Progress in Development of Superconducting Fault Current Limiting Transformer (SFCLT)

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***Abstract*— We have been developing Superconducting Fault Current Limiting Transformer (SFCLT), which has multifunction of both a superconducting transformer in a steady state as well as a superconducting fault current limiter in a fault condition. This paper introduces the progress in our SFCLT project since 1998, from Step-1 to the latest Step-5, with the concept, design, fabrication and test results of SFCLT. In the latest Step-5, we developed a 2 MVA, 22/6.6 kV class SFCLT with YBCO coated conductors and verified the fundamental function as a transformer, effective current limiting function as a fault current limiter, and recovery characteristics after the fault clearance with its operational criterion.**

***Index Terms*—Superconducting transformer, superconducting fault current limiter, YBCO coated conductor, system coordination, recovery under load.**

I. Introduction

TRANSFORMERS are one of main power apparatus in electric power transmission and distribution systems during their 120-years history. With the increase in the short-circuit current due to the enlargement of electric power network, the impedance of transformers have been increased, together with the capacity of circuit breakers, in order to maintain and improve the transient stability in the fault condition of power system. As the result, the impedance of conventional transformers have reached as high as 20 %, which means that the transformers play the role of fault current limiters as one of their fundamental functions. However, the high impedance of transformers would sacrifice the transmission capacity and static stability in the steady state of power system. Thus, if the transformers could exhibit the fault current limiting function only in the fault condition and reduce the impedance in the steady state, the efficient and reliable power system will be established.

Superconducting Fault Current Limiting Transformer (SFCLT) can satisfy the above request. SFCLT is an advanced power apparatus using HTS power technology to solve the dilemma on transformer impedance between in the steady state and in the fault condition of power system. SFCLT can exhibit multifunction of both a HTS transformer (low impedance) in the steady state, as well as a HTS fault current limiter (high impedance) in the fault condition. We have started to investigate the technical feasibility of SFCLT since 1998, and recently developed a 2 MVA, 22/6.6 kV class demonstrator with YBCO coated conductors. In this paper, we will review our SFCLT project and discuss the future perspective of SFCLT development.

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II. Concept of SFCLT

Generally, a superconducting transformer (SCTR) can transmit bulk power with lower power loss, reduced footprint, lighter weight etc. than conventional transformers in the steady state. On the other hand, a superconducting fault current limiter (SFCL) can suppress the fault current owing to the impedance generation only in the fault condition. Here, SFCLT as the integrated HTS power apparatus of both SCTR and SFCL is characterized by the following 4 features:

(1) Reduction of leakage impedance as a transformer,
(2) Suppression of fault current as a fault current limiter,
(3) Coordination of static and transient system stability, and
(4) Recovery into superconducting state after fault clearance.

Figure 1 shows the introduction concept of SFCLT, compared with individual introduction of SCTR and SFCL, respectively, into conventional transmission systems. The benefits of SFCLT are schematically expressed in terms of impedance and efficiency of transformers (TR), duty and cost of circuit breakers (CB), stability and cost of power system

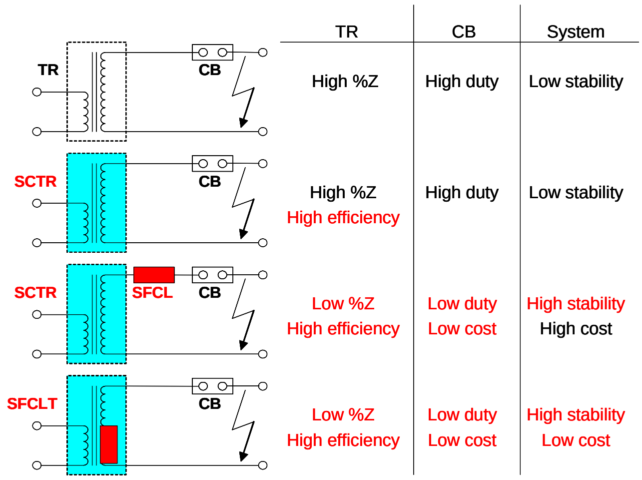


Fig. 1 Introduction concept of SFCLT

(System). SFCLT will exhibit not only the high efficiency and compactness of a transformer, but also the high stability of power systems as well as the high reliability and rationalization of their construction and operation.

It should be noted that the impedance of SFCLT in the steady state means the leakage impedance (%Z) as a transformer, whereas the impedance of SFCLT in the fault condition is resistance as a resistive-type SFCL in our project. The limiting impedance generated in the SFCLT coils on the low-voltage side can be magnified by the square of turn ratio on the high-voltage side. Then, the generated impedance per unit length of HTS conductor can be reduced, compared with the normal resistance due to quench, for the fault current limitation. These features contribute to reduce the temperature rise of HTS conductor and facilitate the recovery into superconducting state after fault clearance. In our SFCLT project, the flux-flow resistance of HTS conductor is utilized for the current limitation and recovery performance.

III. History of SFCLT Development

Figure 2 shows the progress of SFCLT project in the following steps:

STEP-1: EMTP simulation was carried out for fault current limitation and system stability improvement [1], [2]. Figure 3 shows the model system with SFCLT introduced into a 500 kV transmission system. The current limitation and stability improvement could be coordinated by appropriate parameters of SFCLT.

STEP-2: Fundamental functions of SFCLT as both SCTR and SFCL were experimentally verified using a 3-phase model of 6.25 kVA and 275/105 V using NbTi wire immersed in liquid helium at 4.2 K [3]. The fault current was effectively suppressed in each phase as shown in Fig. 4.

STEP-3: Experimental verification of SFCLT function was carried out using HTS Bi2212 bulk material immersed in liquid nitrogen at 77 K [4]-[6]. Figure 5 shows the current waveform before and after the fault in the short-circuit test, where not only the current limitation but also recovery performance of SFCLT were found out.

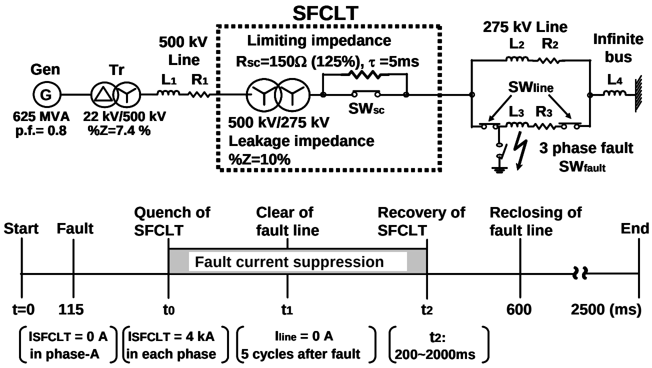


Fig. 3 EMTP simulation model with SFCLT (STEP-1)

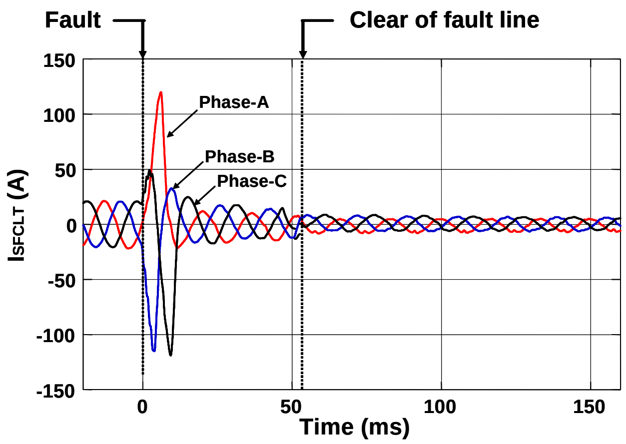
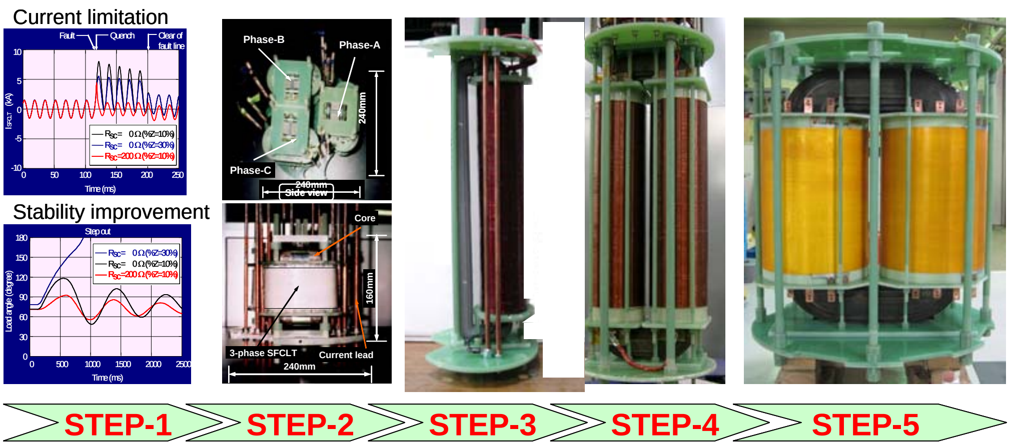


Fig. 4 Current waveform at 3-phase fault (STEP-2)



EMTP analysis	6.25 kVA		100 kVA	2 MVA
	275 V / 105 V		6600 V / 210 V	22 kV / 6.6 kV
	NbTi wire	Bi2212 bulk	YBCO tape	
	4.2K (LHe)	77K (LN_2)		

Fig. 2 Progress of SFCLT project

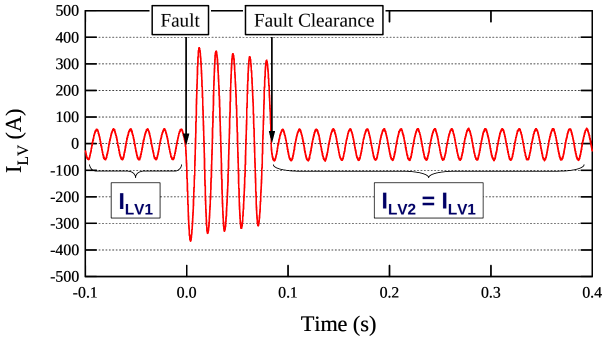


Fig. 5 Current waveform at recovery case (STEP-3)

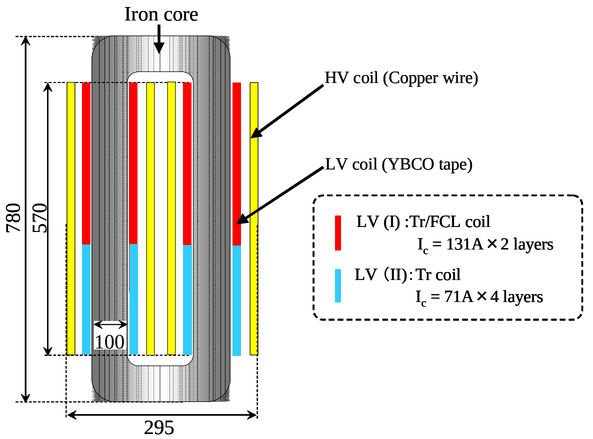


Fig. 6 Hybrid arrangement of HTS coils (STEP-4)

STEP-4: YBCO coated conductors were applied to a 100 kVA and 6600/210 V SFCLT [7], [8]. Hybrid construction using different types of HTS tapes in the low-voltage coils, as shown in Fig. 6, enabled a flexible and controllable design of current limiting function of SFCLT.

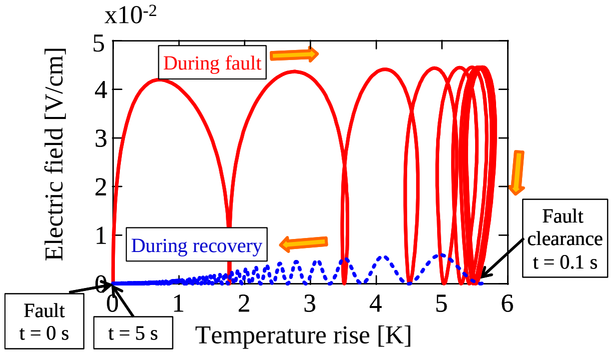


Fig. 8 Trajectory during fault and recovery (STEP-5)

STEP-5: A 2 MVA and 22/6.6 kV SFCLT was designed, and the single-phase demonstrator supposing Y-Y connection was fabricated and tested [9]-[12]. The fundamental function as SCTR [10], current limiting function as SFCL and recovery performance in Fig. 7 [11] were experimentally obtained. Furthermore, the experimental results were reproduced by numerical simulation for electrical and thermal behavior of SFCLT. The current limitation and recovery process was calculated and interpreted in terms of E-ΔT trajectory in Fig. 8 [12], where E is the absolute value of electric field in YBCO coated conductor. A large loop during fault corresponds to the trajectory for a half ac cycle. The simulation could also verify the experimental criteria between recovery case and non-recovery case in Fig. 7.

IV. Future Perspective of SFCLT Development

As introduced in the previous section, we have developed a SFCLT demonstrator of 2 MVA, 22/6.6 kV distribution voltage class and verified the multifunction of both SCTR and SFCL in

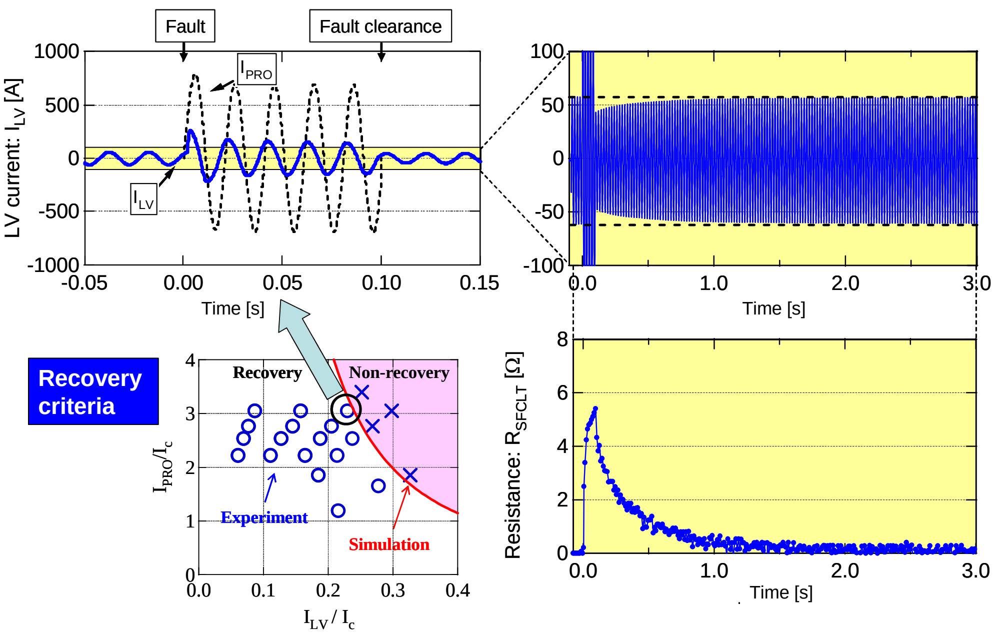


Fig. 7 Current limitation and recovery characteristics of 2 MVA class SFCLT (STEP-5)

Table I Key technologies for SFCLT development

SCTR	1. Reduction of load loss and no-load loss 2. Electrical insulation at cryogenic environment 3. Optimization of coil arrangement 4. Lead connection
SFCL	1. Optimization of current limiting function 2. Electrical insulation during fault current limitation 3. Evaluation of recovery characteristics
HTS material	1. Optimization of specifications 2. Reduction of ac loss 3. Parallel connection for larger current capacity
System	1. Optimization of SCTR and SFCL design 2. Thermal insulation and cryogenic refrigeration 3. Rating and test procedure 4. Coordination of static and transient stabilities

the STEP-5 of our project. Table I summarizes the key technologies to be solved and established for the practical and rational design and operation of SFCLT from the viewpoints of SCTR, SFCL, HTS material and system. The SFCLT development toward the transmission voltage class with larger capacity and higher voltage ratings is expected.

The principal idea or concept of SFCLT lies in the multifunction of HTS power apparatus and the coordination with the background power system. Thus, the concept of SFCLT will be extended to the other HTS power apparatus, e.g. HTS-FCL cables [13], where the recovery under load after current limitation and fault clearance should be the key technology.

V. Conclusion

We have developed Superconducting Fault Current Limiting Transformer (SFCLT) up to 2 MVA, 22/6.6 kV class using YBCO coated conductors, as an advanced HTS power apparatus in a future electric network with efficiency and reliability of power transmission and distribution. Our research works and experience as a pioneer of SFCLT development could exhibit the technical feasibility of SFCLT and will be the foundations for the practical and rational design and operation of SFCLT as well as the extension to the other advanced HTS power apparatus.

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