begin{matrix} \text{charging state} \\ \text{discharging state} \end{matrix}$$

For the grid-side converter of the excitation system, the capacity design should consider the power requirement for different control objective. Supposing the system can compensate the power fluctuation within the 50% rating power of the DFIG, the grid-side converter is designed as 45 kVA, which is higher than the capacity of rotor-side converter. According to the application objective, the SMES is designed to compensate the power fluctuation with duration.

#### IV. SIMULATION RESULTS

To evaluate the system performance, the model of the SMES based excitation system for DFIG is established using MATLAB SIMULINK. The model contains a DFIG wind turbine, three power converters and associated controllers, a DC-link capacitor, a superconducting magnet, and an equivalent power grid. According to the system parameters of the electric power system dynamic simulation laboratory, the parameters of DFIG are designed as shown in Table.

For the grid-side converter of the excitation system, the capacity design should consider the power requirement for different control objective. Supposing the system can compensate the power fluctuation within the 50% rating power of the DFIG, the grid-side converter is designed as 45 kVA, which is higher than the capacity of rotor-side converter. According to the application objective, the SMES is designed to compensate the power fluctuation with duration of 2s. Considering the current carrying level of the high temperature superconducting tapes, the rating current of the magnet is selected as 150 A. According to the above condition, the rated energy storage capacity of the magnet is designed at 100 kJ, which satisfy the energy requirement of short-time power compensation.

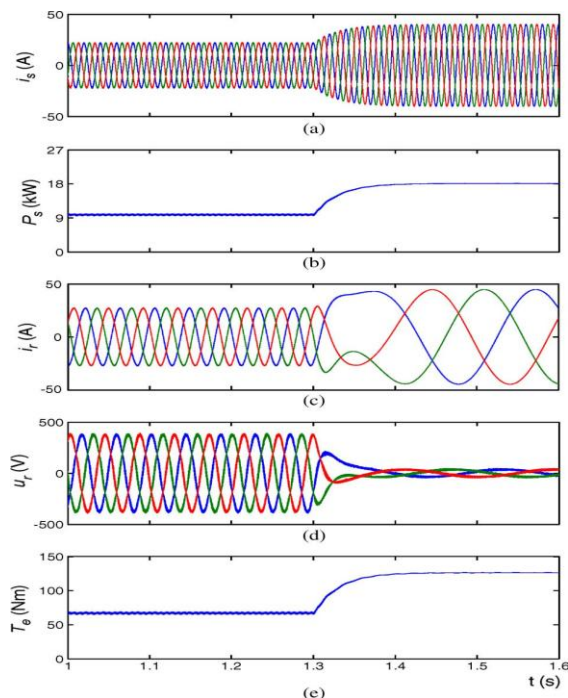


Fig. 8. Waveforms of the DFIG. (a) stator current; (b) active power of stator side; (c) rotor current; (d) rotor voltage; (e) electromagnetic torque.

Firstly, the function of wind speed tracking and

power compensation of DFIG is simulated. The simulation parameters are set as follows:

1) DFIG

Initially, at the time of  $t = 1$  s, the wind speed  $v = 6.5$  m/s, the output power of the DFIG is 10 kW, and the output reactive power is set to be zero.

At the time of  $t = 1.3$  s the wind speed  $v = 8$  m/s.

2) power compensation for the grid

Initially, at the time of  $t = 1$  s, the active and reactive power demand of the grid is 1.2 kW and 1.2kVar, respectively.

At the time of  $t = 1.15$  s, the active power demand is set to

2.4 kW, and the reactive power demand remains invariant. At the time of  $t = 1.5$  s, the active power demand is remains constant, and the reactive power demand is set to 2.4kVar.

According to the variety of the wind speed, the rotor-side converter regulates the amplitude and phase of the rotor excitation currents, and the frequency of the stator currents can be maintained constant. This operation mode can utilize the wind energy effectively. The stator and rotor waveforms of the DFIG are shown in Fig. 8. In the condition that the energy storage capacity is not limited, the slip power can be handled

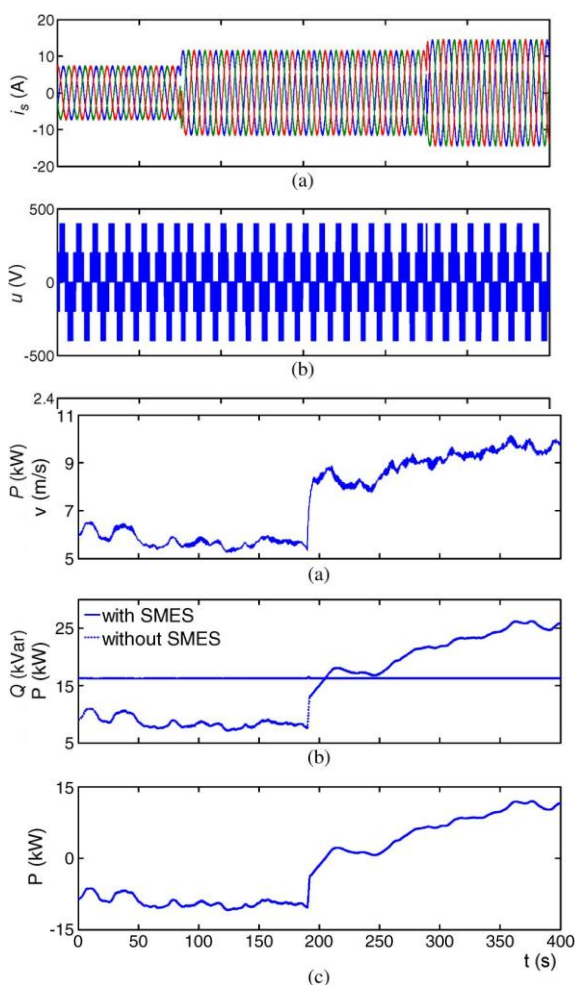
Fig.9. Waveforms of the grid-side converter. (a) line current of AC side; (b) AC output voltage of converter; (c) active power of AC side; (d) reactive power of AC side.

by the SMES, which have little influence on the grid. Due to the independent active and reactive power control capabilities of PWM converters, the DFIG can control the power factor at the power coupling point with the grid.

Fig. 9 shows the waveforms of grid-side converter. It can be seen that the SMES can quickly respond to power compensation in less than 5ms. The active power and reactive power flow have little influence on each other, the decoupled characteristic is satisfactory. SMES acts at the energy storage unit, the power transfer of the DFIG rotor have no influence on the grid, which realize the independent operation of the two converters. Then, the function of smoothing the power fluctuation is simulated. The power system with the DFIG connected is simulated as a simple power system with an infinite bus bar. The operation of the system is simulated with and without SMES respectively, and the results are shown in Fig. 10. The wind signal driving the wind turbine is simulated as a group of random wind, as shown in Fig. 10(a). Fig. 10(b) shows the active power at the power coupling point, with the dotted line representing the output active power of DFIG. By

introducing the SMES into the excitation system of

through control method, it will be discussed in the following work.



DFIG, the active power which is delivered to the power grid can be smoothen, as shown with the solid line in Fig. 10(b). The output power of the SMES during the operation is shown in Fig. 10(c). It can be seen that the SMES can smooth the power fluctuation of DFIG effectively.

## V. CONCLUSION

This paper proposes a SMES based excitation system for DFIG used in wind power generation. The double level

Fig. 10. Smoothing the power fluctuation of DFIG. (a) wind speed; (b) the output power at the power coupling point; (c) the output power of SMES

controller is designed to improve the stability and reliability of the wind power grid-connected system. To evaluate the dynamic response of the SMES based excitation system for DFIG, simulation tests are carried out using MATLAB SIMULINK. The simulation results show that the excitation system can respond very quickly to the active and reactive power demands and the power fluctuation of DFIG can be smoothen effectively. As to the fault ride-

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