Research on improving transient voltage stability of wind power grid connected system by SFCL and STATCOM

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Abstract: Aiming at the problem of transient voltage instability in the grid-connected wind power system, a combined method of superconducting fault current limiter (SFCL) and static synchronous compensator (STATCOM) was proposed to suppress voltage sags. In this method, a superconducting fault current limiter (SFCL) is connected in series on the transmission line, and a static synchronous compensator (STATCOM) is connected in parallel on the bus of the wind farm. SFCL shows zero impedance when the system is in normal operation, and quickly shows high impedance when the fault occurs, so as to effectively suppress the short-circuit current and provide the bus voltage support. At the same time, STATCOM provides reactive power during the fault period, so that the system voltage can quickly recover. By establishing the corresponding simulation model, SFCL and STATCOM are used to jointly improve the voltage stability of the wind power grid-connected.

1. Introduction

Due to the strong intermittence and randomness of wind power, power system integrated with large wind farm is prone to grid problems, one of the most important problems is voltage sag [1]. When the system voltage drops, in order to ensure the safety of the wind turbine, the common practice is to cut off the wind turbine from the system. Cutting off the wind turbine will increase the time for the power grid to return to the normal state. At present, doubly fed induction generator (DFIG) is the mainstream model in wind farms. In order to maintain the terminal voltage, DFIG will absorb a lot of reactive power from the grid when the system fails, which will bring a greater reactive load to the power system. In addition, when the short-circuit fault occurs in the system, the voltage loss caused by the huge short-circuit current will lead to further drop of bus voltage, which will lead to the occurrence of wind turbine tripping [2]. If the short-circuit current is not limited by proper measures, the short-circuit current will cause damage to the power equipment.

Aiming at the voltage drop of wind power grid connected system in the fault state, researchers generally improve the voltage stability of the system by changing the control strategy of converter or changing hardware system. In reference [3], STATCOM adopts double closed-loop control strategy, which verifies that STATCOM has good reactive power compensation effect for different degrees of voltage sag of wind turbine. In reference [4], crowbar protection circuit and MSVC are controlled coordinately to improve the voltage stability of the system.

The above method changes the hardware circuit of the system, and can improve the voltage stability of the system. However, it ignores that the rapidly increasing short-circuit current will cause excessive...
line voltage loss, lead to serious bus voltage drop, and even damage the power equipment when serious short-circuit fault occurs. On the basis of making full use of the voltage control ability of DFIG, reference [5] directly controls the voltage of DFIG by controlling its output power. In reference [6], considering that wind power grid connection will reduce the moment of inertia of the system, additional virtual inertia control is adopted to improve the voltage stability of the system. Other researchers have proposed some advanced control methods of DFIG converters, such as linear ADRC[7], adaptive control[8]. These methods are economical, but due to the limited capacity of DFIG converters, they can only deal with the mild voltage sag of the system. Therefore, it is necessary to limit the short-circuit current while compensating the reactive power of the grid connected system.

Superconducting fault current limiter (SFCL) can improve the operation performance of power system from limiting short-circuit current, improving transient stability, improving power quality and other aspects [9]. SFCL has zero impedance in normal operation and high impedance in fault state, and it can limit fault current to about 2 times of system rated current [10]. As the static synchronous compensator (STATCOM) in Flexible AC Transmission System, due to the advantages of large reactive power compensation capacity, convenient control, STATCOM has become a popular representative in the field of reactive power compensation [12]. In order to make full use of the advantages of SFCL and STATCOM, this paper proposes a method of combining SFCL and STATCOM to jointly provide voltage support for the bus in case of system failure and jointly improve the voltage stability of the system.

2. Basic principle and mathematical model of bridge type SFCL

2.1 The basic principle of SFCL

The single-phase structure of SFCL[10] in three-phase AC system is shown in Figure 1. It is composed of bridge circuit composed of four power diodes D1-D4, bias voltage source \( V_b \) and superconducting coil \( L \). Among them, \( V_b \) is used to supply bias current to superconducting coil.

![Figure 1. The structure of Bridge SFCL](image)

Under normal operation condition, the peak line current is lower than the bias current, all diodes D1-D4 are in the positive conduction state, so the whole device only shows a very small positive conduction voltage drop of diode. In the fault state, the peak value of short-circuit current is higher than the bias current. One pair of four diodes in SFCL always turns on and the other pair turns off in the reverse direction. At this time, whether it is in the positive half cycle or negative half cycle of the current, the superconducting coil is always connected to the line in the form of large inductance, so as to suppress the sharp increase of short-circuit current and reduce the voltage loss on the line, providing voltage support for bus bar.

2.2 Mathematical model of SFCL

Because the current flowing through SFCL and the voltage at both ends are not sine waves, the current limiting impedance changes periodically. The fundamental impedance of SFCL can be calculated by Fourier transform (FFT). Assuming that the voltage is constant, the impedance between the bus and the fault point is used for analysis, as shown in Figure 2.
In the fault state, without considering the aperiodic component of the fault current, let $I_d$ be the fault action current of SFCL, $X_{sfcl}$ be the impedance of the superconducting coil, $X$ be the line impedance, $\alpha_1 = \arcsin (I_d)$, $\alpha_2 = \pi - \alpha_1$. The half cycle current waveform of bridge type SFCL is shown in Figure 3.

Assuming that the voltage is a sine function with an amplitude of 1, the current within the time $[0, \pi]$ can be expressed as follows:

$$[0, \alpha_1]: i(t) = \frac{\sin \omega t}{X}$$

$$[\alpha_1, \alpha_2]: i(t) = \frac{\sin \omega t}{X + X_{sfcl}} + \frac{X_{sfcl}}{X + X_{sfcl}} I_d$$

$$[\alpha_2, \pi]: i(t) = \frac{\sin \omega t}{X}$$

The amplitude of fundamental component of short circuit current is as follows:

$$I_{i1m} = \frac{V}{X} - \frac{V X_{sfcl}}{X + X_{sfcl}} \left[ \frac{\pi - 2 \alpha_1 + \sin (2 \alpha_1)}{X} - 4 \frac{i_d}{V} \cos \alpha_1 \right]$$

The equivalent impedance of the simple system is as follows:

$$Z_{eq} = \frac{1}{I_{i1m}}$$

Compared with the resistance type superconducting fault current limiter, the bridge type superconducting fault current limiter can recover from the second fault within 0.5 s and cooperate with the automatic reclosing of the system; $V_b$ can control the action current of SFCL, and its parameters are easy to set; The bridge type SFCL has no iron core, which is low cost and light weight.

3. Basic principle and control of STATCOM

3.1 The Basic principle of STATCOM

The control element of STATCOM [11] based on VSC are forced commutation power electronic devices (such as GTO or IGBT). The DC side of the device is also equipped with a capacitor, which provides energy storage for STATCOM and supports DC voltage. Compared with SVC, STATCOM has higher output reactive power and faster dynamic response speed when the system bus voltage drops seriously, which can better improve the voltage stability of wind power grid connected system.

The equivalent circuit diagram of STATCOM is shown in Figure 4 below, which can achieve voltage stability by providing enough reactive power to the wind power grid connected system in case of failure.

$$P = \frac{V V \sin \delta}{X_1}$$
\[ Q = \frac{V_s (V_s - V \cos \delta)}{X_s} \]  

(7)

Under steady-state operation condition, \( V_s \) and voltage \( V \) are in phase \( (\delta = 0) \), and \( P = 0 \). If \( V_s > V \), STATCOM absorbs reactive power from the grid and reduces the system voltage, which shows as inductive. If \( V > V_s \), STATCOM generates reactive power to support system voltage, which shows as capacitive. Therefore, the reactive power absorbed by STATCOM can be adjusted by changing the size of \( V \).

3.2 The control strategy of STATCOM

In terms of device control, STATCOM control adopts voltage current double closed loop control mode. The outer loop of the controller adopts DC voltage regulator and AC voltage regulator, which feed back DC side Capacitor Voltage \( V_{DC} \) and grid side voltage \( V_s \) of STATCOM respectively. By comparing with the corresponding given value, the proportional control with static error is carried out. The inner loop of the controller adopts a current regulator, which can control the output current of the inverter, and can control the active and reactive current separately \([11]\).

4. Control scheme of SFCL-STATCOM

With the increasing installed capacity of wind farms, when the wind power grid connected system fails, the short-circuit current on the transmission line will increase sharply. The high short-circuit current will seriously damage the equipment. At present, the response time of conventional circuit breaker is 20ms ~ 150ms, but the maximum peak value of system short-circuit current appears in the first half wave (10ms), and the action time of SFCL is about milliseconds or even microseconds. It is obvious that SFCL has advantages in restraining the rising speed and size of short-circuit current. In addition, when the system operates normally, SFCL shows zero or low impedance, which has no effect on the system; When the fault occurs, it shows high impedance immediately to suppress the sharp increase of short-circuit current, and it can actively return to the superconducting state after the fault is cleared. SFCL can restrain the increase of short-circuit current in a very short time and provide voltage support for bus.

When three-phase short-circuit fault occurs in the system, due to the limited capacity of DFIG converter, it is difficult to achieve the requirement of low voltage ride through only relying on the reactive power regulation ability of DFIG. Therefore, it is necessary to compensate the reactive power of DFIG. For large-scale grid connected wind farms, the outlet of each wind turbine is connected with a capacitor bank in parallel. In case of system failure, the parallel capacitor bank provides reactive power for DFIG. However, the capacitor bank regulation has some disadvantages, such as operation failure in case of voltage drop, slow compensation speed and low compensation accuracy. STATCOM, as a typical representative in the field of reactive power compensation, is considered to be paralleled in the wind power access point to provide dynamic reactive power compensation for wind turbine under voltage drop.

5. Simulation and result analysis

5.1 Example

In this paper, a wind power grid connection system based on DFIG is built on Matlab/Simulink platform, as shown in Figure 5 below. The parameters of single wind turbine are listed in Table 1. The inductance parameter of superconducting magnet in SFCL is 0.5H.

Figure 5. Wind power integrated system based on SFCL-STATCOM
Table 1. Parameters of single DFIG in the wind power system

| Parameters                          | Value   | Parameters                          | Value   |
|------------------------------------|---------|------------------------------------|---------|
| Unit capacity /VA                  | $1.5 \times 10^6$ | Mutual inductance /pu               | 2.9     |
| Stator voltage /V                  | 575     | Polar logarithm                    | 3       |
| Stator and rotor resistance /pu    | 0.023, 0.016 | Frequency /Hz                      | 50      |
| Stator and rotor inductance /pu    | 0.18, 0.16 |                                      |         |

5.2 Analysis of simulation results

Fault setting: when $t = 8s$, three-phase short circuit ground fault occurs on 120kv transmission line of grid connected system, and fault is cut off after 0.2S. Wind speed is 12m / s during simulation. In order to study the joint improvement of SFCL and STATCOM on transient voltage stability of wind power grid connected system, four simulation conditions are set when the system is subject to large disturbance. SFCL- STATCOM is not included in working condition 1, only SFCL is included in working condition 2, only STATCOM is included in working condition 3, and SFCL- STATCOM is included in working condition 4. The corresponding simulation model is built on Matlab/Simulink platform, and the simulation waveform comparison diagram is shown in Figure 6- Figure 9.

![Figure 6](image1.png)  
**Figure 6.** Bus B2 voltage comparison under condition 1 and condition 2

![Figure 7](image2.png)  
**Figure 7.** Bus B2 voltage comparison under condition 1 and condition 3

![Figure 8](image3.png)  
**Figure 8.** Bus B2 voltage comparison under condition 1 and condition 4

![Figure 9](image4.png)  
**Figure 9.** Comparison diagram of 25kV transmission line current under four conditions

Figure 6 is the voltage curve comparison diagram of condition 1 and condition 2 in the grid connected wind power system. When the system is only connected in series with SFCL, the voltage of the parallel node can be increased by about 0.1pu during the fault period, which indicates that SFCL can suppress the short-circuit current, reduce the loss of voltage on the line, and will not affect the process of the grid connected system entering a stable state after the fault is removed.
Fig. 7 is the voltage curve comparison diagram of the grid connection point B2 under condition 1 and condition 3. After the wind power grid connected system is connected with STATCOM in parallel, the voltage of the grid connection point will increase by about 0.31pu compared with that without any compensation during the fault period, and after the fault is removed, adding STATCOM will make the system quickly enter a stable state. This shows that STATCOM can improve the transient voltage stability of wind power grid connected system obviously. It can be seen from Figure 8 that the wind power grid connected system connected with SFCL and STATCOM will increase the voltage of parallel node by about 0.42pu, and make the grid connected system stable faster.

In terms of fault current, it can be seen from Figure 9 that during the fault period, when the system does not take compensation or only uses STATCOM for compensation, the amplitude of short-circuit current exceeds 1.5pu, and the amplitude of current also changes greatly, which indicates that only using STATCOM can better improve the voltage of parallel point, but cannot suppress excessive short-circuit current. When only using SFCL or SFCL-STATCOM compensation, the peak value of short-circuit current is less than 1.3pu, and the variation range of short-circuit current is small, which indicates that SFCL has a good effect in suppressing short-circuit current.

6. Conclusions

This paper proposes a method to improve the voltage stability of wind power grid connected system by using SFCL and STATCOM, and carries out simulation analysis when three-phase short-circuit fault occurs in the system. The following conclusions are obtained: SFCL can suppress short-circuit current, reduce voltage loss on transmission lines, and reduce the degree of bus voltage sag at the grid connected point to a certain extent. STATCOM can provide reactive power in time during the fault period, and has obvious effect on improving the bus voltage of the parallel node, but adding STATCOM alone can not suppress the short-circuit current during the fault period. When SFCL and STATCOM are used together in the wind power grid connected system, the amplitude and variation of short-circuit current can be effectively suppressed during the fault period, and the voltage of the grid connected point can be quickly restored.

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References

[1] Izanlo A , Gholamian S A , Kazemi M V . Direct power control of a DFIG-based wind turbine under unbalanced grid voltage without rotor position sensor[J]. IIUM Engineering Journal, 2017, 18(1):57.
[2] Vrionis T , Koutiva X , Vovos N A . Closure to Discussion on "A Genetic Algorithm-Based Low Voltage Ride-Through Control Strategy for Grid Connected Doubly Fed Induction Wind Generators"[J]. Power Systems IEEE Transactions on, 2015, 30(1):549-549.
[3] Li Hongnan, Jin Tao. Analysis of low voltage ride through capability of DFIG wind turbine based on STATCOM [J]. Journal of Chongqing University, 2016,39 (06): 34-40
[4] Yuan Xin, Jiang Junfeng, Luo Jun, et al. Low voltage ride through control strategy for DFIG based on MSVC and Crowbar [J]. Electrical applications, 2017,36 (21): 72-76.
[5] Wang Yajing, Ma Yiping, Wang Jiqing, et al. Study on direct voltage control strategy of doubly fed wind turbine [J]. Power capacitor and reactive power compensation, 2019, 040 (002): 172-177.
[6] Saniye mahmuti, Wang Haiyun. Study on voltage stability of wind power system based on virtual inertia control [J]. Power capacitor and reactive power compensation, 2019,40 (03): 182-188.
[7] Lian Xiaqin, An Sa, Li Zhen. Design of improved linear active disturbance rejection control strategy for DFIG grid side inverter [J]. Computer simulation, 2020,37 (12): 98-102.
[8] Xie Mei, Jia Yupei, Hou Jinxiu, et al. Research on low voltage ride through control mechanism of wind farm based on adaptive model prediction [J]. Renewable energy, 2019,37 (08): 1152-
[9] Zhang Yixiao, Wang Xianyong, Zou Yuhong, et al. Cooperative Control of SFCL and Reactive Power for Improving the Transient Voltage Stability of Grid-Connected Wind Farm With DFIGs [J]. IEEE Transactions on Applied Superconductivity: A Publication of the IEEE Superconductivity Committee, 2016, 26(7): 1-1.

[10] Yu Jiang, Duan Xianzhong, He Yangzan. Application of superconducting fault current limiter with different structures in power system [J]. Power system automation, 2001, 25 (12): 42-42.

[11] Zheng Liping, Kuang Honghai, Zhang Shuyun, et al. Improvement of voltage stability of wind power grid connected system by tcsc-statcom control [J]. Power system protection and control, 2017, 045 (022): 90-95.