Feasibility Study of Superconducting Power Flow Controller and Fault Current Limiter (SPFCL)

N. Hayakawa, *Member IEEE*, X. Mao, H. Kojima, *Member IEEE*, M. Hanai, *Member IEEE*, H. Okubo, *Member IEEE*, N. Kashima, S. Nagaya, S. Sugimoto

***Abstract*—A superconducting power flow controller and fault current limiter (SPFCL) is proposed in this paper, which can not only control power flow in the steady operating state, but also limit fault current in the fault condition. We verified that SPFCL will contribute to the enhancement and coordination of both static stability in the steady operating condition and transient stability in the fault condition.**

***Index Terms*—fault current limiter, power flow controller, recovery, stability.**

I. Introduction

TOWARD the environment-friendly electric power system for the next generation, plenty of distributed generators such as renewable energy power plants and gas turbines will be introduced, which may increase the power flow fluctuation and short-circuit capacity in the power system. Thus, not only the power loss reduction and power flow control in the steady operating state, but also the fault current limitation and recovery in the fault condition are requested in the future power system. As one of the countermeasures to the above requests, FACTS (Flexible AC Transmission Systems) [1] and SFCL (Superconducting Fault Current Limiters) [2] have been investigated, respectively.

FACTS and SFCL have the common function of impedance control for power flow control and fault current limitation, respectively. In this paper, we focused on this common function and propose a novel superconducting power apparatus, i.e. Superconducting Power Flow Controller and Fault Current Limiter, abbreviated to SPFCL. SPFCL is expected to exhibit the multifunction of the power flow controller in the steady operating state and the fault current limiter in the fault condition. This paper describes the concept, construction of SPFCL and the technical feasibility of SPFCL introduced into a simplified power system model.

II. Concept of Superconducting Power Flow Controller and Fault Current limiter (SPFCL)

A. Concept of SPFCL

The power flow distribution in a power system is determined by the reactance balance of transmission lines and transformers in an electric network. Fig. 1 shows the concept of SPFCL introduced into a transmission line. SPFCL has the resistance R_{SC}=0 and the variable reactance X_{SPFCL} in the steady operating state under the critical current I_C. If X_{SPFCL} is comparable to the reactance of the line with SPFCL, the power flow of the line is affected by X_{SPFCL}, e.g. the decrease of X_{SPFCL} cam increase the power flow of the line without power loss, and vice versa.

On the other hand, when the fault current larger than I_C flows in the line, SPFCL immediately generates the impedance much higher than X_{SPFCL} and suppress the fault current. When SFCL function of SPFCL is based on the resistive type, $R_{SC}>>X_{SPFCL}$ is necessary in the fault condition. After the fault clearance, SPFCL is expected to recover into the superconducting state (R_{SC}=0).

FIG. 1 HERE

B. Construction of SPFCL

Fig. 2 shows possible ideas how to control X_{SPFCL} of SPFCL in the steady operating state; (a) Coil-drive/Shield type, (b) Coil-drive/Non-inductive type, (c) Core-drive type, (d) TCSC (Thyristor Controlled Series Capacitor) type, and (e) SSSC (Static Synchronous Series Compensator) type. The coil-drive type (Fig. 2(a) and 2(b)) and core-drive type (Fig. 2(c)) adjust the geometric arrangement between superconducting coils or between superconducting coil and iron core, respectively. TCSC type (Fig. 2(d)) has the series connection of thyristor-controlled capacitor and superconducting coil with tap changer. SSSC type (Fig. 2(e)) consists of superconducting transformer with tap changer and thyristor-controlled capacitor in the secondary winding.

From the viewpoints of driving method and power of coil and iron core, complexity and controllability, etc., in this paper, we adopted the SSSC type for the conceptual design of SPFCL. A SPFCL was designed with the specifications of 77 kV and 36 MVA for the discussion on the technical feasibility in the following section. Fig. 3 shows the construction of HTS transformer in SSSC-type SPFCL, where the configuration of

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N. Hayakawa, H. Kojima and M. Hanai are with the EcoTopia Science Institute, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan (phone: +81-52-789-3325, fax: +81-52-789-3143, e-mail: nhayakaw@nuee.nagoya-u.ac.jp; h-kojima@esi.nagoya-u.ac.jp; mhanai@esi.nagoya-u.ac.jp).

X. Mao and H. Okubo are with the Department of Electrical Engineering and Computer Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan (e-mail: mosho@okubo.nuee.nagoya-u.ac.jp; okubo@nuee.nagoya-u.ac.jp).

N. Kashima, S. Nagaya and S. Sugimoto are with the Chubu Electric Power Co., Inc., Odaka-cho, Midori-ku, Nagoya 459-8522, Japan (e-mail:Kashima.Naoji@chuden.co.jp; Nagaya.Shigeo@chuden.co.jp; Sugimoto.Shigeyuki@chuden.co.jp).

superconducting fault current limiting transformer (SFCLT) at STEP-5 with YBCO tapes [3] is taken as a reference. Using the taps A-E in the secondary winding, the leakage reactance of transformer can be adjusted by the tap ratio N_1/N_2. Fig. 4 shows the total reactance X_{SPFCL} of SPFCL. By the combination of the tap ratio N_1/N_2=0.5-1.0 and the thyristor-controlled capacitor X_C=3.5-32 Ω (83-758 μF) in the secondary winding, X_{SPFCL} viewed from the primary winding can be controlled in the range between -6 Ω and 10 Ω, which is comparable to the reactance of transmission lines with the length of km order. It should also be noted that X_{SPFCL} can be controlled both in negative (capacitive) and positive (inductive).

The HTS transformer in SPFCL has the YBCO tape with the length of 2,094 m/phase in the primary winding and 4,965 m/phase in the secondary winding. The resistance R_{SC} of the YBCO tape in the fault condition is estimated to reach 100 Ω, which is 1-2 order higher than X_{SPFCL}. Thus, effective current limitation of SPFCL can be expected as the resistive-type SFCL in the fault condition.

FIG. 2 AND 3 AND 4 HERE

III. Power Flow Control Function of SPFCL

A. Model system

Fig. 5 shows a model system for the discussion on the technical feasibility of SPFCL, i.e. power flow control in the steady operating state and fault current limitation in the fault condition. The model system is based on the Roy Billinton test system (RBTS) [4], i.e. 275 kV / 77 kV T&D system. The model system in this paper contains 3 generators (G1 - G3), 6 substations (SS1 - SS6), 4 transformers (Tr4 - Tr7), 275 kV overhead lines (Line1 - Line6), 77 kV XLPE cable (Line7 - Line9) and 5 loads (Load A - Load E) with a total load of 185 MW. The leakage reactance of transformer is 5 % and the load factor is 0.9.

SPFCL(7) and SPFCL(8) with the controllable reactance X_{SPFCL} in Fig. 4 are assumed to be introduced in Line7 and Line8, respectively, in Fig. 5. Fig. 6 shows the equivalent circuit between SS3 and SS5 composed of Tr5, Line7 and SPFCL(7). $X_{SPFCL}(7)$ in the range between -6 Ω and 10 Ω is comparable to the total impedance (0.962 Ω + j9.29 Ω) of Tr5 and Line7. The power flow on Line7 and Line8 can be cooperatively controlled by both $X_{SPFCL}(7)$ and $X_{SPFCL}(8)$.

FIG. 5 and 6 HERE

B. Power flow control function

Fig. 7 shows (a) active power flow P_7 and P_8 (b) reactive power flow Q_7 and Q_8 on Line7 and Line 8, respectively, as a function of $X_{SPFCL}(7)$ and $X_{SPFCL}(8)$. For example, in Fig. 7(a), P_7 decreases and P_8 increases, respectively, with the increase in $X_{SPFCL}(7)$ and the decrease in $X_{SPFCL}(8)$. When $P_7=P_8$=20 MW at $X_{SPFCL}(7)=X_{SPFCL}(8)$=0 Ω is defined as a reference (100 %), P_7 and P_8 can arbitrarily be controlled in the range of 30 % - 170 %. The power flow control can also be confirmed for the reactive power flow in Fig. 7(b). These results verify that SPFCL can exhibit the power flow control function by the appropriate combination of $X_{SPFCL}(7)$ and $X_{SPFCL}(8)$.

FIG. 7 HERE

C. Fault current limitation and recovery function

The fault current analysis is carried out, supposing that the fault point is near the substation SS5 in Fig. 5 and the fault making switch at SS5 in Fig. 6 is closed for 5 cycles. The temporal change of current I, resistance R and temperature T of HTS transformer winding of SPFCL is calculated by solving the electric circuit equation and heat conduction equation [5].

The short-circuit fault is assumed to occur near SS5, when SPFCL(7) and SPFCL(8) have an arbitrary reactance $X_{SPFCL}(7)$ and $X_{SPFCL}(8)$, respectively, for the power flow control in the steady operating state. Fig. 8 shows (a) current and (b) resistance and temperature in the case of $X_{SPFCL}(7)$=0 Ω, $X_{SPFCL}(8)$=10 Ω and N_1/N_2=0.5. The fault current is limited to 1,244 A at the first half cycle against the prospective fault current I_{PRO}=5,862 A, i.e. the limitation factor η=21 %. Though the resistance during the fault reaches as high as 180 Ω and the maximum temperature is 92.4 K, both of them return to those before the fault, i.e. SPFCL can recover into superconducting state after the fault clearance. On the other hand, in the case of N_1/N_2=0.7 in Fig. 9, the fault current limitation is similar to that in Fig. 8(a), whereas the resistance and temperature continue to increase even after the fault clearance, i.e. SPFCL cannot recover into superconducting state.

FIG. 8 and 9 HERE

D. Coordination between power flow control, fault current limitation and recovery

According to the results of fault current analyses for different combinations of $X_{SPFCL}(7)$, $X_{SPFCL}(8)$ and N_1/N_2, the effective fault current limitation (η<30 %) is confirmed in each case such as in Figs. 8(a) and 9(a). However, the recovery characteristics depend on the operating parameter of SPFCL such as N_1/N_2, as was shown in Figs. 8(b) and 9(b).

Fig. 10 shows the consequence of recovery after the fault clearance at (a) N_1/N_2=0.5 and (b) N_1/N_2=0.7. In Fig. 10(a), an arbitrary combination of $X_{SPFCL}(7)$ and $X_{SPFCL}(8)$ for the power flow control results in the recoverable current limitation in the fault condition. On the other hand, in Figs. 10(b) and 10(c), there exist criteria, designated by the broken curves, for the recoverable current limitation. By reflecting such simulation results into the design and operation of SPFCL, the coordination between the power flow control in the steady operating state, fault current limitation and recovery in the fault condition will be improved and optimized.

FIG. 10 HERE

IV. Conclusion

We proposed a Superconducting Power Flow Controller and Fault Current Limiter (SPFCL) for the enhancement of efficiency, controllability and stability of future power system. The scheme for reactance control of SPFCL in the steady operating state was introduced with the combination of HTS transformer and thyristor-controlled capacitor. Through the analyses for both power flow control, fault current limitation and recovery, the technical feasibility of SPFCL was verified in a model power system.

The concept of SPFCL can be extended to other applications, e.g. condition monitoring and optimum maintenance of aged power apparatus by power flow control from the viewpoint of asset management, active and flexible power flow control between adjacent power systems in an emergency, and so on.

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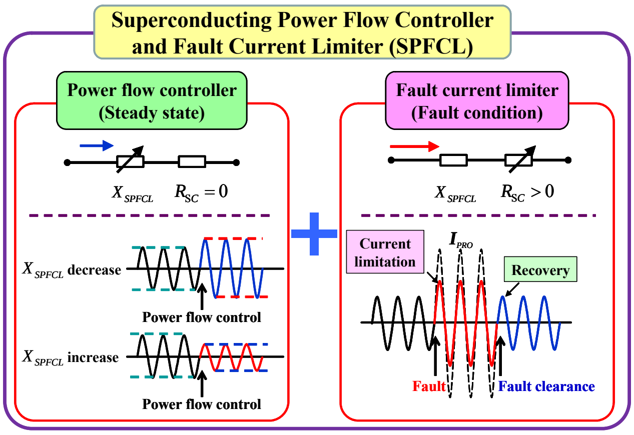


Fig. 1. Concept of SPFCL

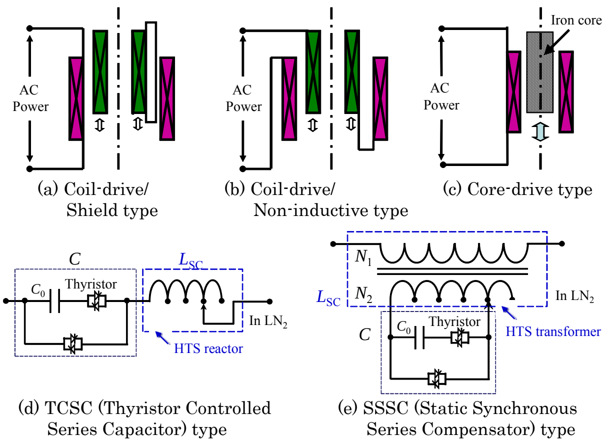


Fig. 2. Construction of SPFCL

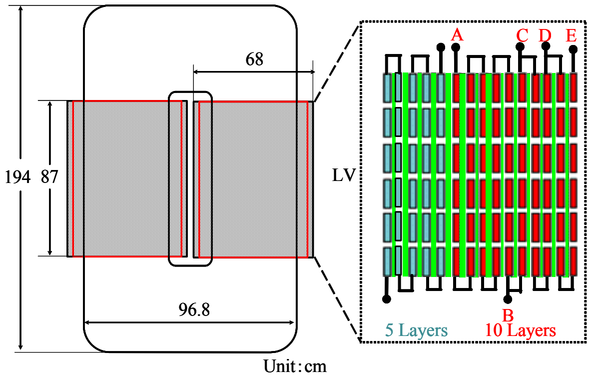


Fig. 3. Construction of HTS transformer in SPFCL

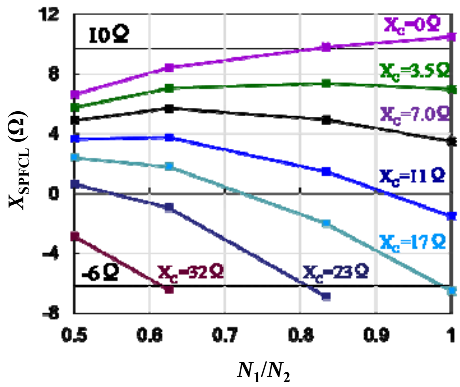


Fig. 4. Controllable range of reactance in SPFCL

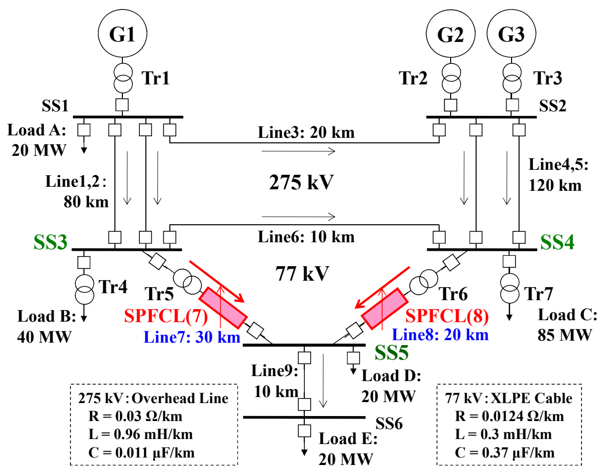


Fig. 5. Model system with SPFCL

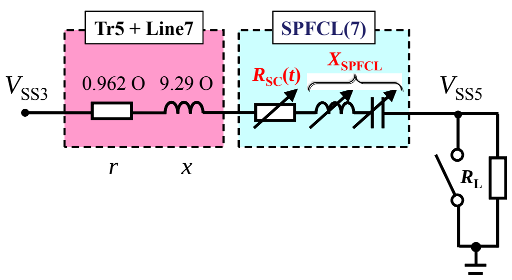
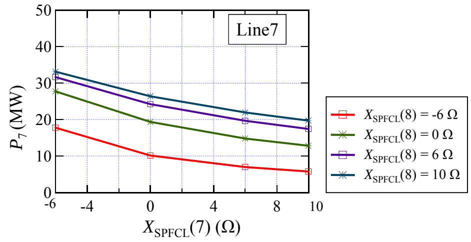
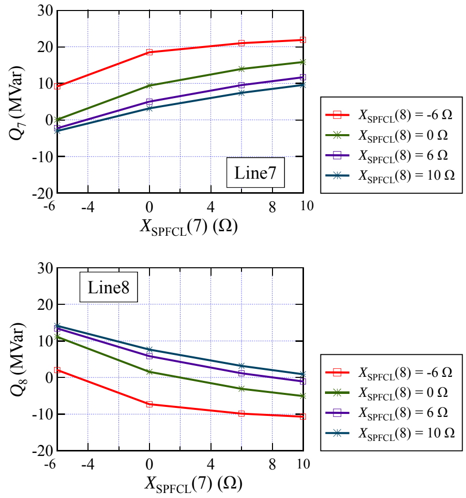


Fig. 6. Equivalent circuit of Line7 with SPFCL(7)

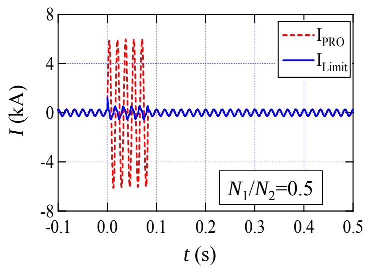


(a) Active power flow

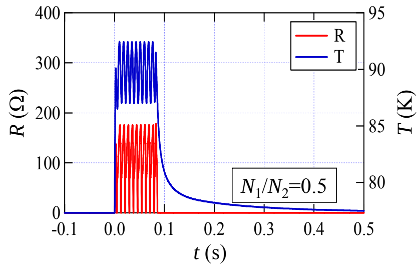


(b) Reactive power flow

Fig. 7. Power flow control of SPFCL

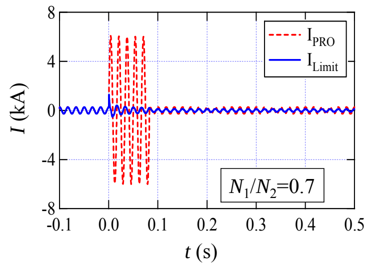


(a) Current waveform

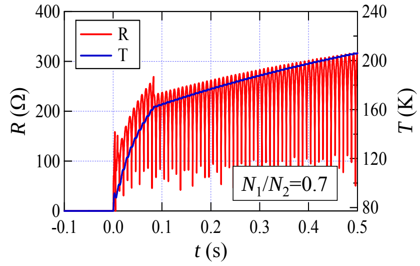


(b) Resistance and temperature

Fig. 8. Current limitation of SPFCL (N_1/N_2=0.5)

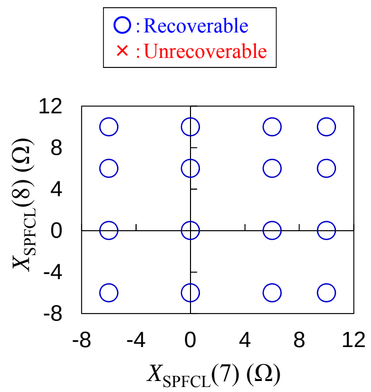


(a) Current waveform

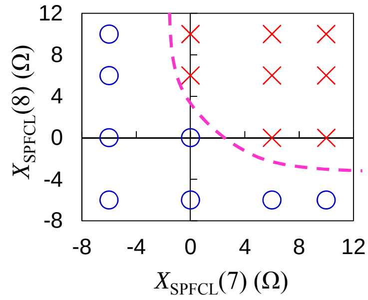


(b) Resistance and temperature

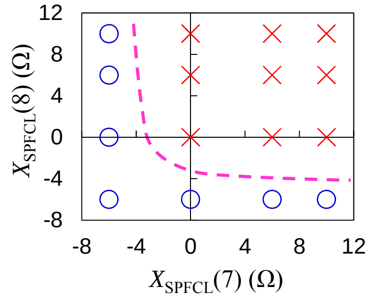
Fig. 9. Current limitation of SPFCL (N_1/N_2=0.7)



(a) N_1/N_2=0.5



(b) N_1/N_2=0.7



(c) N_1/N_2=0.8 and 1.0

Fig. 10. Recovery after current limitation of SPFCL