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# Application of a voltage compensation type active superconducting current controller to current limiting capability of power grid

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ABSTRACT

This paper introduces a laboratory prototype of 800 V/30 A active superconducting current controller (SCC). The SCC has three main components, a series connected superconducting transformer, a controllable compensation voltage source, and a supercapacitor energy storage unit. To solve the issue of transformer magnetic saturation, an air-core superconducting transformer is adopted. The controllable compensation voltage source is composed of voltage source PWM converter and DC chopper, which control the amplitude and phase of the output voltage of SCC. The supercapacitor module is adopted to compensate the dynamic power during current control process. To evaluate the dynamic characteristic of the SCC, a series of experiments are carried out in the laboratory. With the energy storage support, the SCC can control the current level quickly and effectively, which can cooperate with the action of circuit breaker.

## 1. Introduction

With the growing of power system capacity and power system interconnection, the grid structure tends to be more complex, and short-circuit current level increases significantly. Excessive fault current causes stresses and leads to high electrical, mechanical instabilities of electric networks. To alleviate the influence of short-circuit fault on the power system and customer, fault current limiting (FCL) technology is needed urgently [1–5]. Until now, there exists two kinds of fault current limiters, including solid-state fault current limiters and superconducting fault current limiters (SFCLs). The solid-state FCL generally adopts power electronic switch to control the access of resistor and reactance. Through regulating the impedance level of the power line, the fault current can be limited accordingly [6]. For different schemes of solid-state FCL, the power electronic switch needs to endure short-term fault current, which is a challenge for the power electronic switch in high voltage and large current power system. Based on the quenching characteristic, as well as the large through-current capability of superconductor, various forms of SFCL have been developed [7–12]. According to the development status, there are still some technical challenges in large-scale engineering application of FCL, including high voltage, large capacity, capability of repetition action, and coordination with circuit breaker, etc.

This paper focuses on the voltage compensation type active superconducting current controller (SCC). The SCC has three main components, a series connected superconducting transformer, a controllable compensation voltage source, and a supercapacitor energy storage unit. In addition, the principles of superconducting transformer, DC-DC converter and supercapacitor can be introduced as follow: (1) The superconducting transformer is used to connect the series compensation device with power system. (2) The DC-DC converter serves to connect the supercapacitor with DC bus of converter, in order to realize the bidirectional flow of energy. (3) The supercapacitor is used as an energy storage unit of SCC, which can effectively improve the regulation characteristics of dynamic current. Adopting the principle of series compensation, this device can control the transmission line current effectively. In order to solve the issue of transformer magnetic saturation, an air-core superconducting transformer is adopted. Moreover, the air-core structure has no iron losses. The controllable compensation voltage source is composed of a voltage source PWM converter and a DC/DC chopper, which control the amplitude and phase of the output voltage of SCC. The supercapacitor module is adopted to compensate the dynamic power during the system current control process. In the condition that the energy storage capacitor is adequate, the SCC not only limits fault current, but also can be used to optimize the power flow. To evaluate the dynamic characteristic of the SCC, a laboratory prototype of 800 V/30 A SCC is developed, and series of experiments are carried out in the laboratory.

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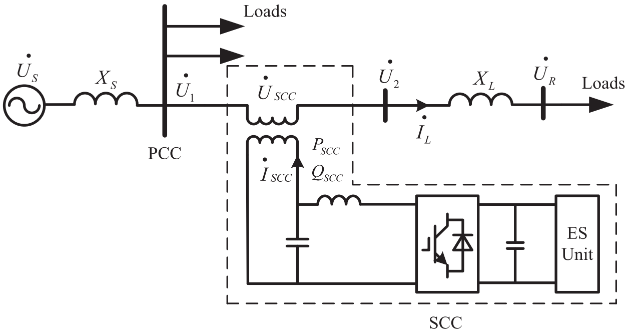

**Fig. 1.** Schematic configuration of SCC in power system.

## 2. Theoretical analysis

### 2.1. Operation principle of SCC

The schematic configuration of SCC connected with the single-phase power system is shown in Fig. 1. This SCC is mainly composed of an air-core superconducting transformer, a controllable compensation voltage source, and a supercapacitor energy storage unit. For analyzing the basic principle of SCC, some assumptions are made as follows,

(1) The impedance of the series connected transformer is ignored.
(2) The power factor of important loads remains constant.
(3) The controllable voltage source generally adopts the PWM converter, and the nonlinearity of the converter is not considered.
(4) The losses of transmission lines is ignored.

Where, $\dot{U}_s$ is the source voltage, $X_s$ is the impedance of the power source, $\dot{U}_{scc}$ is the output voltage of the SCC, and $\dot{U}_R$ is the voltage of the power load.

When the power system is in normal state, the main magnetic flux of series transformer can be compensated to zero approximately. From the power system side, the SCC can be equivalent to the transformer's leakage inductance, which is very small. Thus, the normal operation of SCC has no effect on the power line current. In the condition that short-circuit fault occurs, the SCC, connected in series with the power line, can control the amplitude and phase of the compensated voltage. Supposing that the capacity of compensation voltage source is unlimited, the fault current is able to be controlled to different expected level. The dynamic compensation of SCC can be demonstrated in Fig. 2. The system current in normal and fault state are represented as $\dot{I}_L$ and $\dot{I}_f$, respectively. When the SCC output voltage is regulated to $\dot{U}_{SCC1}$, the system current can be suppressed to $\dot{I}'_{f1}$, which is identical to the system current in normal state. When the SCC output voltage is regulated to $\dot{U}_{SCC2}$, the system current can be suppressed to $\dot{I}'_{f2}$, which is indicated as dotted line in the phasor diagram. According to the phasor diagram, the compensation voltage is determined by the control objective of system current ($\dot{I}'_f$). Therefore, the control objective of system current is the key parameter which influences the compensation capacity of SCC.

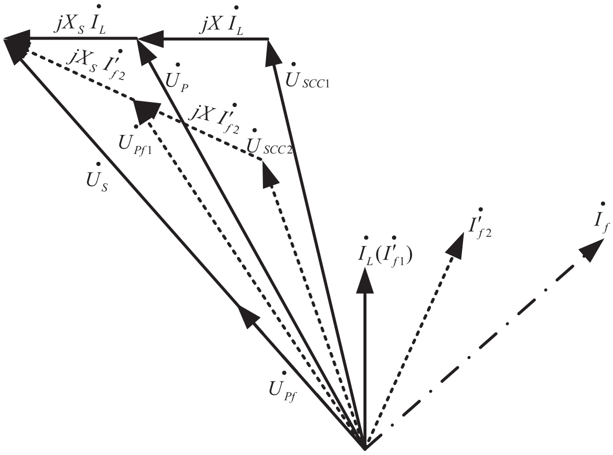

**Fig. 2.** Phasor diagram of current regulation with SCC.

### 2.2. Control strategy

Based on the above analysis, the SCC can realize the following functions:

(1) Limiting fault current. The function can alleviate the influence of short-circuit fault on the power system and the custom, and ensure the security, reliability and stability of power system.
(2) Regulating power flow. In the scope that the energy storage capacity is adequate, the power flow can be regulated to fulfill grid requirement.
(3) Enlarging power transmission capacity. The SCC can be utilized to enhance the controllability of the power line, and improve the power transmission limit.
(4) Application in DC power system. Utilizing the series compensation principle, the SCC can be applied in DC power system to limit the DC fault current [13].

When the SCC is utilized to regulate the power line current, the impedance characteristic of the power line is altered. So, the transient stability should be considered. Especially, when the power system is subjected to a large disturbance, such as a short circuit on a transmission line or the loss of a major generating unit, not only the fault current occurs, but also the transient stability will be influenced. Therefore, the control strategy design of the SCC should consider the fault current and power oscillation synthetically. Fig. 3 shows the synthetic control diagram of the SCC.

### 2.3. Simulation analysis of SCC

The established simulation system is shown in Fig. 4, and the simulation parameters are listed in Table 1. Moreover, the source voltage is 132 V, and the value of normal operating current is 12 A. In order to simulate the short circuit condition, the line equivalent impedance is divided into load 1 (4 Ω) and load 2 (6.8 Ω). Load 2 is removed from the main circuit as soon as the circuit breaker is disconnected, and the amplitude of fault current is up to 33 A.

Simulation condition are described as a three-phase line-to-ground fault occurring at $t = 0.05$ s in the first terminal of transmission line. Later at $t = 0.2$ s, the fault is removed. The simulation results are shown in Fig. 5. It is learned that the effective value of normal-level current is 12 A. Once the fault occurs, the effective value of fault current is restricted to 20 A with the SCC. In Fig. 5(b), it is shown that SCC prompts the converter to provide a compensation voltage as soon as a short circuit fault or a current regulatory demand is detected. Fig. 5(c) shows the output current waveform of converter. During the normal operation of power grid, the measured output current is actually the transformer's second side induced current, and its value is equal to that of system current. During the process of fault, the output current varies due to the change of output voltage. The waveform of supercapacitor terminal voltage is shown in Fig. 5(e). During the compensation process, the extra energy is absorbed to charge the supercapacitor. Owing to the short transition time, supercapacitor terminal voltage creates a slight variation. From the simulation results shown in Fig. 5(f), it is clear that the output-voltage control and the system current control tasks can be achieved through the coordinated control of chopper and inverter.

Adopting the SCC is able to control the level of short-circuit current for the reason that this device can control the output voltage. Fig. 6 shows the comparisons of current limiting effect of SCC. For case 1, the