The Impact of SFCL and SMES Integration on the Distance Relay

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Abstract

The superconducting fault current limiter (SFCL) is an ideal short-circuit fault current limiting device that can limit the fault current without any delay and control the voltage drop of the non-fault line. The superconducting magnetic energy storage (SMES) device can exchange the active and reactive power independently, so it is applied broadly to improve power system stability. With SFCL, the low voltage ride-through capability of SMES can be enhanced as well as its MW and MJ capacities. The distance relay is a key electrical apparatus that will trip circuit breakers to protect electrical devices from short circuit faults. Due to the application of SFCL and SMES integration, the voltage and current in power grid will change accordingly, and the operation characteristic of distance relay may be affected. In this paper, the impact of a bridge-type SFCL and SMES integration on the circle distance relay is studied. And simulation results show that the integration of SFCL and SMES does influence the measured impedance of distance relay, which can lead to mal-operation of the circle distance relay. Furthermore, an improved distance relay is proposed and verified.

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1 Introduction

With the development of superconducting technology, an increasing number of superconducting devices are efficiently used in power grid, such as superconducting fault current limiter (SFCL) and superconducting magnetic energy storage (SMES). The SFCL is becoming a more and more promising alternative approach to reduce the fault current because the device can limit fault current during fault period without presenting high impedance in the circuit during normal operating conditions. The SMES has high energy conversion efficiency and rapid response speeds, most importantly it can regulate real power and reactive power independently and simultaneously in bi-directions [1]. With SFCL, the low voltage ride-through capability of SMES can be enhanced as well as its MW and MJ capacities [2]. Therefore the combination of SFCL and SMES can achieve a better control performance on enhancing the transient stability of an electric power system.

However, the application of SFCL and SEME integration will definitely change the voltage and current of the power system, so that the operation characteristic of distance relay may be affected. As an important component, the distance relay applied for the transmission line is able to play a key role in preventing system crashes after a large disturbance. Therefore it's of vital importance to analyze the impact of SFCL and SMES integration on the distance relay.

Some related research works were carried out to investigate SFCL, SMES and relay. Literature [3] investigates the influence of three current-limiting modes of the

voltage compensation type active SFCL on power system transient stability. The method for the protection coordination of a flux-lock type superconducting fault current limiter with an over-current relay has been proposed, as well as the setting method of specific parameters of an SFCL installed at a bus-tie in a trunk substation [4, 5]. Literature [6] presents a stochastic-based approach to evaluate the probabilistic transient stability index of the power system incorporating the wind farm and the SMES. In literature [7], the joint operation of SFCL and SMES devices can ensure better performance on dynamical stability of power system than their single operation. However, the coordination of SFCL and SMES integration with the protection relay has never been studied.

This paper aims to investigate how the joint operation of SFCL and SMES devices influences the impedance of distance relay when a short circuit fault occurs in the power system. The tripping characteristics of distance relay with and without the access of the SFCL and SMES integration to transmission line are analyzed. Also, an improved operation characteristic of distance relay is proposed to avoid possible mal-operation in this paper.

The rest of this paper is organized as follows. Section 2 describes the structure and principle of the bridge-type SFCL. Section 3 introduces the model of SMES. The distance relay with circle characteristic is presented in section 4. Simulations and analysis are stated in section 5, and a measure preventing relay from mal-operation is suggested in section 6. Finally, conclusion is drawn in section 7.

2 The model of the bridge-type SFCL

In general, the SFCL works in the superconducting state with low-resistance under normal power system operation, and switches into the non-superconducting state once a fault occurs. Specifically, the SFCL's working impedance will increase during state-transition to limit the excessive current after a short circuit fault appears in the system. The structure of a bridge-type SFCL used in this paper is shown in Fig. 1.

The bridge-type SFCL mainly consists of four diodes (D1 to D4) and a gate turn-off thyristor (GTO). R_1 is the current limiting resistance and L_1 is the current limiting inductance. In this paper, the resistance R_1 is set as 8Ω and L_1 is set as 3H. An s-function whose input is the current difference between faulty state and stable state is designed to monitor the state of power system. When the electric system operates in stable state, the GTO will receive a high level signal from the s-function and it keeps closed to bypass the resistance R_1 . Otherwise, the resistance is series-connected in the circuit to limit the current of the grid when a low level signal is sent to the controlled switch. So that the bridge-type SFCL can switch between the current limiting state and the normal state automatically to limit the short circuit current and ensure the stability of the power system.

3 The model of a voltage source type SMES

Fig. 2 shows the basic structure of a voltage source type SMES. Actually, a control system shown in Fig.3 is used to replace the SMES model in simulation work. The SMES control scheme is usually based on a pulse width modulation (PWM) voltage

source converter (VSC), which makes it capable to control the active power and reactive power rapidly and independently in all four quadrants. As shown in Fig.3, the power regulation of the SMES unit consists of the outside loop control and the inner loop control. The outside loop control provides the power reference value (P_{ref} , Q_{ref}). The inner loop control offers the active and reactive power compensation based on the power reference value in all four quadrants. Therefore, the SMES can be applied for both active and reactive power compensation for power system stabilization [8, 9].

Based on the Kirchhoff's voltage law (KVL) and the Kirchhoff's current law (KCL), the following equations can be obtained [10].

$$\begin{cases} L_2 \frac{di_d}{dt} = -R_2 i_d + \omega L_2 i_q + u_{sd} - S_d u_d \\ L_2 \frac{di_q}{dt} = -R_2 i_q - \omega L_2 i_d + u_{sq} - S_q u_q \end{cases} \quad (1)$$

$$\begin{cases} L_2 \frac{di_d}{dt} + R_2 i_d = -u_{rd3} \\ L_2 \frac{di_q}{dt} + R_2 i_q = -u_{rq3} \\ S_d u_d = u_{rd1} + u_{rd2} + u_{rd3} \\ S_q u_q = u_{rq1} + u_{rq2} + u_{rq3} \end{cases} \quad (2)$$

$$\begin{cases} u_{rd1} = u_{sd}, u_{rd2} = \omega L_2 i_q \\ u_{rq1} = u_{sq}, u_{rq2} = -\omega L_2 i_d \end{cases} \quad (3)$$

where d and q denotes the variables under the synchronous rotating coordinate system. i_d and i_q are the grid currents at d axis and q axis, respectively. u_{sd} and u_{sq} are the grid voltages at d axis and q axis, respectively. $S_d u_d$ and $S_q u_q$ are the output voltages of the converter at d axis and q axis, respectively. R_2 and L_2 are the equivalent resistance and the equivalent inductance of both transformer and line, respectively.

In order to control the ac current independently, the voltages of $s_d u_d$ and $s_q u_q$ are divided into three parts. According to equation (2), the PWM can be equalized to a controlled voltage source. The grid current can also be controlled to response the power demand of the electric system. Fig. 4 shows the single-phase equivalent circuit diagram of the VSMES system. E_s is the ac grid voltage. U_r is the ac output voltage of converter. In this paper, R_2 is 0.2Ω and L_2 is $0.006H$. The application of SMES can influence the voltage and current of power system. As a result, the characteristics of distance relay will be impacted.

4 The distance relay protection

The distance protection can determine the fault position by measuring the apparent impedance, which is proportional to the distance from the fault point to the relay install point [11]. Step I is the first step of the distance relay protection that can protect 80~85% of the line length without time delay. As the backup protection for step I, step II can cover the whole length of the line and extend to the next line. However, the protection zone of step II will not exceed the protection range of step I in next line. And the action time of step II is greater than that of step I. According to the phase-to-phase distance protection and phase-to-ground distance protection, the measured impedance can be denoted as follows:

$$Z_{\varphi\varphi} = \frac{U_{\varphi\varphi}}{I_{\varphi\varphi}} \quad (4)$$

$$Z_{\varphi} = \frac{U_{\varphi}}{I_{\varphi} + K \cdot 3I_0} \quad (5)$$

$$K = (Z_0 - Z_1) / 3Z_1 \quad (6)$$

where the subscript $\varphi\varphi$ denotes AB, BC or CA phase, and the subscript φ means A, B, or C phase. K is the compensation factor, which compensates the phase current for mutual coupling between the fault phase and the other two normal phases. Z_0 and Z_1 are the zero-sequence impedance and the positive sequence impedance of the transmission line, respectively.

The relay criterion with circle characteristic used in this paper can be denoted as follows:

$$|Z_m| \leq |Z_{set}| \quad (7)$$

$|Z_m|$ is the measured impedance of the distance relay, and $|Z_{set}|$ is the setting impedance of the distance relay. The operation zone of the distance relay is shown in Fig.5. When the measured impedance $|Z_{m1}|$ falls into the protected zone, the relay will trip the fault line. Otherwise, the distance relay will not trip when $|Z_{m2}|$ is outside the protected zone [12].

5 Simulation and discussion

To investigate the impact of SFCL and SMES integration on the distance relay, numeral simulations based on a benchmark power grid in Fig. 6 are carried out in Matlab. The generator parameters are shown in Table 1. In this benchmark power grid, distance relay 1 with circle characteristic is installed in Bus1. The SFCL is installed at the start point of transmission line and the SMES is installed in Bus2. The setting impedance of step I for relay 1 is $12.69 + j76.96\Omega$ in this paper, which means 80% of the line length is covered by relay 1.

Fig.7 and Fig.8 show the time domain results of voltage and current in the relay with a three-phase-to-ground fault occurring at 50% of the line length at 0.1s. Both voltage and current remain nearly the same level before a fault occurs with or without the installation of SFCL and SMES integration. However, when a fault occurs, the fault current with the installation of SFCL and SMES is smaller than that without SFCL and SMES. And the fault current can be limited within an acceptable range. Also, the installation of SFCL and SMES integration has little influence on the voltage and current at normal state.

With or without SFCL and SMES integration, the three-phase-to-ground faults at different positions are applied in this paper. Figs. 9-12 show the relationships between the measured impedance and operation zone of the distance relay when fault occurs at 30%, 50%, 80% and 85% of the line length, respectively.

As shown in Fig. 9 and Fig. 10, with or without SFCL and SMES integration, the measured impedance of relay 1 will fall into the operation zone when fault occurs at 30% and 50% of the line length, respectively. As a result, the distance relay could successfully trip the line with the fault in protected zone. Also, the locus of measured impedance shows that the bridge-type SFCL has great impact on the measured impedance in preliminary fault period because of the SFCL's inductive reactance. However, the introduction of the SMES only has little effect on the measured impedance.

As shown in Fig. 11, the locus of measured impedance only with the SMES will

fall into the boundary of the protected zone when fault occurs at 80% of the line length. Therefore, it will result in the mal-operation of relay 1 with external fault. With the other integration of SFCL and SMES, the mal-operation of relay 1 will not occur. As shown in Fig. 12, with or without SFCL and SMES integration, the measured impedance will not fall into the protected zone when fault occurs at 85% of the line length. And relay 1 will not trip the line with external fault.

Therefore, the integration of SFCL and SMES does affect the measured impedance of distance relay, which may lead to mal-operation of circle distance relay.

6 The improvement of distance relay

In this paper, an improved distance relay is proposed to ensure successful operation with the SFCL and SMES integration. According to the analysis in aforementioned section, the most serious error that will cause mal-operation happens when fault occurs just at the boundaries of the protecting zone. So the improved operation zone can be calculated to avoid the most serious case, where the fault occurs at 80% of the line length.

To avoid the locus of measured impedance falling among the operation zone, the criterion of an improved distance relay considering some margins is denoted as:

$$\left\{ \begin{array}{l} |Z_m| \leq |Z_{\text{set}}| \\ \text{Re}(Z_m) \leq (1-\alpha)R \end{array} \right. \cup \left\{ \begin{array}{l} |Z_m| \leq |Z_{\text{set}}| \\ \text{Im}(Z_m) \leq (1-\beta)X \end{array} \right. \quad (8)$$

where R and X can be obtained from $Z_{\text{set}} = R + jX$, respectively. α and β are the safety margin coefficients. Considering some margins, α is calculated according to the abscissa value of the point whose real part is the minimum on the locus of measured

impedance when the fault occurs at the boundaries of the protecting zone. Considering some margins, β is calculated according to the ordinate value of the point whose imaginary part is the minimum on the locus of measured impedance when the fault occurs at the boundaries of the protecting zone. Different R and X can be obtained by using Equation (8) considering all the operation conditions of SMES, and the smallest ones will be chosen as the final setting value of the distance relay. In this paper, $\alpha = 1.04$ and $\beta = 0.14$.

The improved operation zone of distance relay is no longer a circle because a part of operation zone is cut off to avoid mal-operation when faults occur at the boundary of the protection zone.

Figs. 13-14 show the measured impedance and the improved operation zone. It can be observed that, with or without SFCL and SMES integration, the measured impedance of relay 1 will not fall into the operation zone when fault occurs at 80% and 85% of the line length, respectively. Therefore, the mal-operation of distance relay will not occur when faults occur outside the line length. However, step II of the relay can be used to make up the shortened protection zone of step I.

7 Conclusions

Due to the application of SFCL and SMES integration, the voltage and current in power grid will change accordingly, and the operation characteristic of distance relay may be affected. In this paper, the models of the bridge-type SFCL and the SMES have been described in detail. Also, the distance relay with circle characteristic is introduced.

To investigate the performance of the distance relay with or without the access of the SFCL and SMES integration to the transmission line, the operation characteristic of the relay is analyzed in a benchmark power grid with different fault positions. Simulation results show that the bridge-type SFCL has great impact on the measured impedance, and the introduction of SMES only has little effect on the measured impedance. When the fault occurs at the boundary of the protected zone, the mal-operation of distance relay may occur. Therefore, the integration of SFCL and SMES does influence the operation of distance relay. To prevent relay from mal-operation, an improved distance relay is proposed and verified in this paper.

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Table1. Generator parameters

	G1	G2
MVA	192	128
R_s (pu)	0.003	0.003
X_l (pu)	0.052	0.074
X_d (pu)	0.896	1.313
X_q (pu)	0.865	1.258
X_d' (pu)	0.120	0.181
X_q' (pu)	0.865	0.400
X_d'' (pu)	0.089	0.107
X_q'' (pu)	0.089	0.107
T_{do}' (pu)	6.000	5.890
T_{qo}' (pu)	0.540	0.600
T_{do}'' (pu)	0.033	0.030
T_{qo}'' (pu)	0.078	0.070
H (s)	12.800	6.020

Fig. 1 The structure of a bridge-type SFCL.

Fig. 2 The structure of a voltage source type SMES.

Fig. 3 The power control diagram of a SMES device.

Fig. 4 The single-phase equivalent circuit diagram of a VSMES system.

Fig. 5 The operation zone of the distance relay with circle characteristic.

Fig. 6 The simulation model of the benchmark power grid.

Fig. 7 The voltage and current without SFCL and SMES integration.

Fig. 8 The voltage and current with SFCL and SMES integration.

Fig. 9 The measured impedance with the fault occurring at 30% of the line length.

Fig. 10 The measured impedance with the fault occurring at 50% of the line length.

Fig. 11 The measured impedance with the fault occurring at 80% of the line length.

Fig. 12 The measured impedance with the fault occurring at 85% of the line length.

Fig. 13 The measured impedance of the improved distance relay with the fault occurring at 80% of the line length.

Fig. 14 The measured impedance of the improved distance relay with the fault occurring at 85% of the line length.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

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Fig.9

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Fig. 12

Fig. 13

Fig. 14