Enhancement test of Critical Clearing Time of One-machine Infinite Bus Transmission System by Use of SFCL

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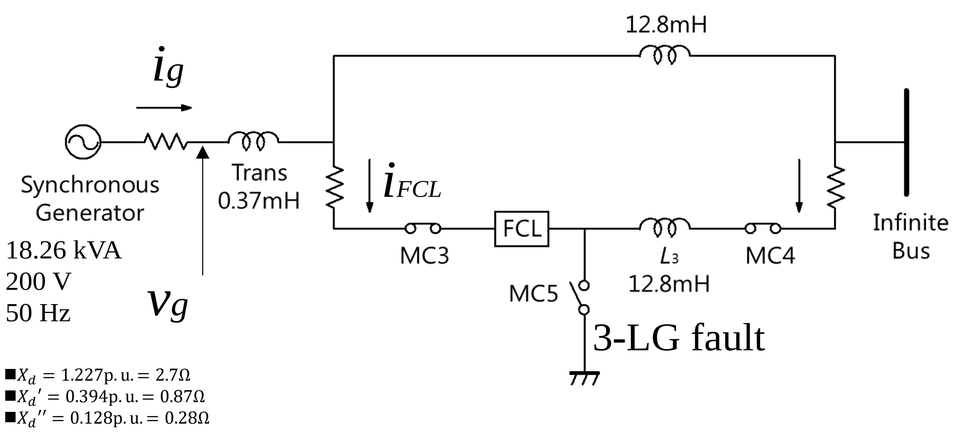
Abstract

- A transformer type field shielding Superconducting Fault Current Limiter (SFCL), which is made of REBCO for primary and secondary windings, is designed and made for demonstration of not only fault current limiting but also power system stability improvement performance.
- A lab-scale test power system consists of one machine (18.26 kVA, 200 V) and double transmission route to an infinite bus.
- The simulated fault occurs at the sending end bus of one of the transmission route and after a certain time (fault clearing time), the fault route was rejected by circuit breakers.
- While the clearing time is short, the generator can continue to operate with one healthy transmission route, however, it becomes longer than a certain time CCT(critical clearing time), the genera-tor loses its synchronism and fails into step out.
- The test SFCL was installed at the generator side bus of the fault route.
- The peak fault current was reduced to less than half of that without SFCL
- and the generator terminal voltage was kept 20 % of rated voltage.
- It was confirmed experimentally that CCT can be enhanced by introducing the SFCL.
- It is confirmed that the SFCL can not only limit the fault current but also improve the system stability.

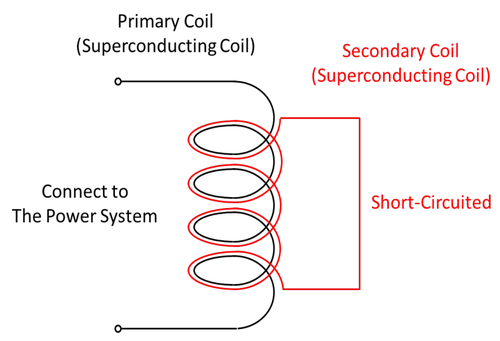
Lab-scale experimental power system



- Magnetic switches MC3 and MC4 work as circuit breakers (CBs).
- MC5 is closed to simulate a 3-phase ground fault.
- The fault current from the sending end to the ground is reduced by the SFCL.
- The CBs (MC3 and MC4) are open to clear the fault line after a certain time (Clearing Time).-> single line transmission.
- Longer Clearing Time results in the step out of the synchronous generator.
- Critical Clearing Time (CCT) means the longest time for the stable operation after the fault line clearing.
- CCT is one of the reference parameter of the system stability.
- SFCL works to not only limit the fault current but also keep the sending end voltage to a certain extent.
- Since a part of the generator power is transmitted through the non-fault line
- Generator acceleration is mitigated.
- CCT of the system introducing SFCL may become longer than that without SFCL.

Trans-type Field shielding SFCL

$$Z_{FCL} = \left(R_1 + \frac{\omega^2 M^2 R_2}{R_2^2 + \omega^2 L_2^2}\right) + j\omega\left(L_1 - \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2}\right).$$



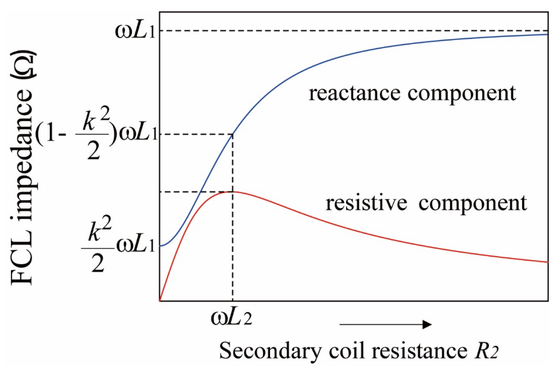
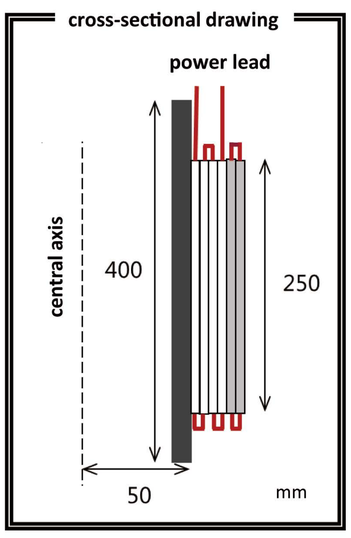


TABLE II
SPECIFICATION OF TEST SFCL

	FCL-A	FCL-B	FCL-C
Primary coil wire	REBCO* I_c=87 A@77 K , 62.8 m		
Secondary coil wire	REBCO* I_c=169 A@77 K, 10.6 m		
Coil diameter		100 mm	
Coil height		250 mm	
Turn (primary)		50 x 4 turn	
Turn(secondary)		17 x 2 turn	
Inductance(primary)	1.34 mH	1.37 mH	1.31 mH
Inductance(secondary)	42.1 μH	43.3 μH	44.4 μH
Mutual inductance	229.3 μH	236.7 μH	235.7 μH
Trigger current level	30.8 A	31.0 A	31.8 A

* SuperPower® 2G HTS Wire Type - SCS4050 - AP

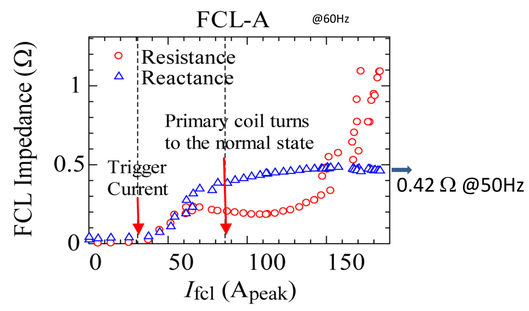


bobbin primary coil secondary coil

Design:

1. To reduce the sub-transient fault current less than half of that without SFCL.
   > Assuming the internal induced voltage V_0 is 240 V (field current is 23 A), the sub-transient fault current without SFCL is given as
   $$I_{Ftra} = V_0 / \left(X_d'' + X_t\right) = 240/(0.28+0.12) = 600\mathrm{A_{rms}}. \quad (2)$$
   To make the fault current with SFCL
   $$I'_{Ftra} = V_0 / \left(X_d'' + X_t + Z_{FCL}\right) = I_{Ftra}/2 = 300\mathrm{A_{rms}}, \quad (3)$$
   Z_{FCL} is selected as 0.4 Ω or more.
2. To keep the generator voltage 40 V_{rms}(1/5 of rated) during the fault period.
   > The generator voltage during the fault (steady state) is given as,
   $$V_{gF} = V_0(X_t + Z_{FCL})/(X_d + X_t + Z_{FCL}). \quad (4)$$
   Z_{FCL} is selected as 0.41 Ω or more.
3. The trigger current level is 30 A (21 A_{rms}).

SFCL impedance



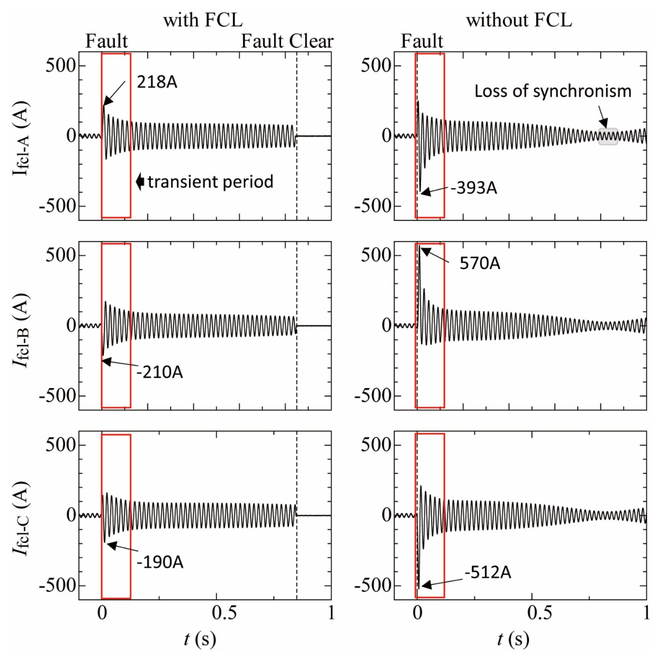
The REBCO wire of I_c=87 A@ 77K is selected for the primary coil and that of I_c= 169 A@77K is for the secondary coil.

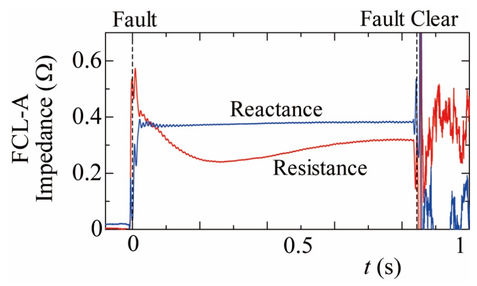
1. Turn ratio is set to 5.63=169 A/30 A.
2. Since only the secondary wire is normal when the fault current (primary coil current) is between 30 A and 87 A, the reactance component is larger than the resistance one (see Fig.2). After the transient state during the fault period, the steady state fault current is reduced to 76.9 Arms = $V_0/(X_d+X_t+Z_{FCL})$ by mainly reactance component of the SFCL. Therefore the SFCL can limit the fault current for several seconds without any damage and smoothly recover to the waiting mode after the fault line clear.
3. When the fault current is larger than 87 A, that is, in the

- With the current exceeds 87 A, the primary coil resistance is added to the resistance component and increases with the current.

Current Limiting at 3LG fault

- Three phase ground fault tests were carried out w and wo SFCL.
- Generator output power was set 4.5 ~ 7.5 kW.
- Field current of the generator was set 21 ~ 23 A to keep the terminal voltage 200 V.
- The fault clearing time increased step by step up to about 4 s.
- The generator was investigated whether the synchronization is kept or not.

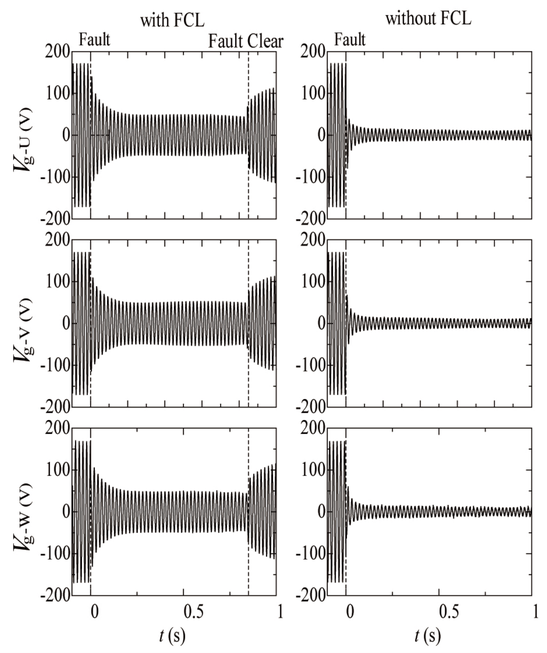




- The sub-transient fault current was reduced (206 A average) by SFLC half or more of those (492 A average) without SFCL.
- The reactance component was saturated to 0.39 Ω. The current limiting impedance is agree well with the designed value.

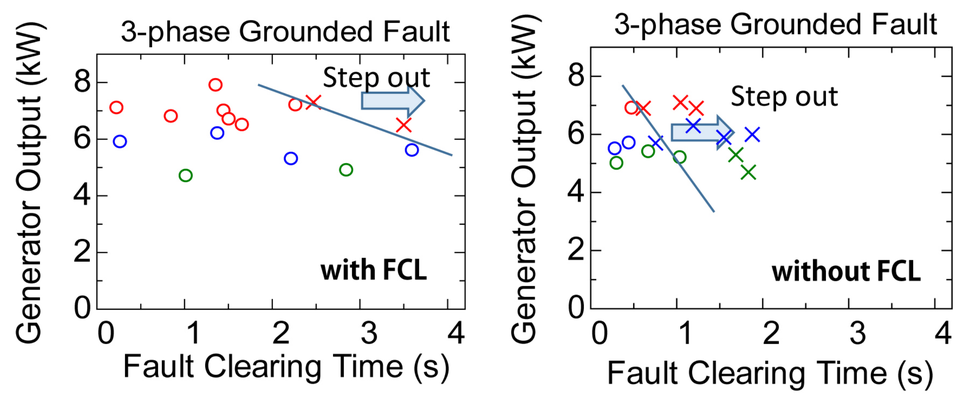
Generator voltage

- The peak value of the U-phase voltage increases from 10 V without SFCL to 50 V with SFCL (steady state period).
- The peak phase voltage 50 V means 73 V line to line voltage, which is larger than that designed (40 V).



Critical Clearing Time with and without SFCL

- All the test cases are shown with stable (o) and unstable (x) on the generator output and the fault clearing time plane.
- The power system needs a quick fault clear less than 1 s to avoid a step out of the generator without SFCL.
- CCT of the system with SFCL is enhanced 2.5 s or more.
- It is confirmed that the SFCL can not only limit the fault current but also improve the system stability.



Conclusion

- In order to demonstrate the SFCL performances not only in the current limitation but also in the power system stability improvement, a model SFCL of transformer type field shielding was designed and made for the lab-scale one-machine and double transmission line system.
- The demonstration tests were successfully carried out. The current limiting performance of the SFCL was agree well with the designed one. The critical clearing time (CCT) was investigated by changing the generator output. CCT was drastically enhanced by installing the SFCL. It is confirmed that the SFCL can not only limit the fault current but also improve the system stability