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SIMULATION OF A VOLTAGE COMPANSATION TYPE SUPERCONDUCTING FAULT CURRENT LIMITER

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Abstract: Introduction of superconducting fault current limiter (SFCL) into electrical distribution system might be a good choice with economy as well as practicability. The parameter design and current-limiting characteristics of a voltage compensation type active SFCL are studied in this paper. First of all, the SFCL's circuit arrangement and operating principle are presented. Then, taking a practically 10 kV distribution system as its application object, the SFCL's basic parameters are designed such way that it can meet the system requirements. In addition, by using MATLAB software, the complete current-limiting performances of the 10 kV active SFCL are simulated under different fault conditions. The results of simulations show that the active SFCL can deals with the faults very well, and the parameter design's correctness can be tested. Therefore, in the view of the engineering feasibility of the 10 kV active SFCL, some preliminary discussions are carried out in this paper.

Keywords: Voltage compensation type active SFCL, Distribution network, Current-limiting performances.

I. INTRODUCTION

With the continuous growth of power system installed capacity, and the increase of interconnected network, the level of short-circuit current increasing continuously. To reduce the effect of over current on the electric devices simulation model of the 10 kV active SFCL, and to improve the security and stability of whole power system network, it is necessary to suppress the fault current to a lower level where circuit breakers can easily operate. Amongst all the proposed current limiting methods, superconducting fault current limiter (SFCL), due to its some special advantages, has been wide attention at home as well as in abroad [1–3]. Based on the results of a survey on possible applications of FCL distributed by CIGRE Working Group A3.10 at 53 power companies and industries in 14 countries, there is a occurrence for the interest of a limiter in medium voltage networks [4]. It is considered that, the introduction of SFCL into distribution network is a good choice which can achieve good balance between economy and practicability.

In addition, along with the development of flexible AC transmission system (FACTS) technique (such as series active filter) into fault current limitation, some studies have been carried out [5–7], and taking into account superconducting material, the concept of active SFCL was put forward [8]. We have studied voltage compensation type active SFCL [9], and analysed the active SFCL's control approach and its effect on power system [10, 11]. In addition, a 800 V/30 A laboratory model was made, and its working performances were confirmed [12]. In this paper, by taking a practical 10 kV distribution network as the active SFCL's application object, the basic parameters of SFCL are designed to satisfy the system necessities. Using MATLAB software, a 10 kV active SFCL is constructed, and its current characteristics of limiting are calculated under different fault conditions.

II. THE ACTIVE SFCL : STRUCTURE AND PRINCIPLE

Fig. 1 indicates the structure of the integrated 3 phase voltage compensation type active SFCL. It is consist of three air cored superconducting transformers and a three phase four wire voltage type PWM converter with fully controlled power electronics devices. L_{s1} and L_{s2} are the self-inductances of the superconducting windings, and M_s is the mutual inductance. Z_1 and Z_2 are the circuit impedance and the load impedance respectively. L_d and C_d are used for filtering the high order harmonics generated by the converter.

In normal operating state, the injected current in the secondary winding of the each phase of superconducting transformer will be controlled in certain value, where the magnetic field in the air-core can be compensated to zero, so the active SFCL will have no effect on the performance of the main circuit. When the fault is detected, the injected currents (i_a, i_b, i_c) equivalent to the fault phase will be adjusted in amplitude or phase angle. Hence the controlling of the primary voltage of superconducting transformer, which is in series with the main circuit, and additional the fault current can be suppressed. By taking phase A as an example to explain the regulating mode in details. In normal state, Eq. (1) can be achieved.

$$\dot{U}_{sA} = \dot{I}_A(Z_1+Z_2) + j\omega L_{s1}\dot{I}_A - j\omega M_s\dot{I}_a \quad \text{---- (1)}$$

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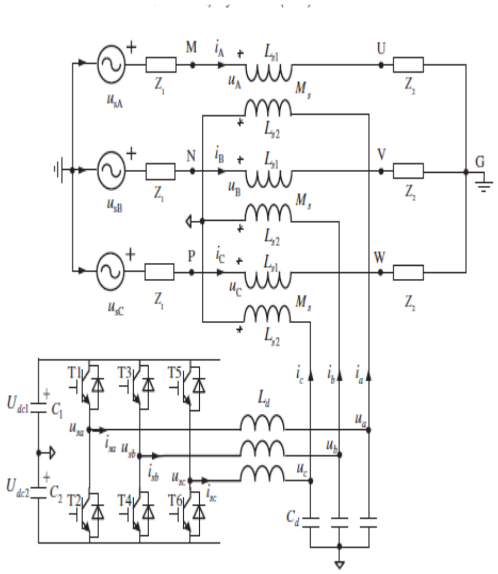


Fig.1: The integrated three-phase voltage compensation type active SFCL.

Controlling $\dot{I}_a$ to make $j\omega L_{s1}\dot{I}_A - j\omega M_s\dot{I}_a = 0$ and the A-phase superconducting transformer primary voltage u_A will be regulated to zero. Thereby, the SFCL will have no influence on phase A, and i_a can be set as:

$$\dot{I}_a = \dot{I}_A L_{s1}/M_s = \dot{I}_A \frac{\sqrt{Ls1/Ls2}}{K} \quad \text{---- (2)}$$

Where k is the coupling coefficient

$K = M_s/\sqrt{L_{S1}L_{S2}}$

When the node U is grounded and the single to phase fault occurs, the line current will increase from i_A to i_{Af}, and the primary and secondary voltages of A-phase superconducting transformer of will increased to u_{Af} and u_{af}, respectively.

$$\dot{I}_{Af} = \frac{\dot{U}_{sA} + j\omega M s \dot{I}_a}{Z1 + j\omega Ls1} \quad \text{- (3)}$$

$$\dot{U}_{Af} = j\omega L_{s1}\dot{I}_{Af} - j\omega M_s\dot{I}_a = \frac{\dot{U}_{sA}(j\omega Ls1) + (j\omega Ms)\dot{I}_a Z1}{Z1 + j\omega Ls1} \quad \text{---- (4)}$$

$$\dot{U}_{af} = j\omega L_{s2}\dot{I}_a - j\omega M_s\dot{I}_{Af} = j\omega L_{s2}\dot{I}_a - j\omega M_s\frac{\dot{U}_{sA} + j\omega M s\dot{I}_a}{Z1 + j\omega Ls1} \quad \text{---- (5)}$$

From Eq. (4), the primary voltage can be adjusted by regulating i_a. The current-limiting impedance ZSFCL can be controlled in the following equation

$$Z_{SFCL} = \frac{\dot{U}_{Af}}{\dot{I}_{Af}} = j\omega L_{s1} - \frac{j\omega M s\dot{I}_a(Z1 + j\omega Ls1)}{\dot{U}_{sA} + j\omega M s\dot{I}_a} \quad \text{---- (6)}$$

As per the difference in the regulating objectives of ia, there are three operation modes:

1. Making ia remain the original state, $Z_{SFCL\text{-}1} = Z_2(j\omega L_{s1})/(Z_1 + Z_2 + j\omega L_{s1})$
2. Controlling i_a to zero, and , $Z_{SFCL\text{-}2} = j\omega L_{s1}$
3. Regulating the phase angle of i_a to make the difference in $\dot{U}_{sA}$ and $j\omega M_s\dot{I}_a$ be 180^o.

The air cored superconducting transformer has many advantages, such as no iron losses and no magnetic saturation, and more possibility of reduction in size and weight than the and other conventional transformer and iron-core superconducting transformer [13]. As there is no existence of transformer saturation in the air-core superconducting transformer, adopting it can contribute to keep the linearity of $Z_{SFCL.}$ As the air cored Super-conducting transformer has no particular path for the flowing of the magnetic flux, the magnetic flux produced by its windings will act directly on each turn of the superconducting winding [14], and the ac losses of the superconducting windings will increase to a certain level. In addition, the transformer's stability may be affected harmfully.

III. PARAMETER DESIGN OF THE 10 KV ACTIVE SFCL

As shown in Fig. 2, it shows the main connection of a practically 10 kV distribution network used for installing the active SFCL. As per the circuit equivalent principle, Fig. 3 shows the distribution network's simplified single-phase circuit with the SFCL.U_s is the equivalent power source with its internal impedance Z_s, and T is the step-down transformer with series impedance is Z_T. The line 1 is the feeder line connected to some important loads. Its load resistance is $R_1$and inductance L_1. The feeder line 2 is a line where faults often occur, and k_1, k_2 and k_3 are the hypothetical fault locations. R_2, L_2 as well as R_3, L_3 are the equivalent resistance and inductance before and after k_1, respectively

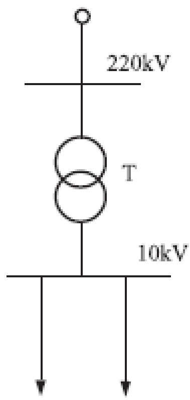


Fig. 2: Main connection to line

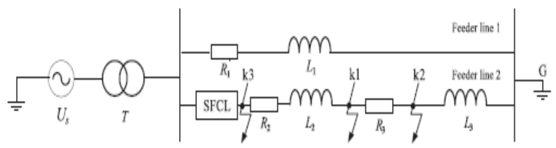


Fig. 3: single phase equivalent circuit.

3.1. Parameter design of the superconducting transformer

Under normal state, the current through the feeder line 2 can be shown as:

$$\dot{I}_{L2} = \frac{\dot{U}_s}{(Zt + Zs) + \frac{Z1(Z2 + Z3)}{Z1 + Z2 + Z3}} * \frac{Z1}{Z1 + Z2 + Z3} \quad \text{---- (7)}$$

Where $Z1= R_1+ j\omega L_1$, $Z2= R_2+ j\omega L_2$, $Z3= R_3+ j\omega L_3$

Once the ground fault happens at point k_1, the short-circuit current without SFCL can be written as:

$$\dot{I}_{L2-f}=\frac{\dot{U}_s}{(Zt+Zs)+\frac{Z1Z2}{Z1+Z2}}*\frac{Z1}{Z1+Z2}=\frac{\dot{U}_s\,Z1}{(Zt+Zs)(Z1+Z2)+Z1Z2} \quad \text{-- (8)}$$

In the case of installing the active SFCL into the feeder line's initial port, the limited fault current will be expressed as:

$$\dot{I}_{L2-Lim}=\frac{\dot{U}_s}{(Zt+Zs)+\frac{Z1(Z2+Zsfcl)}{Z1+Z2+Zsfcl}}*\frac{Z1}{Z1+Z2+Zsfcl} \quad \text{---- (9)}$$

As per Eqs. (7) and (9), in case of $Z_{SFCL}= Z_3$ then the current flowing through the line 2 will remain its original amplitude before and after the occurrence of the fault. It is not needed to utilize this design principle, and the oversize of design parameter will cause to increase of device cost.
Assuming that the current-limiting ratio $R_{cm}=|\dot{I}_{L2-Lim}/\dot{I}_{L2-f}|=0.5$ is achieved that $(Z_t+Z_s)(Z_1+Z_2+Z_{SFCL})+Z_1(Z_2+Z_{SFCL})=2(Z_t+Z_s)(Z_1+Z_2)+2Z_1Z_2$

Therefore the SFCL's impedance can be set as:

$$Z_{SFCL\text{-}set}=\frac{(Zt+Zs)(Z1+Z2)+Z1Z2}{Zt+Zs+Zs} \quad \text{--- (10)}$$

On the basis of the 10 kV distribution system's actual electrical parameters: $Z_t=(0.0048+0.2j)\Omega$, $Z_s=(0.03+0.628j)\ \Omega$, $Z_1=(0.738+3.768j)\ \Omega$, $Z_2=(0.0005+0.5625j)\ \Omega$,

$Z_3=(19+6.28j)\ \Omega$. It is calculated such way that $Z_{SFCL\text{-}set}=(0.1+1.35j)\ \Omega$. If the fault point is at k_2, the limiting impedance will be $Z_{SFCL\text{-}set}=(19.1+1.35j)\ \Omega$ by Eq. 10.It is fact that, the introduction of the SFCL should satisfy the system demands for current limitation under different different fault locations. By observing the active SFCL's current-limiting impedances under the three modes, it can be found that they will all mainly depend on the transformer's inductance of primary winding L_{s1}.

For simplifying the design of primary inductance's process to some degree, it can be approximately thought that $|Z_{SFCL\text{-}set}| \le |j\omega L_{S1}|$ and $0.42\ mH \le L_{S1} \le 61\ mH$ can be obtained. After taking into account the SFCL's overall performance under different situation, the value of the inductance may be averaged and L_{s1} = 40 mH. For designing the superconducting transformer's secondary inductance L_{s2} and to reduce the rated voltage class of the converter connected to inductance coil, the step-down ratio ($L_{s2} < -L_{s1}$) must be applied. Then, the ratio of L_{s1} and L_{s2} is taken as 2, and L_{s2} = 20 mH can be achieve. Additionally, based on experience of manufacturing the laboratory example, the coupling coefficient may be designed as k = 0.9, so M_s = 25.5 mH.

3.2. Capacity design of the converter

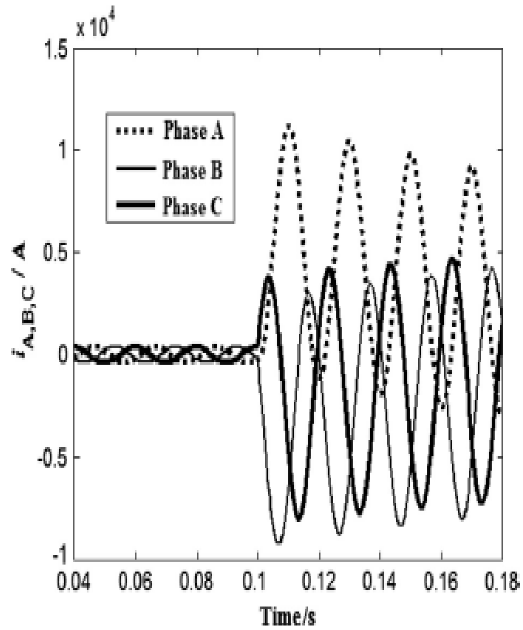
As per [15], it can be seen that, for a 230 V/5000 VA power system, the required capacities of the converter, which can make the active SFCL switch to its corresponding current-limiting modes 1–3, are respectively 2300 VA, 600 VA, 3200 VA. The converter's design capacity under the mode 2 will be smallest. Sometimes this mode may cause negative impact on the transient stability of power system. The mode 1 is selected for the estimation of the converter's design capacity.

Under normal operating state, the RMS value of the current through the feeder line 2 is about I_{L2} = 283 A, and it is based on Eq. (2) the superconducting transformer's secondary current will be 283*√2/0.9=445A.

Under faulty condition at the fault location is k1, the superconducting transformer's secondary voltage equivalent to the mode 1 can be roughly estimated by referring to the mode 2, and there is a little difference between the results of the two modes as per the previous simulation studies. The 10 kV active SFCL's limiting impedance is about 12.56j Ω under the mode 2, and the limited fault current's RMS value will be 413 A based Eq. (9). Then, according to Eq. (5), the secondary voltage's steady-state value will be 3.3 kV. In consideration of $Z_{SFCL-1} < Z_{SFCL-2}$ and supposing that the difference scope is 15%, the secondary voltage under the mode 1 will be 2.8 kV. As a result, the variation range of the converter's DC-link voltage will be 3(0.53 kV–2.8 kV)/M, where M is the pulse width modulation ratio. Assumption that M = 1, the dynamic region of the DC-link voltage will be (1.59 kV–8.4 kV). Therefore, the design capacity of the converter can be selected as 9 kV/500 A.

IV. SIMULATION ANALYSIS

For evaluation the suitability and accessibility of the designed 10 kV active SFCL, the three-phase simulation model corresponding to Fig. 3 is developed in MATLAB software. The parameters are expressed as the following: $Z_s = (0.03 + 0.638j)\ \Omega$, $Z_t = (0.0048 + 0.2j)\ \Omega$, $R_1 = 7.38\ \Omega$, L_1 = 12 mH, $R_2 = 0.0005\ \Omega$, L_2 = 1.8 mH, $R_3 = 19\Omega$, L_3 = 20 mH, f = 50 Hz, L_{s1} = 40 mH, L_{s2} = 20 mH, M_s = 25.5 mH



(a)

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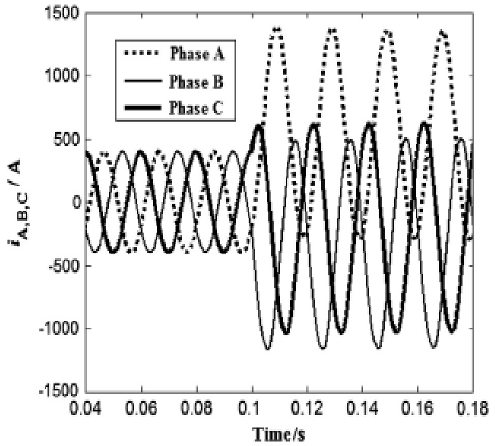


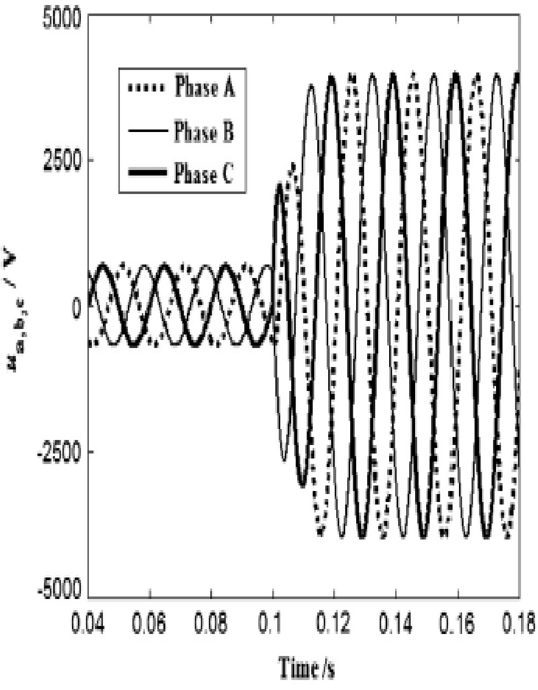
(b)

Fig.4: Fault current through the feeder line 2 when the three-phase short-circuit occurs at k1 point: (a) without SFCL, and (b) with the 10 kV active SFCL.

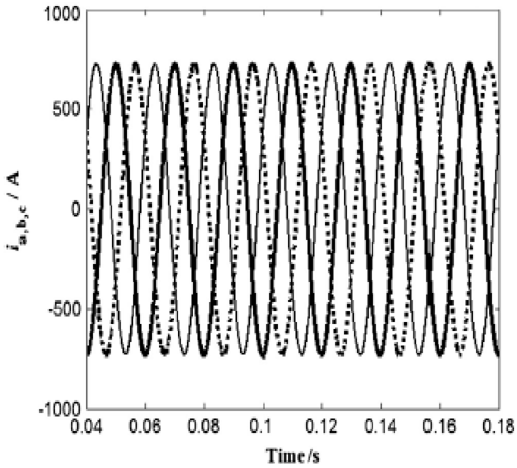
By making the active SFCL works on the mode 1, its simulation characteristics under different fault locations and initial fault angles are both studied.

4.1. Different fault locations

Assuming that the fault point k_1 is grounded (three-phase Short circuit) at time t = 0.1 s and the fault angle is 0^o for phase A, Fig. 4 shows the fault current through the feeder line 2 with and without the 10 kV active SFCL. After the installation of the active SFCL, the fault currents (i_{Af}, i_{Bf}, i_{Cf}) can be limited to 1.38 kA, 1.17 kA, 1.04 kA respectively, as compare with 11.2 kA, 9.26 kA, 8.03 kA under the condition without SFCL. The decrease rate of the expected fault currents will be 87.7%, 87.4%, 87.1%, respectively.



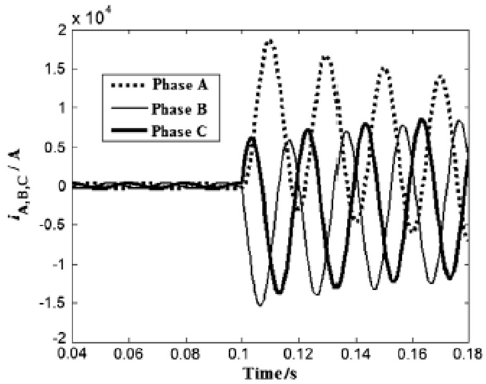
(a)



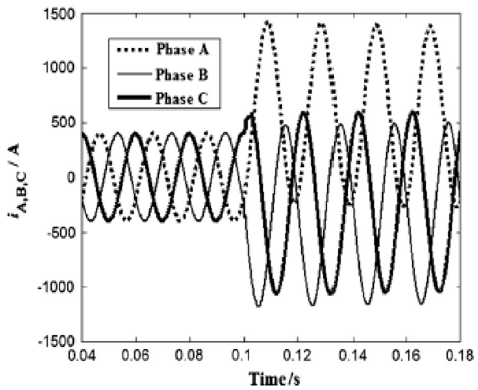
(b)

Fig. 5: AC Output characteristics of the converter when the three-phase short circuit occurs at k1 point: (a) voltage, and (b) current.

Fig. 5 indicates the converter's AC output characteristics under this case. Corresponding to normal as well as fault conditions, the RMS value of the converter's AC output voltage will be respectively 551 V and 2.85 kV, and the two values are about equal to the design calculation results. By observing Fig. 5b, there is no change in the converter's AC output current before and after the fault, and it can be said that the SFCL can availably maintain the mode 1.



(a)



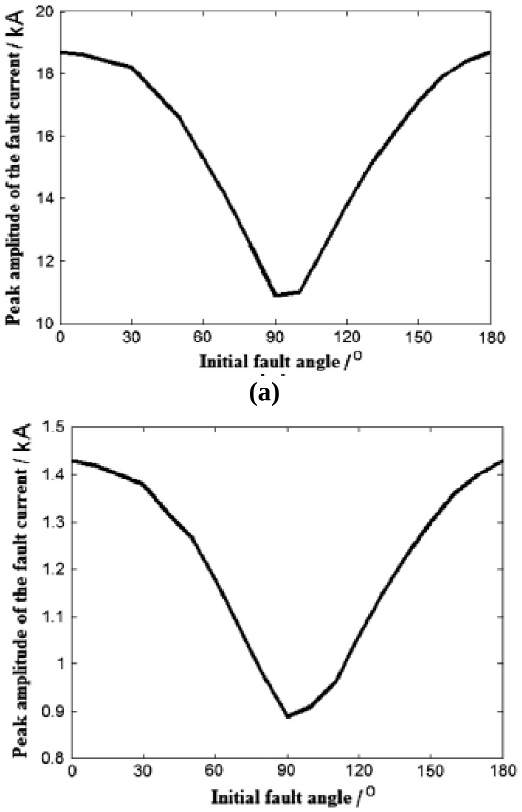
(b)

Fig. 6: Fault current through the feeder line 2 when the three-phase short-circuit occurs at k3 point: (a) without SFCL, and (b) with the 10 kV active SFCL.

For the SFCL's current-limiting performances checking under the most serious fault, it is considered that the fault point k_3 is three phase grounded at time t = 0.1 s. As shown in Fig. 6, it signify the detailed fault current waveform under this circumstances. In case of without SFCL, the 10 kV bus-bar voltages will reduce to zero, and the power distribution system will be damaged seriously. Thereupon, the first peak value of the fault currents (i_{Af}, i_{Bf}, i_{Cf}) will increase to 18.6 kA, 15.3 kA, 13.9 kA, respectively. After installing the active SFCL, they can be respectively reduced to 1.41 kA, 1.19 kA, 1.08 kA, and the corresponding descent rate of the expected fault currents will be 92.4%, 92.2%, 92.1%.

4.2. Different initial fault angles

As one part of fault current, natural response is an exponential decay DC wave, and its initial value has a direct relation with fault angle. In another words, with consider to different initial fault angles, the peak amplitudes of short circuit current will be different. Taking the 10 kV active SFCL into explanation, the effect of initial fault angle on the peak amplitude of the A-phase short circuit current is analyzed in Fig. 7, where the fault location is k_3 point.



(a)

(b)

Fig. 7: Influence of initial fault angle on the peak amplitude of the A-phase short circuit current: (a) without SFCL, and (b) with the 10 kV active SFCL.

From Fig. 7, it is seen that, under the conditions with the SFCL and without the SFCL, the short-circuit current's peak amplitude will be smallest when the fault angle is 90^o. The power distribution system can immediately attain the steady transition from normal state to fault state at this fault angle, and the natural response is approximately equal to zero.

V. ENGINEERING FEASIBILITY DISCUSSION

By taking the superconducting transformer's AC loss and the converter's structure and power electronic device selection for examples, the engineering feasibility of the 10 kV active SFCL is investigated in details. Equivalent to different temperatures, the ratios of superconducting device's AC loss and refrigeration power will be respectively 1:25(77 K), 1:30(64 K) and 1:150(40 K). In a way, the AC loss of superconductor will be an important factor impacting the engineering application of the superconducting power equipment. According to [16], the AC loss of a HTS air cored transformer used for the 800 V / 30 A laboratory prototypes are calculated. It can be observed that the AC loss of the superconducting windings under fault state is much bigger than that under normal operation state. Furthermore, the AC loss is also affected by the compensating current's phase angle as well as magnitude, and its total difference range may be 42W to 75W (three phase, fault state). For the 10 kV active SFCL, since a kA class fault current will flow through the transformer's primary coil, this coil may be made-up by using conventional materials and the secondary coil used for current compensation will still be consisting of superconducting materials, so as to avoid the quench of superconductor and reduce the active SFCL's total AC loss and refrigeration cost to a certain degree. The complete loss estimation and magnetic field analysis will be carried out in the future.

As the active SFCL of 10 kV is designed to work on the current-limiting mode 1, the converter will always output three-phase symmetrical current whether there is a fault or not. Therefore, to replace the original three-phase four-wire converter, a three-phase three-wire voltage-type PWM converter can be used, and this type converter is commonly applied in electrical power system and has a superior engineering practicability. For the possible implementation of the DC side in practice, an additional voltage source inverter connected in shunt with the AC power system through a shunt transformer can be used, and then the common dc storage capacitor shared by the two voltage source inverters . The shunt inverter is operated to keep the voltage across the storage capacitor V_{dc} constant, and the series inverter is controlled to keep its output current constant. Also, in view of the power electronic devices used in the 9 kV/500. A converter, the integrated gate-commutated thyristor (IGCT), which has improved turn-off characteristics and lower conduction loss as compared to gate turn-off thyristor (GTO), and resist higher rates of voltage rise, will be a good choice. Nowadays, typical ratings of IGCTs in the market are 6 kV/6 kA (Mitsubishi) and 10 kV/2.3 kA (ABB).

VI. CONCLUSION

Hence in this paper, to encourage the application of the voltage compensation type active SFCL into the electrical power distribution system, the parameter design and current-limiting characteristics, MATLAB simulation of a 10 kV active SFCL are carried out. The results of the simulation indicate that the active SFCL can deal well with the faults occurring at the power distribution system, and the parameter design's correctness can be testified. Furthermore, in view of the beginning discussions on the 10 kV active SFCL's engineering feasibility; some positive results can be achieved. However, there are many problems are need to be solved, such as the SFCL's AC loss calculation, analysis of economic performance and cooperation with line protection. These things will be performed in the future.

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