A System Study on Superconducting Fault Current Limiting Transformer (SFCLT) with the Functions of Fault Current Suppression and System Stability Improvement

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***Abstract*—In this paper, we propose a "Superconducting Fault Current Limiting Transformer (SFCLT)"; superconducting transformer equipped with the function of superconducting fault current limiter. We discussed the operating characteristics of SFCLT introduced into a simplified power transmission model system. Fault current, transient stability, overvoltage and thermal characteristics of SFCLT were analyzed in the model system. It was finally revealed that SFCLT could satisfactorily bring about the functions of fault current suppression and power system stability improvement.**

***Index Terms*—Superconducting fault current limiter; Superconducting transformer; Power transmission system; Power system stability**

I. INTRODUCTION

For the large-scale power application of superconducting technology, prototypes of superconducting power apparatus such as transformers, fault current limiters, cables, generators, and SMES have been developed [1]-[3]. The superconducting power apparatus should be coordinated with the background power system in order to improve the total efficiency, controllability and stability in a future power system [4]-[5].

In the electric power system, the system stability is essential to be improved, and at the same time, the fault current should be suppressed by the current limiter. From this viewpoint, in the future superconducting power system, we may combine the superconducting transformer with the superconducting fault current limiter to enhance the power system stability. We have proposed, therefore, the apparatus as "Superconducting Fault Current Limiting Transformer (SFCLT)" [6]. In the normal condition of a power system, SFCLT works as a transformer with zero resistance and low leakage impedance, which increases the static stability and transmission capacity of the power system. When a fault occurs in the power system, SFCLT acts as a fault current limiter with limiting impedance due to quench of SFCLT windings, which improves the transient stability of the power system.

This paper discusses the operating characteristics of SFCLT introduced into a simplified power transmission model system. Fault current, transient stability, overvoltage and thermal characteristics of SFCLT were analyzed in the model system.

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II. CONCEPT OF SFCLT

SFCLT proposed in this paper is characterized by the following concepts:

(1) SFCLT works as a transformer in the normal condition, and also as a fault current limiter in the fault condition.
(2) Quench-induced impedance of SFCLT is positively utilized as a current limiter in the fault condition.
(3) In the fault condition, limiting impedance of SFCLT is activated, and leakage impedance of a transformer can be reduced, compared with that of conventional transformers.
(4) Fault current limiting function of SFCLT improves the transient stability of power system in the fault condition.
(5) Reduced leakage impedance of SFCLT enhances the static stability and transmission capacity of power system in the normal condition.

As described above, SFCLT has the combined functions of fault current suppression and system stability enhancement in the power system. The concept of SFCLT can be applied to both high-temperature and low-temperature superconductors.

III. MODEL SYSTEM

Figure 1 shows a simplified power transmission model system associated with SFCLT. The model system consists of a synchronous generator, a conventional transformer, 500 kV and 275 kV transmission lines, 500 kV/275 kV SFCLT and an infinite bus. SFCLT is represented by the leakage impedance %Z (10~30 % on the per-unit basis of rated voltage and rated capacity) and the limiting impedance to be increased exponentially up to R_{sc} (20~500 Ω) with the time constant τ (1~20 ms) after the quench-onset ($t=t_0$). The switch SW_{SC} is closed in the normal condition, and will open in the fault condition when the fault current I_{SFCLT} at the secondary winding of SFCLT reaches 4 kA.

A 3-phase fault is assumed to occur at the sending end of the single circuit of 275 kV transmission line in Fig. 1. Figure 2 shows the switching operation and the time sequence after the fault. The limiting impedance of SFCLT is activated during $t_0<t<t_1$ (t_1: time at clear of fault), and suppresses the fault current. Through a series of switching operation after the fault in Fig. 2, the model system and SFCLT returns to those in the normal condition. The dynamics associated with the fault and the resultant switching operation in the model system were analyzed using Electro-Magnetic Transients Program (EMTP).

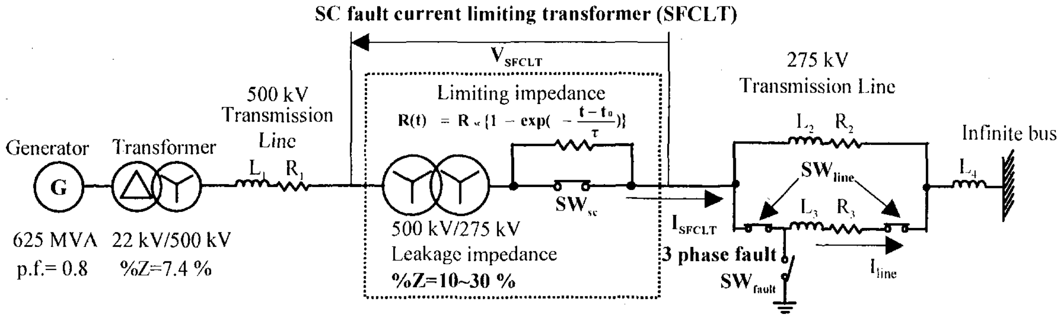


Fig.1. Model system.

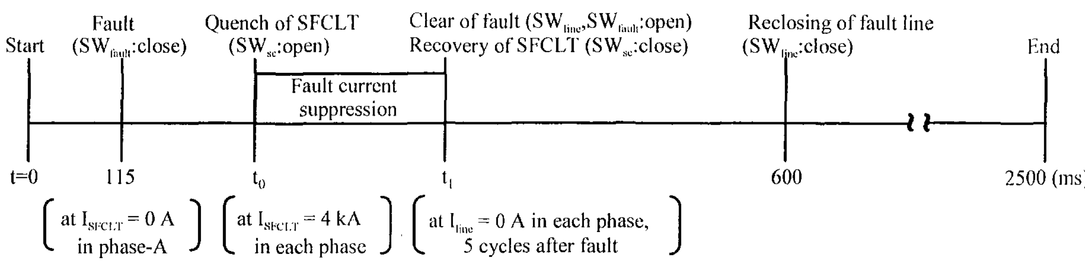


Fig.2. Switching operation and time sequence after fault.

IV. Simulation Results

A. Introduction of SFCLT in Model System

Figure 3 shows the typical results of the simulation on (a) current I_{SFCLT} in the secondary winding of SFCLT and (b) load angle oscillation in the synchronous generator in phase-A for %Z=10 %, R_{sc}=200 Ω and τ =1 ms. Broken line designates the waveforms of the case without the limiting impedance (R_{sc}=0 Ω). As shown in Fig. 3 (a), the prospective fault current in the case of R_{sc}=0 Ω reaches 8 kA. On the other hand, the fault current in the case of R_{sc}=200 Ω is suppressed to 4.5 kA in the first cycle after the fault. Furthermore, the subsequent fault current is reduced into the load current level in the normal condition. In Fig. 3 (b), the amplitude of load angle oscillation in the case of R_{sc}= 200 Ω is reduced into about 1/2 in the case of R_{sc}=0 Ω, which means the improvement of transient stability in the fault condition. The oscillation tends to converge into the load angle level in the normal condition with the cycle of about 0.8 seconds.

B. Balancing the Fault Current Suppression with the System Stability Improvement

Simulation results are summarized in Fig. 4 (a) maximum current I_{max} and (b) amplitude $\Delta\delta$ of load angle oscillation as a function of limiting impedance R_{sc} of SFCLT, where the leakage impedance is fixed at %Z=10% and the time constant τ is taken as the parameter. In Fig. 4 (a), I_{max} decreases with the increase in R_{sc}, and with the decrease in τ. In other words, for the purpose of suppressing the fault current, the higher and the

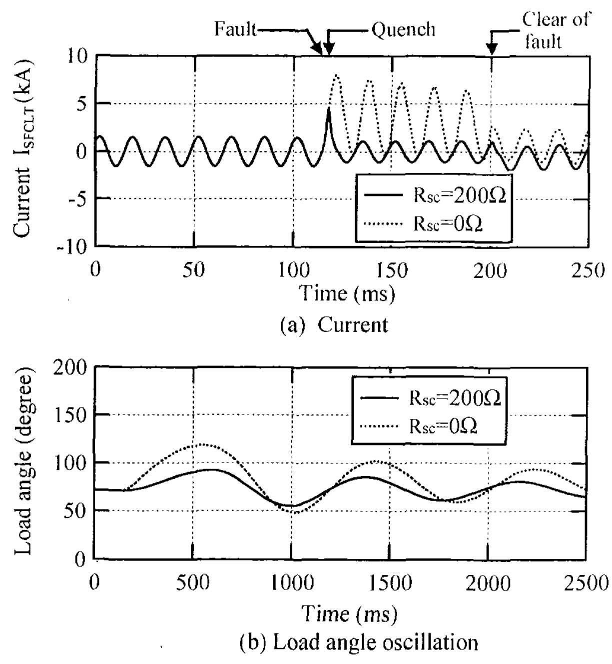
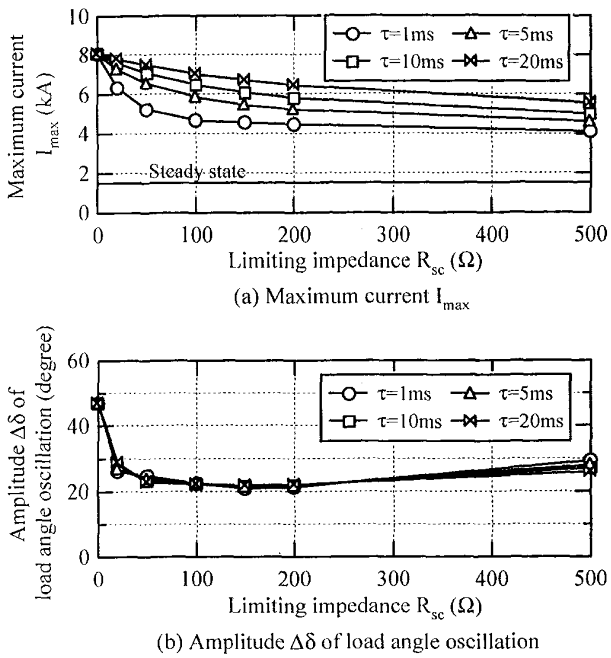


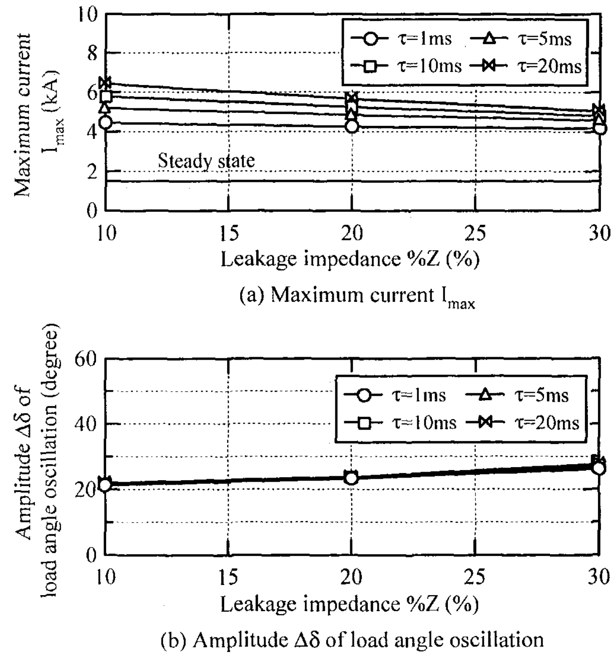
Fig. 3. Current and load angle oscillation (%Z=10%, Rsc=200Ω, τ=1ms).



(a) Maximum current I_{max}

(b) Amplitude Δδ of load angle oscillation

Fig. 4. Maximum current I_{max} and amplitude Δδ of load angle oscillation as a function of limiting impedance (%Z=10 %).



(a) Maximum current I_{max}

(b) Amplitude Δδ of load angle oscillation

Fig. 5. Maximum current I_{max} and amplitude Δδ of load angle oscillation as a function of leakage impedance (R_{sc}=200 Ω).

faster increasing limiting impedance is effective. Figure 4 (b) shows that the fault current suppression for R_{sc}<150 Ω is also effective to reduce Δδ and improve transient stability. However, the higher R_{sc} than 150 Ω makes the model system rather unstable. This is because the open/close operations of higher R_{sc} can be regarded to be a disturbance as well as the fault in the model system. In other words, the acceptable values of R_{sc} and τ should also be discussed from the viewpoint of transient stability.

Figure 5 shows (a) I_{max} and (b) Δδ as a function of leakage impedance %Z at R_{sc}=200 Ω. The lower %Z brings about the slight increase in I_{max} at the shorter τ, and the decrease in Δδ irrespective of τ.

C. Overvoltage Characteristics

For the insulation design of SFCLT, overvoltage characteristics associated with the switching operations in Fig. 2 should be investigated. Figure 6 shows (a) terminal voltage V_{SFCLT} of SFCLT in Fig. 1 (%Z=10 %, R_{sc}=200 Ω, τ=1 ms), (b) R_{sc} dependence of the maximum voltage V_{max} (%Z=10 %), and (c) %Z dependence of V_{max} (R_{sc}= 200 Ω). In Fig.6 (a), a high voltage surge of 1.7 p.u. is induced by the quench (generation of limiting impedance) of SFCLT. In Figs. 6 (b) and (c), V_{max} increases with the increase in R_{sc}, and with the decrease in τ and %Z. This means that the higher and the faster increasing limiting impedance, which was effective for the fault current suppression in Fig. 4 (a), induces the rather higher overvoltage.

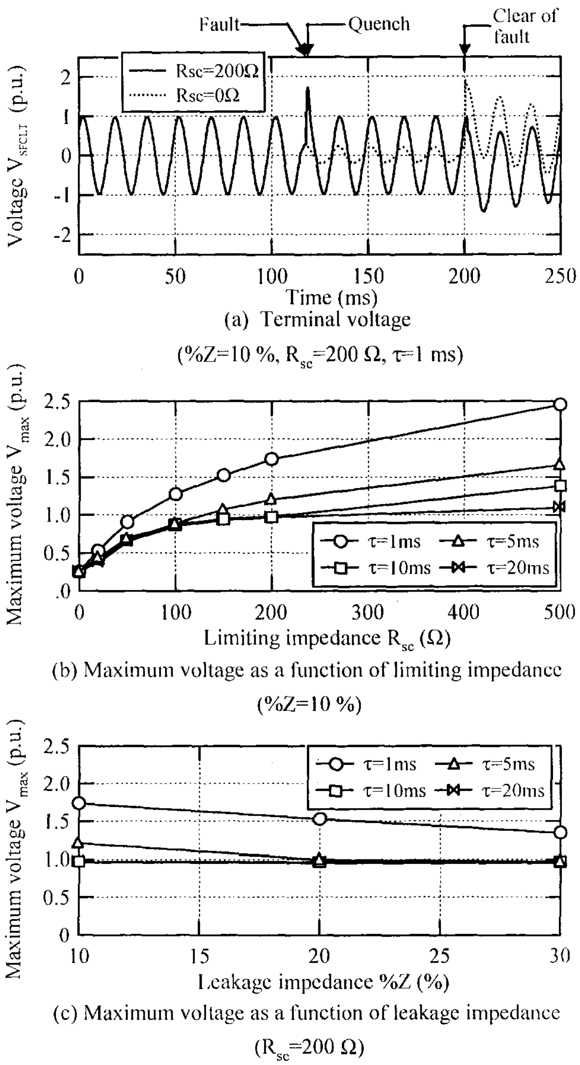
D. Thermal Characteristics

It is important to consider the thermal behavior of SFCLT winding during the fault current suppression (t_0<t<t_1). Figure 7 shows (a) thermal energy and injected power of SFCLT (%Z=10 %, R_{sc}=200 Ω, τ=1 ms) (b) R_{sc} dependence of the accumulated thermal energy J_{max} (%Z=10 %), and (c) %Z dependence of J_{max} (R_{sc}=200 Ω). In Fig. 7 (a), an injected power of 1700 MW is generated in the first cycle of fault current suppression, and the thermal energy of 13 MJ is accumulated during the current limiting operation. In Fig.7 (b), J_{max} becomes maximum at R_{sc}=50~100 Ω, where the transient stability was effectively improved in Fig. 4 (b). On the other hand, in Fig. 7 (c), J_{max} slightly increases at the lower %Z.

E. Discussions

The above simulation results indicate that the superconducting transformer with the lower leakage impedance is expected by coordinating with the limiting impedance of SFCLT. The lower limiting impedance is not only less effective to suppress the fault current, but also makes the model system rather unstable. According to the simulation results, the limiting impedance of about R_{sc}=150 Ω can balance the fault current suppression with the system stability improvement.

Taking account of overvoltage and thermal characteristics, the limiting impedance of about R_{sc}=150 Ω with τ=5~10 ms is



(a) Terminal voltage

(%Z=10 %, R_{sc}=200 Ω, τ=1 ms)

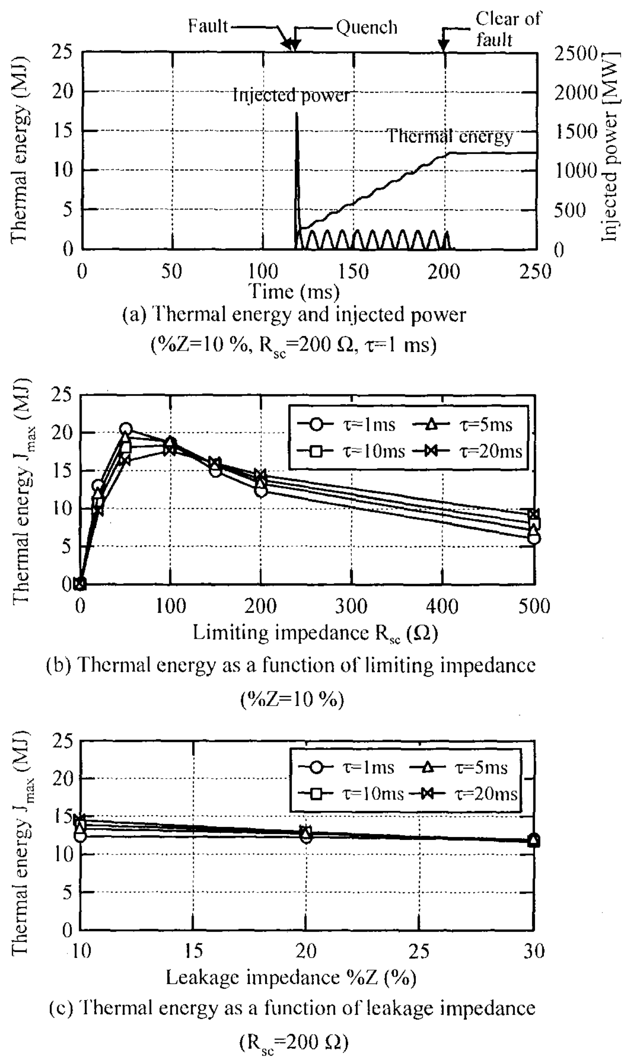
(b) Maximum voltage as a function of limiting impedance

(%Z=10 %)

(c) Maximum voltage as a function of leakage impedance

(R_{sc}=200 Ω)

Fig. 6. Overvoltage characteristics of SFCLT.



(a) Thermal energy and injected power

(%Z=10 %, R_{sc}=200 Ω, τ=1 ms)

(b) Thermal energy as a function of limiting impedance

(%Z=10 %)

(c) Thermal energy as a function of leakage impedance

(R_{sc}=200 Ω)

Fig. 7. Thermal characteristics of SFCLT.

acceptable in the model system. A SFCLT with %Z=10 %, R_{sc}=150 Ω, τ =5 ms brings about the suppression of fault current into 70 % as well as load angle oscillation into 45 %, compared with the case of R_{sc}=0 Ω.

V. Conclusions

From the viewpoint of coordination of superconducting power apparatus with the background power system, we proposed a "Superconducting Fault Current Limiting Transformer (SFCLT)" with the functions of transformer and fault current limiter. Using Electro-Magnetic Transients Program (EMTP), operating characteristics of SFCLT such as fault current, transient stability, overvoltage and thermal characteristics were analyzed. Simulation results in a power transmission model system suggested that the leakage impedance of SFCLT could be reduced, simultaneously suppressing the fault current. This means that the introduction of SFCLT enables us to realize the highly stable and efficient superconducting power system withstanding the fault current.

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