Effects of bias power supply on bridge type superconducting FCL

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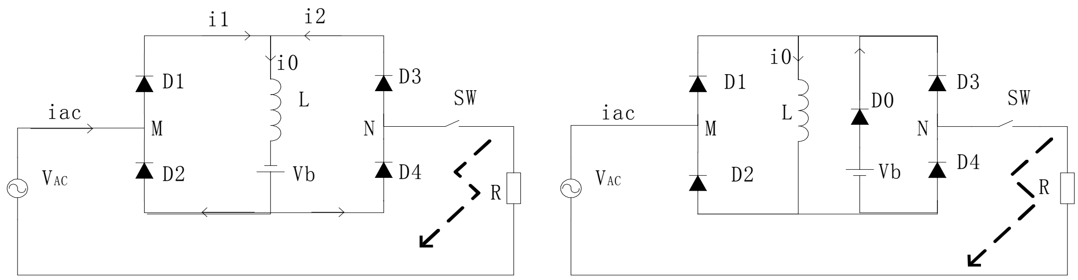
The effects of bias power supply (BPS) on bridge type of SFCL are studied in this paper. The main research method is a superconducting reactor charging analysis. With shift of charging path and change of charging power source in a process of short fault, on the condition of the SFCL with BPS in two connection modes, load current distortion is eliminated and the SFCL limiting capability is enhanced, And the parameters of the BPS is also optimized. Simulation and experimental results validate the necessary of the BPS to enhance the limiting capability of the SFCL.

INTRODUCTION

For enhancing reliability of power system, fault current limiter is becoming an essential part in the modern power grid. More and more researchers and scholars are focused on the R&D of bridge type of high temperature superconducting fault current limiter. There are different viewpoints of introducing bias power supply (BPS) into the bridge. Some researchers are interested in designing such SFCL without using BPS. Taking no account of the BPS, the simpler makeup of SFCL and the lower investment cost of the SFCL is available [1]. Meanwhile, others are paying more attention to designing such SFCL with using BPS. In order to enhance quality (e.g. mitigating line voltage sags, decreasing line phase-angle jumps, reducing line current distortion, and etc.) of distribution networks, improve the limiting capability of the SFCL, and conceal the effects of load changing, it is necessary to analyze the effects of BPS on the



(a) Series Mode (b)Parallel Mode

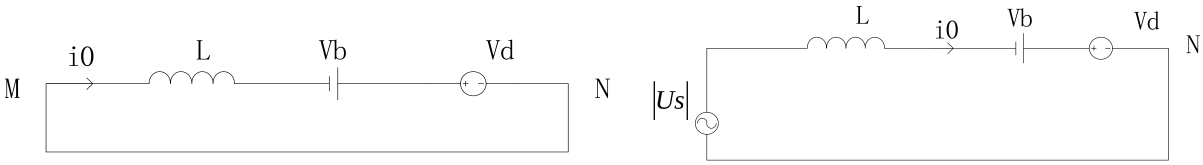
Fig.1 Circuit diagram of FCL with BPS

SFCL and on the networks [2,3,4]. Two kinds of typical connection modes are described [4], in which the connection modes are determined by the connection relationship between the BPS and a superconducting reactor L. One of them is series mode (Fig.1 (a)), and another is parallel mode (Fig1 (b)). In order to design a large scale SFCL used in three phases 10.5kV, 400A system, a diodes bridge is chosen and further study of the function of the BPS in the SFCL is present in this paper. The two-mode SFCL are discussed. The reactor charging law is analyzed in theory. Based on the law in the two circuits, the interrelationship of enhancing limiting capability of the SFCL in fault state and removing steady-state current distortion in steady-state is discussed.

CHARGING PRINCIPLE OF THE REACTOR IN THE SFCL

For a FCL to have a good performance, the two requirements must be matched: in steady state, load current distortion must be removed so that the effects of the SFCL to the load current must be minimized. In fault state, the limiting capability of the SFCL must be big enough so that the fault current is restricted availably. Though, both the limitation of fault current and the elimination of load current distortion are carried out by the reactor, the contradiction of them is still existing. If the voltage amplitude of the BPS is smaller, the load current distortion can't be eliminated in steady state, and the reactor current can't keep constant. If the amplitude of the BPS is larger, the fault current limiting capability of the SFCL can be weakened in fault state because the reactor is constantly charged by the BPS. The contradiction can be solved by investigating a special charging law of the reactor in the SFCL.

It is noted that a current increment of a single reactor is determined by charging voltage, charging time and the inductance. For a FCL, there are two operating states. It is the current relationship of the load and the reactor that determining the change of the operating states and selection of charging power



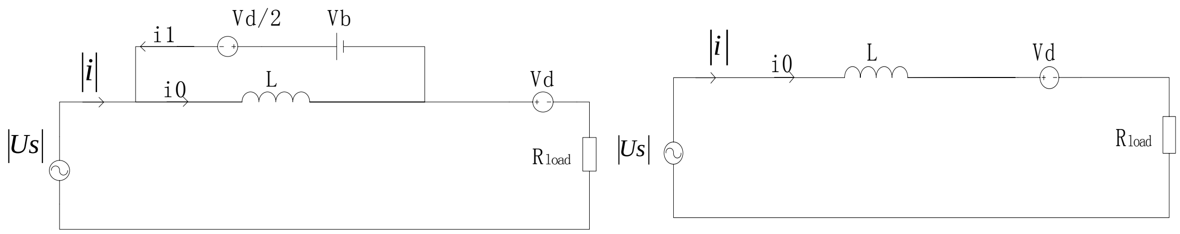
(a) $|i| < i0$ (b) $|i| = i0$

Fig.2 Reactor charging equivalent circuit diagram of FCL in series mode

sources. Both the BPS and the power source act as the reactor charging power source and they work at different state and different time. When Vd and $|Us|$ are defined as the forward voltage of two of four diodes and the equivalent voltage of the power source, respectively, the charging law can be described by equations. For the series mode, the reactor charging equivalent circuits are shown in Fig.2 (a) and (b) and the equivalent circuits are presented as:

$$
\begin{aligned}
&Vb - Vd = L\frac{di0}{dt} && (|i| < i0) \\
&|Us| - Vd + Vb = L\frac{di0}{dt} && (|i| = i0)
\end{aligned}
\qquad (1)
$$

In steady state or when the reactor current is larger than the load current, in order to keep the reactor



(a) $|i| < i0$ (b) $|i| = i0$

Fig.3 Reactor charging equivalent circuit of SFCL in parallel mode

current constant and also avoid distortion occurrence near the peak of the load current, the BSP voltage Vb must match the following relationship: $Vb \geq Vd$. In fault state, in order to restrict the rate of the increment of load current, the voltage of BSP should be small or even a negative voltage so as to restrict the charging speed of the power source and limit the fault current of the grid. So the constant value of the voltage of the BPS is of benefit to the steady process and goes against the fault process. For the parallel mode, the charging equivalent circuits are shown in Fig.3 (a) and (b). The BPS act as a fly-wheel path and the fly-wheel current through the BPS reduces to zero in limiting process. In steady state or when the load current $|i|$ is smaller than the reactor current $i0$, the charging sources of the reactor take on by both the power source of the grid and the BPS in parallel. So the current relationship can be described:

$$Vb - Vd/2 = L\frac{di1}{dt}$$

$$|Us| - Vd = L\frac{d|i|}{dt} + |i|Rload \qquad (|i| < i0) \tag{2}$$

$$i0 = |i| + i1$$

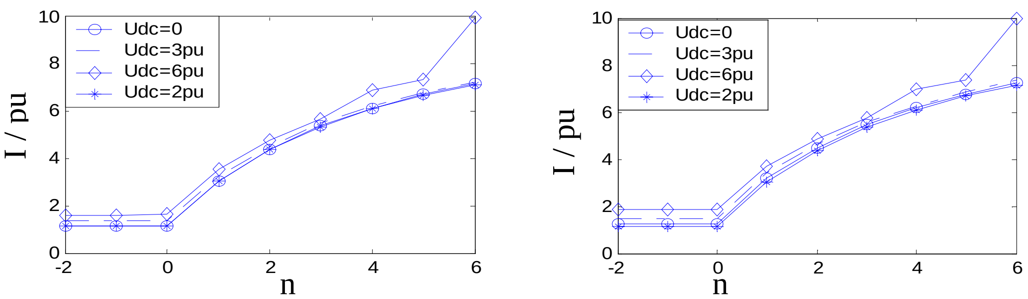
The BPS is necessary to hold on the reactor current $i0$ constantly and the load current waveform distortion can also be removed by the BPS. In fault state, when the load current $|i|$ arrives to the value of the reactor current $i0$, the fly-wheel current $i1$ will decreases to zero accordingly and the charging function is only taken on by the power source. The charging equation is obtained:

$$|Us| - Vd = L\frac{d|i|}{dt} \qquad (|i| = i0) \tag{3}$$

From the above discussion, the key of implementing the SFCL performance is how to regulate the reactor current to control the current paths change, and restrict fault current increasing, and minimize load current waveform distortion.

SIMULATION AND EXPERIMENT

Using SIMULINK of MATLAB, the SFCL performance analysis and the load current distortion discussion both in steady state and in fault state are carried out. We have considered a 10.5kV, 400A and 50Hz system with 10% source impedance. The inductance value of the reactor and the forward voltage of the diodes are assumed 80 mH and 16V respectively. Per unit of current and voltage are 400A and 16V respectively. If the fault takes place at a zero crossing time of the current waveform, the value of the BPS is chosen in order to remove load current waveform distortion in steady state. The peaks of the load



(a) series mode (b) parallel mode

Fig.4 Reactor current of SFCL with BPS

current of two modes of the SFCL are showed in Fig.4 (a) and (b) respectively. The parameter n represents the times of the peaks. When the BPS voltage increases, whether the SFCL in series mode or in parallel one, the distortion of the steady state load current can be removed satisfactorily, but the limiting capability of the SFCL is decreased. If the voltage of the BPS is higher, the steady current of the reactor is no longer constant and tends to increasing, especially in parallel mode.

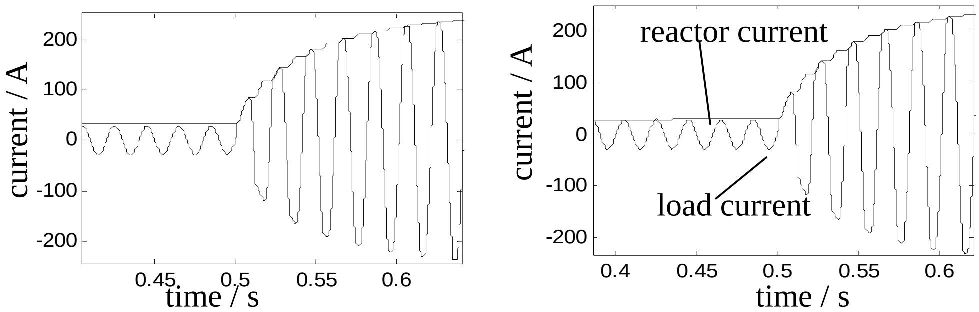
Considering the influence of the BPS to the limiting capability, we make the voltage of the BPS to be zero when fault occurs. The difference of the limiting results of the change is negligible because the power source is very bigger than the BPS. It is noted that the small change of the BPS voltage makes few effects to the limiting capability. So we can optimize the parameters of the BPS to remove the distortion of the steady state load current and at same time enhance the limiting capability. The optimized results are shown in table 1. The current through the BPS in series mode is far great than in parallel mode because, in parallel mode, the BPS acts as a flywheel path and no fault current through the path. The voltage of the

BPS is to remedy the loss of the diodes forward voltage drop. In conclusion, the BPS in series mode is more advantageous to enhance the limiting capability, but its volume is far larger than the BPS in parallel mode.

The experiment of the SFCL with the BPS in different connection modes were made in the single-phase 220V, 50Arms system. The inductance of the superconducting reactor is 23mH. The voltage of the BPS is two times of the forward voltage of the diodes. Data acquisition and monitoring process is carried out on a LabVIEW platform. Fig. 5 (a) and (b) show the reactor current and the load current waveform when the SFCL in different connection with the BPS. The load current distortion is removed in steady state in two circuits. The influence of the BPS to the limiting capability is not obvious if the voltage of the BPS is nearly equal to the forward voltage drops of the diodes.

TABLE 1. Parameters of BPS

	Series mode	Parallel mode
Current /A	3900	$400\sqrt{2}$
Voltage / V	32	48



(a) series mode (b) parallel mode

Fig.5 Current waveform of SFCL with BPS

CONCLUSION

By analysis of superconducting reactor charging, the function of BPS to the SFCL is studied. It is clear that regulation of the reactor charging can eliminate load current distortion and enhance the SFCL limiting capability. So the negative effects of the SFCL to power grid can be obviously eliminated.

ACKNOWLEDGMENT

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