J Electr Eng Technol.2018; 13(2): 533-539
http://doi.org/10.5370/JEET.2018.13.2.533

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Analysis on Current Limiting Characteristics of Transformer Type SFCL with Additionally Coupled Circuit

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Abstract – In this paper, the transformer type superconducting fault current limiter (SFCL) with additionally coupled circuit was suggested and its peak fault current limiting characteristics due to the fault condition to affect the fault current were analyzed through the fault current limiting tests. The suggested transformer type SFCL is basically identical to the previous transformer type SFCL except for the additional coupled circuit. The additional coupled circuit, which consists of the magnetically coupled winding to the primary and the secondary windings together with another superconducting element and is connected in parallel with the secondary winding of the transformer type SFCL, is contributed to the peak fault current limiting operation for the larger transient fault current directly after the fault occurrence. To confirm the fault current limiting operation of the suggested SFCL, the fault current limiting tests of the suggested SFCL were performed and its effective peak fault current limiting characteristics were analyzed through the analysis on the electrical equivalent circuit.

Keywords: Coupled winding, Double quench, Transformer type SFCL, Peak fault current limiting operation

1. Introduction

Due to rapid industrial development, the electrical generation and supply demands have been increasing and make the power systems complex. This growth of electricity usage has made our power system have large fault current that can effect on power systems and electrical machines. To reduce the risks of electrical damages by large fault current, there are a few methods, for example, installation reactor, separation operation of complex power systems and so on. One of them, the superconducting fault current limiter (SFCL) has been one of the most promising protective equipment as countermeasures for large fault current. SFCLs which are made with superconductor have advantages such as:

SFCLs are invisible (no power losses) in the transmission line because superconductor has no resistance in normal state. And SFCLs can detect and limit fault current quickly within 1/4 period through superconductor's quench characteristic in case of fault [1-3].

There are many types of SFCL using high temperature superconductor (HTSC), like transformer type SFCL, flux-lock type SFCL, trigger type SFCL, and double quench SFCL. Each type SFCL has pros and cons. Among them double quench SFCL has characteristics such as:

1) It can divide power burden of HTSCs.
2) Twice Occurrence according to fault amplitude.
3) It can reduce power loss of SFCL due to heat

Another kind of SFCL, transformer type SFCL, has various characteristics. Unlike double quench SFCL, Transformer type SFCL has characteristics such as:

1) It can be controlled current through HTSC by Adjusting turn ratio
2) It is isolated with power system transmission line.
3) It can reduce power loss of SFCL due to heat

The transformer type SFCL and double quench SFCL has been studying because above reasons [4-7].

In this paper, we proposed a new structure transformer type SFCL with additionally coupled circuit. The proposed SFCL, which combines double quench SFCL and transformer type SFCL, has the second secondary winding (tertiary) connected to HTSC in series. Similar existing structure also has second secondary winding that is isolated with first secondary winding [8]. But the proposed SFCL in this paper has second secondary winding that is non-isolated with first secondary winding. Like the previously suggested SFCL, the proposed transformer type SFCL with additionally coupled circuit in this paper can perform the fault current peak cutting operation twice. The operations depend on amplitude of fault current because of its tertiary winding connected to second HTSC. The suggested SFCL can adjust operational current (I_{OP}), which controls the quench occurrence timing, for double quench characteristics.

In this paper, operation characteristics of transformer type SFCL with additionally coupled non-isolated circuit, like peak cutting operation, quench sequence and so on,

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Received: November 23, 2016; Accepted: August 5, 2017

were analyzed through equivalence circuit study and short circuit test.

2. Transformer Type SFCL with Additionally Coupled Circuit

2.1 Principles of transformer type SFCL with additionally coupled circuit

The circuit structure of the transformer type SFCL with additionally coupled circuit is shown in Fig. 1. The transformer type SFCL with additionally coupled circuit is composed of one primary winding and two secondary windings, which are non-isolated and wind on the same iron core as shown in Fig. 1. Primary winding is connected to power system in series and first secondary winding (N_2) and second secondary winding (N_3) are connected to HTSCs $(HTSC_1, HTSC_2)$ respectively in parallel. A distinction of the suggested SFCL structure is that it can alter the position of tertiary winding's dot (polarity) by changing second secondary winding direction or circuit.

The basic operational principle of the transformer type SFCL with additionally coupled circuit is similar with the previous SFCL, transformer type SFCL with two triggering current levels [8]. The first winding current (i_{N1}) flows without any limit because the flux in the iron coil is canceled by the interaction of the three winding in normal mode (without fault). When fault current exceeds the first operational current (I_{OP1}) by fault, which makes a HTSC to be a resistance component firstly, the SFCL starts to limit the fault current (i_{N1}) by one HTSC, because the flux in the iron coil cannot be canceled by the interaction of the three winding any more. In case that fault current exceeds the second operation current (I_{OP2}), which makes another HTSC to be the resistance component secondly, both HTSCs starts to limit the fault current together. Which HTSC is operated in advance is analyzed in this paper later.

2.2 Equivalent circuit configuration of SFCL

By ignoring the transformer's loss, the equivalent circuit of the suggested SFCL is obtained as shown in Fig. 2. Here, the suffixes N1, N2 and N3 of current I, and voltage V indicate the primary winding, first secondary winging and second secondary winging (tertiary winding). Also, the suffixes 1, 2 and 3 of self-inductance L indicate the primary winding, first secondary winging and second secondary winging. And the suffixes SC1 and SC2 of current I, voltage V and resistance R indicate HTSC1 and HTSC2 respectively. For simplicity, mutual-inductances are not written in Fig. 2. Also, it was assumed that coupling coefficient (k) was 1 and the resistances of three windings were ignored.

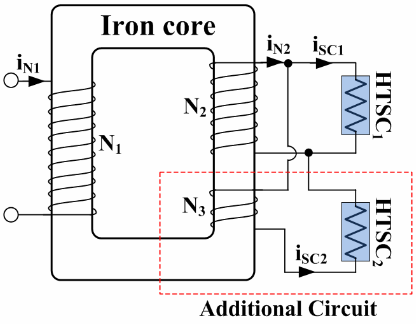

Fig. 1. Schematic configuration of the transformer type SFCL with additionally coupled circuit

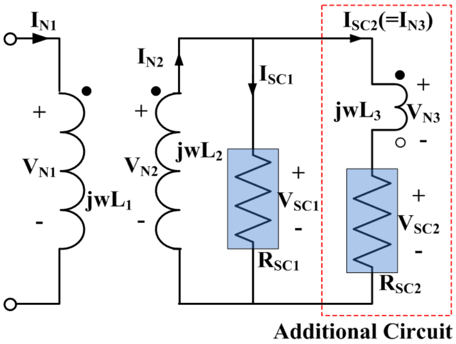

Fig. 2. Electrical equivalent circuit of the transformer type SFCL with additionally coupled circuit

According to polarity in the additional circuit, the electrical equivalent circuits of the transformer type SFCL with additionally coupled circuit were classified to two cases: SFCL with subtractive polarity circuit (filled dot) and SFCL with additive polarity circuit (empty dot) in Fig. 2. In this paper we analyzed the suggested SFCL according to three each case:

case 1: SFCL with subtractive polarity circuit (filled dot).
case 2: SFCL with additive polarity circuit (empty dot).
case 3: SFCL without additional circuit

About all equations in the paper, the double signs ($\pm$ or $\mp$) take in the same order, upper signs deal with case 1 and lower signs deal with case 2.

The impedance of SFCL which influences on the effect of fault current limiting is expressed in Eqs. (1) & (2) and upper suffixes indicate each case.

$$Z_{SFCL}^{case\,1\&2} = \frac{V_{N1}}{I_{N1}} = \frac{jwL_1 R_{SC1} R_{SC2}}{A} \tag{1}$$

$$Z_{SFCL}^{case3} = \frac{V_{N1}}{I_{N1}} = \frac{jwL_1 R_{SC1}}{R_{SC1} + jwL_2} \tag{2}$$

Here,

$$A = R_{SC1}R_{SC2} + jwL_2\left[R_{SC1}\left(1 \mp \sqrt{\frac{L_3}{L_2}}\right)^2 + R_{SC2}\right]$$

In Eq. (1), Z_{SFCL}^{case1} is bigger than Z_{SFCL}^{case2} due to the double signs inside A. From Eqs. (1) & (2), following expression are obtained.

$$\frac{Z_{SFCL}^{case3}}{Z_{SFCL}^{case1\&2}} = 1 + \frac{jwL_2 R_{SC1}\left(1 \mp \sqrt{\frac{L_3}{L_2}}\right)^2}{R_{SC2}(R_{SC1} + jwL_2)} \tag{3}$$

From Eq. (3), it can be clarified that Z_{SFCL}^{case3} is always larger than $Z_{SFCL}^{case1\&2}$. Therefore, SFCLs impedance can be derived:

$$Z_{SFCL}^{case3} > Z_{SFCL}^{case1} > Z_{SFCL}^{case2}$$

The fault current limiting ability of case 3 will be the best and the fault current limiting ability of case 2 will be the worst in cases.

For finding SFCL's operational currents (I_{OP1}, I_{OP2}), to know which HTSC will generate the resistance in advance is needed because the suggested SFCL has difference operational currents according to polarity of additional circuit (according to cases). The mathematically expressed equations of quench sequences can be derived as the Eq. (4). The Eq. (4), which compares scale of I_{SC1} and I_{SC2}, was derived in conditions that both HTSCs are in zero resistance. From the Eq. (4), the $HTSC_1$ will generate the resistance earlier than $HTSC_2$ because the I_{SC1} is always larger than I_{SC2} in case 1. On the other hand, the $HTSC_1$ will generate resistance later than $HTSC_2$ because the I_{SC1} is lower than I_{SC2} in case 2. Therefore, operations sequence of HTSCs is related with polarity of additional circuit and design of self-inductance, not just one.

$$\frac{I_{SC2}}{I_{SC1}} = 1 \mp \sqrt{\frac{L_3}{L_2}} \tag{4}$$

Through the mathematical calculation about equivalent circuit, Eqs. (5)-(9) about relationship of operational current (I_{OP1}, I_{OP2}) and primary current (I_{N1}) can be derived. Eqs. (5) & (6) are concerned about case 1, Eqs. (7) & (8) are concerned about case 2 and Eq. (9) is concerned about case 3.

In the Eqs. (5)-(9), I_{OP1} and I_{OP2} stand for first and second operational current, which are flowing through the primary winding (N_1) when first and second limiting operation are operated respectively. The expression I_C means the critical current (breaking up current from superconducting state to non-superconducting state). Generally, I_C is decided by the material of HTSC.

For example about case 1, $HTSC_1$ generates resistance in advance according to Eq. (4), the I_{OP1} is the primary winding current at the moment of $HTSC_1$'s quench(first limiting operation) and the I_C is the current passing the $HTSC_1$ at that time. The I_{OP2} is the primary winding current at the moment of $HTSC_2$'s quench (second limiting operation) and the I_C is the current passing the $HTSC_2$ at that time.

- Case 1

$$\frac{I_{OP1}}{I_C} = \frac{I_{N1}}{I_{SC1}} = \frac{L_2 + \left(\sqrt{L_2} - \sqrt{L_3}\right)^2}{\sqrt{L_1 L_2}} \tag{5}$$

$$\frac{I_{OP2}}{I_C} = \frac{I_{N1}}{I_{SC2}} = \frac{\sqrt{L_2} - \sqrt{L_3}}{\sqrt{L_1}} \tag{6}$$

- Case 2

$$\frac{I_{OP1}}{I_C} = \frac{I_{N1}}{I_{SC2}} = \frac{L_2 + \left(\sqrt{L_2} + \sqrt{L_3}\right)^2}{\sqrt{L_1 L_2} + \sqrt{L_1 L_3}} \tag{7}$$

$$\frac{I_{OP2}}{I_C} = \frac{I_{N1}}{I_{SC1}} = \frac{\sqrt{L_2}}{\sqrt{L_1}} \tag{8}$$

- Case 3

$$\frac{I_{OP1}}{I_C} = \frac{I_{N1}}{I_{SC1}} = \frac{\sqrt{L_2}}{\sqrt{L_1}} \tag{9}$$

From Eqs. (5) - (9), it is possible to get the values of operational current. To change the operational current criteria is possible by changing the self-inductances because the I_C is already known in design step.

To have large values of Eqs. (5) - (9) means that SFCL needs the large I_{N1} and needs more time for limiting operation.

$$I_{SC2} = \frac{\sqrt{L_1}(\sqrt{L_2} \mp \sqrt{L_3})}{R_{SC2}} V_{N2} \tag{10}$$

From the Eq. (10), it can be known that the direction of I_{SC2} will not be changed even if the self-inductances (L_2, L_3) are changed in case 2. On the other hand, the I_{SC2} will be able to change the flowing direction by changing the self-inductances (L_2, L_3) in case 1. This means that whether the polarity of second secondary winging is reversed or not (case 1 or case 2) does not matter to flowing direction of I_{SC2}.

The voltages of the HTSC elements (V_{SC1}, V_{SC2}) are concerned with the polarity of second secondary winging especially V_{SC2}.

$$V_{SC1} = V_{N2} \tag{11}$$

$$V_{SC2} = V_{N2} - V_{N3} \tag{12}$$

The voltages of the HTSC elements (V_{SC1}, V_{SC2}) are expressed by voltage of windings (V_{N2}, V_{N3}) in Eqs. (11) & (12). The V_{SC1} is always same with V_{N2} because they are connected in parallel. The V_{SC2} has low value relatively in case 1 because of the positive V_{N3}, and the V_{SC2} has large value relatively in case 2 because of the negative V_{N3}.

3. Experiments and Results

3.1 Experimental preparation

To confirm the suggested SFCL's characteristics and above theory, short-circuit test was performed. The detail design specifications for the transformer type SFCL with additionally coupled circuit are listed in Table 1. The transformer's windings using the suggested SFCL had the resistance and reactance respectively and we used the HTSC made of YBCO ($Y_1Ba_2Cu_3O_{7-X}$), which is commonly used for HTSC.

As shown in Fig. 3, the circuit for the short-circuit test consisted of 60-Hz AC power supply (E_{In}), a line impedance $\left(Z_{In}\right)$, a load impedance (R_L) and the SFCL. The circuit was activated or deactivated by closing or opening the SW_1, and by closing the SW_2 a fault (single line fault) at 0° occurred during 6 cycles. As mentioned, the primary winding of transformer type SFCL with additionally coupled circuit was connected with system in series. The detailed setting parameters for the short-circuit tests are listed in Table 2. In the short-circuit test, the voltage and current were measured by using the data acquisition device (DL750 ScopeCorder, YOKOGAWA).

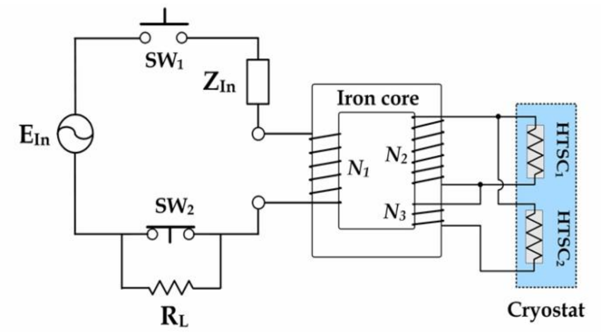

Fig. 3. Simple circuit diagram for short-circuit test

Table 1. The detail design specifications for the transformer type SFCL with additionally coupled circuit

Transformer winding	Value	Unit
L_1	38.874	mH
R_1	2.363	Ω
L_2	20.293	mH
R_2	1.305	Ω
L_3	1.295	mH
R_3	0.555	Ω
HTSC thin films	Value	Unit
Material	YBCO	-
Critical temperature	87	K
Critical current	27	A

Table 2. The setting parameters of the short-circuit test

Setting parameters	Value	Unit
60-Hz AC power supply (E_{In})	440	V
Line impedance(Z_{In})	$0.192 + j1.32$	Ω
Load resistance(R_L)	40	Ω
Fault angle	0	∘
Fault period	6	cycle

3.2 Experimental results and discussion

Fig. 4 shows the moments of transient part (from superconducting state to non-superconducting state) after fault occurred and shows the currents and voltages of the HTSCs and current passing the primary winding. Here, i_{N1}^{peak} is the maximum i_{N1} value of first period after fault current limiting operation.

In case 1 experiment with SFCL with subtractive polarity circuit (Fig. 4(a)), the $HTSC_1$ limited the fault current first. After $HTSC_1$ limiting, it needed more time (1.091 ms) for $HTSC_2$ to act as a fault current limiter (FCL). On the other hand, in case 2 experiment with SFCL with additive polarity circuit (Fig. 4(b)), the $HTSC_2$ limited the fault current first. After $HTSC_2$ limiting, it needed more time (1.174 ms) for $HTSC_1$ to act as a FCL.

In Fig. 4(a) & (b), it is shown that there were differences i_{SC1} and i_{SC2} according to Eq. (4). And it was also confirmed that operation sequences of HTSCs were made by this differences i_{SC1} and i_{SC2}.

In Fig. 4, the fault current limiting effect can be shown by comparing the i_{N1}^{peak} values. The i_{N1}^{peak} value in case 1 (Fig. 4(a)) was 44.14 [A], i_{N1}^{peak} value in case 2 (Fig. 4(b)) was 48.04 [A] and i_{N1}^{peak} value in case 3 (Fig. 4(c)) was 33.19 [A]. It is shown that the fault current was most limited by SFCL in case 3 and was least limited by SFCL in case 2. Therefore, it was clarified that the ability of fault current limiting is determined as confirmed in Eqs. (1)-(3).

Fig. 5 is shown the currents and voltages of the HTSCs and current passing the primary winding. Upper suffix W/O of current i indicates currents when the experiment was performed without SFCL.

In case 1 experiment SFCL with subtractive polarity circuit (Fig. 5(a)), three currents (i_{SC1}, i_{SC2}, i_{N1}) were going up right after the fault occurred. As currents passing the $HTSC_1$ and $HTSC_2$ (i_{SC1}, i_{SC2}) increased over the critical currents of the HTSCs, the HTSCs in the superconducting state were transferred to the non-superconducting state. In Fig. 5(a), it took 3.228 [ms] for the $HTSC_1$ element to be operated as the first fault current limiter. The voltage of the $HTSC_1$ (v_{SC1}) was larger than the voltage of the $HTSC_2$ (v_{SC2}) according to Eqs. (11) & (12).

In case 2 experiment with the SFCL with additive polarity circuit (Fig. 5(b)), three currents (i_{SC1}, i_{SC2}, i_{N1}) were going up right after the fault occurred. As i_{SC1} and i_{SC2} increased over the critical currents of HTSCs, the HTSCs in the superconducting state were turned to non-superconducting state. In Fig. 5(b), it took 38.099 [ms] for the $HTSC_2$ element to be operated as the first fault current limiter. The voltage of the $HTSC_1$ (v_{SC1}) were lower than the voltage of the $HTSC_2$ (v_{SC2}) according to Eqs. (11) & (12).

In Fig. 5(a) & (b), the v_{SC2} in case 2 was larger than the v_{SC2} in case 1, because the v_{SC2} in case 2 took responsible for the voltage summation of v_{N2} and v_{N3} alone in Eq. (12). On the other hand, the v_{SC2} in case 1 shared a responsibility for v_{N2} with second secondary winding. As taking high voltage like case 2 increases a risk of burning, many studies are needed for the installation.

In case 3 experiment with SFCL without additional circuit (Fig. 5(c)), two currents (i_{SC1}, i_{N1}) were going up right after the fault occurred. As i_{SC1} increased over the critical currents of the $HTSC_1$, the $HTSC_1$ in the superconducting state was turned to non-superconducting state. In Fig. 5(c), it took 2.33 [ms] for $HTSC_1$ element to be operated as the fault current limiter.

The value obtained by substituting the experimental parameters in Eq. (5) is 1.126, 1.482 and 0.723 for case 1,

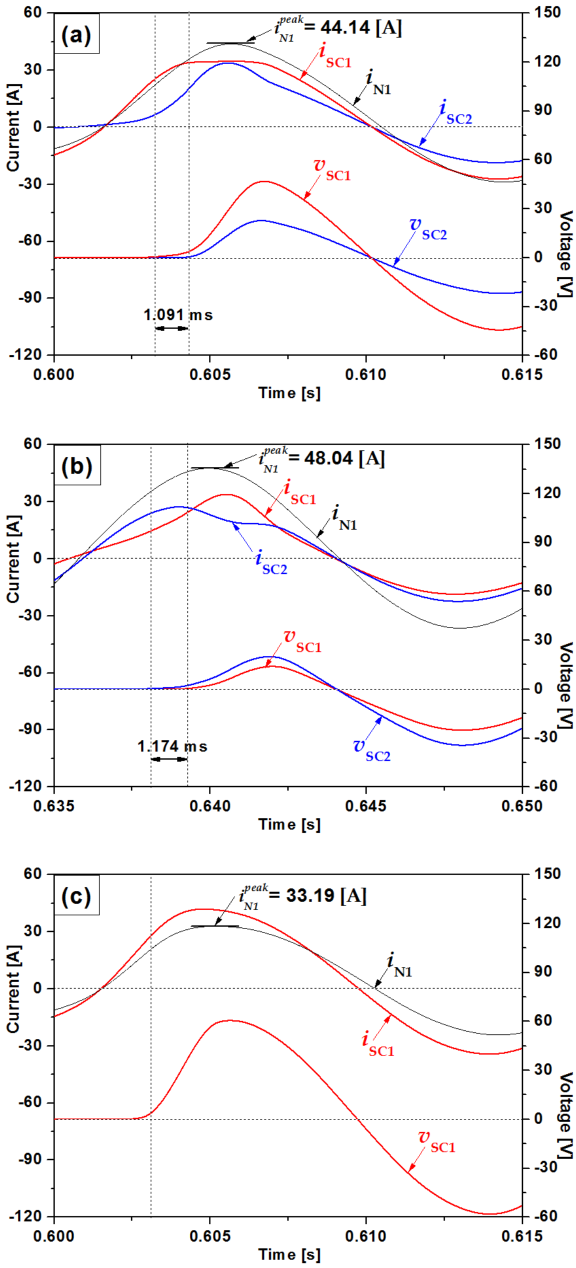

Fig. 4. Fault Current Limiting Sequence of HTSCs: (a) SFCL with subtractive polarity circuit (case 1); (b) SFCL with additive polarity circuit (case 2); (c) SFCL without additional circuit (case 3)

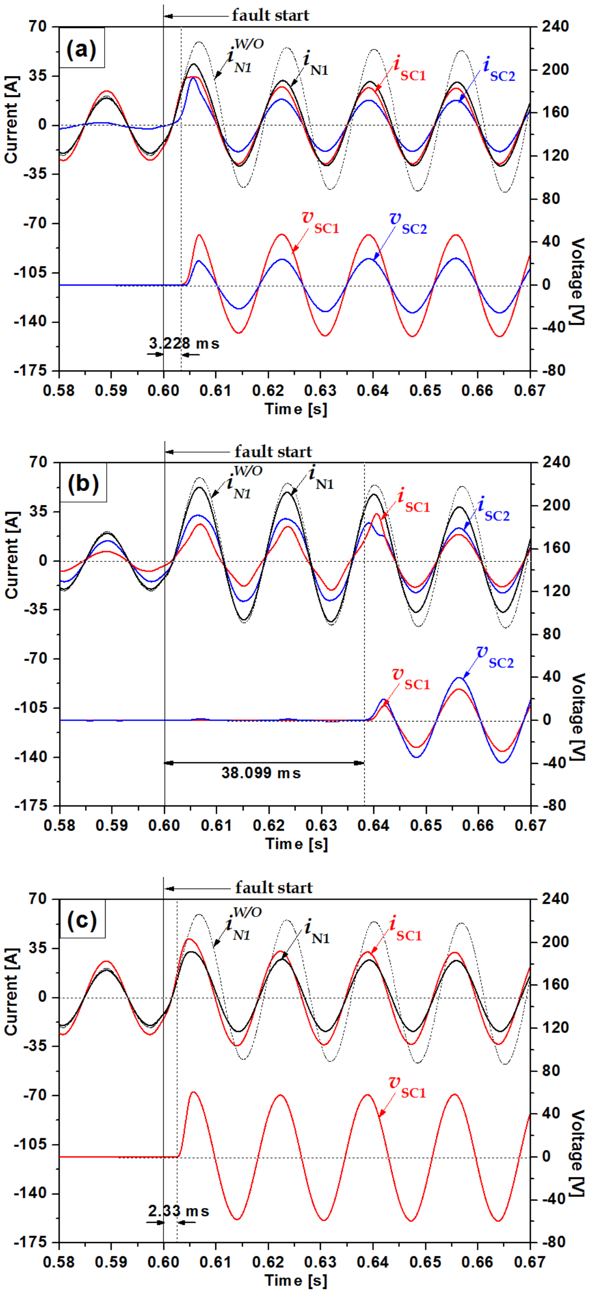

Fig. 5. Characteristics of transformer type SFCL with additionally coupled circuit: (a) SFCL with subtractive polarity circuit (case 1); (b) SFCL with additive polarity circuit (case 2); (c) SFCL without

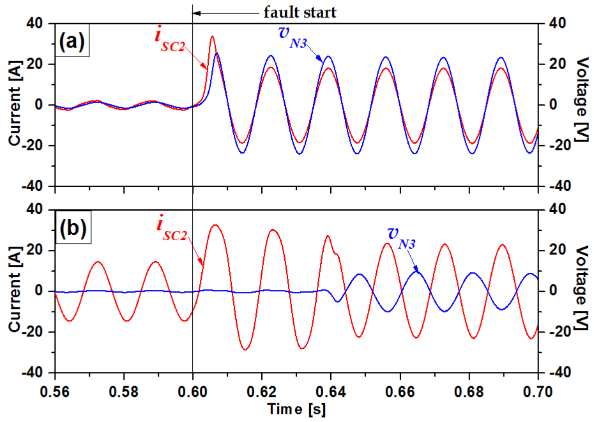

Fig. 6. Current passing the **HTSC**$_2$ ($\boldsymbol{i}_2$) and voltage of second secondary winding in additional circuit($\boldsymbol{v}_3$): (a) SFCL with subtractive polarity circuit (case 1); (b) SFCL with additive polarity circuit (case 2)

case 2 and case 3 respectively. Therefore, it was clarified that as the value of I_{OP1}/I_C is increasing it needs more time to operate the first limiting operation in Fig. 5.

Because the transformers are regarded as an inductance component in the grid, SFCL using the transformer has possibility of causing the phase shifting. The phase shifting due to using the proposed SFCL can be confirmed in Fig. 5. In Fig. 5(a) & (c), i_{N1} and $i_{N1}^{W/O}$ was almost in phase before SFCL acted as a FCL. After SFCL acted as a FCL, the i_{N1} led the $i_{N1}^{W/O}$. This fact means that the proposed SFCL scarcely affects to the phase shift in normal state, and affects to the phase shift when it works as a FCL.

On the other hand, in Fig. 5(b), as i_{N1} and $i_{N1}^{W/O}$ was almost in phase whether the SFCL acted as FCL or not, it is considered that the SFCL with additive polarity circuit scarcely affects to the phase shift.

It is easy to think instinctively that the direction of i_{SC2} will be changed by altering the additional circuits (case 1 & 2). However it was clarified from Eq. (10) that the direction of i_{SC2} is determined by self-inductances (L_2, L_3), not additional circuit.

The Fig. 6 shows the current passing the $HTSC_2$ (i_{SC2}) and voltage of second secondary winding in additional circuit (v_{N3}). In case 1, electrical equivalent circuit with subtractive polarity circuit (Fig. 6(a)), i_{SC2} and v_{N3} are in same phase. According to Eq. (10), it is reasonable these two waves were in same phase because short-circuit test was performed in conditions that the L_2 is bigger than L_3.

In case 2 that electrical equivalent circuit with additive polarity circuit (Fig. 6(b)), the phase of the i_{SC2} and v_{N3} were reserved after fault occurred because the phase of v_{N3} was reserved by changing the second secondary winding (from case 1 to case 2) but the phase of i_{SC2} was same with case 1.

Also, according to Eq. (10), it is reasonable that the phase of i_{SC2} was same with case 1 and these two waves (i_{SC2}, v_{N3}) had a phase difference of 180 degrees when the voltage polarity of second secondary winding (v_{N3}) was changed. It is because the phase of i_{SC2} is only concerned with self-inductance not structure of additional circuit.

4. Conclusion

In this paper, the transformer type SFCL with additionally coupled circuit was suggested. The operational currents through the equivalent circuit of the suggested SFCL were analyzed and its effective peak fault current limiting characteristics from the short-circuit test were confirmed.

The fact that impedance of SFCL without additional circuit (case 3) is always larger than the other SFCLs with additional circuit (case 1 & 2) regardless of transformer's winding was confirmed and abilities of fault current peak cutting are derived and confirmed. It was clarified that operational current related with the sequence of HTSC's quench is different and controllable according to structure of SFCL and self-inductances of windings.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MOE) (no. 2017R1D1A1B03036530).

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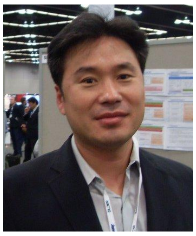

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