Test of 6 kVA 3-Phase Flux-Transfer Type Current-Limiting Transformer

E. Ertekin · S. Gecer · E. Yanmaz · S. Safran · J. Kosa · E.S. Kilicarslan · A. Kilic · N. Amemiya · A. Gencer

Abstract A 6 kVA 3-phase model of the flux-transfer type current-limiting transformer was developed and tested. In this device, the winding loops of YBCO superconducting tapes couple magnetically two independent iron cores: the primary-side iron core and the secondary-side iron core. The former and the latter are equipped with copper primary and secondary windings, respectively. Because the magnetic fluxes linked to the superconducting winding loops must be kept constant, the magnetic flux is transferred by the superconducting YBCO loops between the two iron cores in order to couple magnetically the primary and secondary coils. While the YBCO loops are superconducting, 100% of the magnetic flux is transferred, and the device shows the similar function as usual transformers. Once the YBCO loops become normal by a fault current in any of the windings, the power transfer between two iron cores is limited, and, the current in the secondary winding is limited naturally on a result of decoupling the iron cores.

Keywords Current-limiting transformer · Superconducting loops · Superconducting wire/tape.

1 Introduction

The fault current limitation has been a long standing topic of intensive research over the last decades for the possible applications of superconductors [1-4]. There are already a few of examples of various prototypes of superconducting fault current limiters installed in grids [1-5].

In this paper, we report on the development and test of a novel flux-transfer type current-limiting transformer, in which the current limiting function by using the normal transition of superconductor is integrated into a transformer with copper primary and secondary windings. The objective of this paper is the demonstration of the concept of this type of device and explore its possible use for the system protection.

In section II, we describe the concept of flux-transfer type current-limiting transformer and its advantages. In section III, we give an overview and measured characteristics of the developed 6 kVA 3-phase model. In section IV, experimental results and discussion are provided. Finally, section V brings our conclusion of the work accomplished.

2 Concept of Flux-Transfer Type Current-Limiting Transformer

A usual transformer has an iron core, on which the primary and secondary coils are wound. Meanwhile, a flux-transfer type current-limiting transformer has two independent iron cores (the primary-side (P-S) and secondary-side (S-S) iron cores), which are coupled magnetically by the loops / windings of YBCO superconducting tapes as shown in Fig. 1. The P-S and S-S iron cores are equipped with copper primary and secondary windings, respectively.

Because the magnetic flux linked with superconducting loops / windings must be kept constant, the change in the magnetic flux in the P-S iron core should equal to the change in the magnetic flux in the S-S iron core. Therefore, the primary and secondary coils wound on the independent iron cores behave so that they are wound on an iron core as long as the YBCO loops/windings are in a fully superconducting state.

When a large fault current in the primary or secondary coils lead to the normal transition (quench) of the YBCO loops / windings, two iron cores are decoupled/weakly coupled. As the consequence, lower power is transferred from the primary circuit to the secondary circuit to some extent, and then, the secondary circuit can be protected as a result of decoupling.

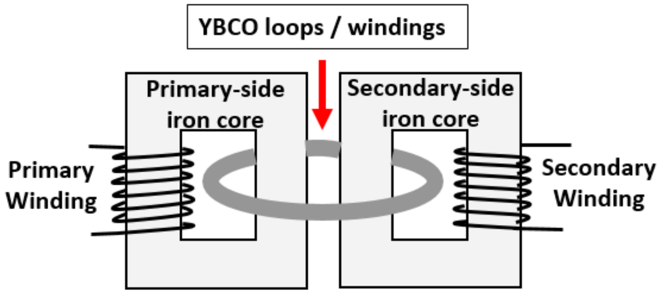

Fig. 1 Concept of the flux-transfer type current-limiting transformer.

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In the most of resistive type fault current limiters and superconducting transformers with current-limiting function using YBCO tapes, current-limiting windings consist of an HTS tape or an assembly of HTS tapes whose critical current is the same as the trigger level current in a grid. In our configuration, a YBCO tape with an arbitary critical current can be used by adjusting the number of turns of YBCO loops / windings for a specific case. As compared to the usual superconducting transformers with current-limiting function [1-7], the required length of expensive YBCO tapes can be reduced because of not using YBCO tapes in the main windings, and the size of the cryostat and the cooling power can be reduced, too. Meanwhile, one likely drawback of the device is lower efficiency because of the use of copper primary and secondary windings in addition to an air core.

3 Overview of Developed 6 kVA 3-phase Model

Specifications of the developed 6 kVA 3-phase model are listed in Table I, and its schematic cross section is shown in Fig. 2, together Table II which shows the explanation of the numbers in the figure.

For the winding loops of YBCO tapes, we used slitted wide YBCO tape without any resistive joint (Fig. 3(a)) and a loop of YBCO tape whose two ends are connected with each other by using OFHC copper terminals (Fig. 3(b)).

Table 1 Specifications of the Transformer

Parameters	Data
Capacity	6 kVA
Number of phases	3
Maximum mic flux density in iron cores	1.7 Tesla
Primary voltage	220 Vrms
Secondary voltage	117 Vrms
Number of turns of primary winding	150
Number of turns of each secondary winding	80
Connection of windings	Star / Star

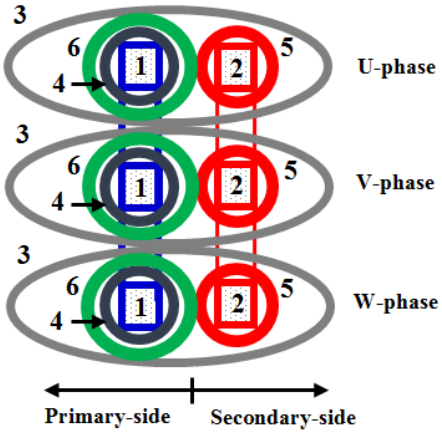

Fig. 2 Schematic cross section of the developed 6 kVA 3-phase model.

Table 2 Explanation of the notation in Fig. 2

Notation	Explanation
1	Primary-side (P-S) iron core (Blue, with three limbs)
2	Secondary-side (S-S) iron core (Red, with three limbs)
3	Closed loops of YBCO tapes (Grey)
4	Primary copper windings (Black)
5	Secondary copper windings (Red)
6	Reference secondary copper windings (Green)

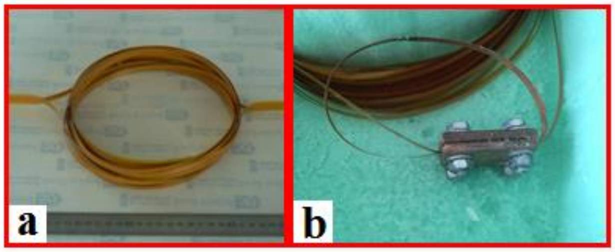

Fig. 3 Two types of closed loops of YBCO tapes: **(a)** slitted wide YBCO tape without any resistive joint; **(b)** Loops with jointed copper terminals.

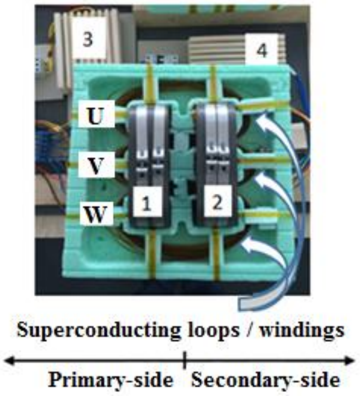

Fig. 4 A top-view photograph of the experimental set up.

Table 3 Explanation of the notation in Fig. 4

Notation	Explanation
1	P-S iron core (with three limbs, primary windings and reference secondary windings)
2	Secondary-side iron core (with three limbs and secondary windings)
3	Load in the primary circuit
4	Load on the secondary circuit
U / V / W	Three phases of the set-up respectively

The P-S iron core is equipped with an additional reference secondary coil whose number of turns is the same as that of the secondary coil on the secondary-side iron core. In order to prove the 100% transfer of magnetic flux between two iron cores by the superconducting loops, the electrical characteristics of the two secondary coils are compared with each other.

Fig. 4 shows a photograph of the experimental set-up. In Table III, we explain the notations used in Fig. 4.

It is required to have a low impedance for higher efficiency of the transformer [5-7]. Special care was applied in winding of the copper coils on the iron cores on both sides in accordance with some considerations published in [5].

4 Results and Discussion

All the experimental results in this paper were obtained for 50 Hz ac operations.

4.1 Drop measurements

Since the transformer power is designed as 2 kVA for each phase, the nominal current is 9.1 A for 220 V of the supplied voltage. We measured the short circuit voltages on both primary and secondary sides when the current reaches at the nominal value of 9.1 A. We determined the drops for the primary and secondary sides as 2.63% and 36% respectively, by using Eq. (1). The secondary side shows a much larger drop as calculated.

A resulting increased drop on the secondary side would be very useful in the case of higher power transformers.

$$\varepsilon = \frac{V_{\text{shortcircuit}}}{V_{\text{nominal}}} \cdot 100\% \tag{1}$$

In our experiment, the fault current was determined as follows:

$$I_{\text{fault current}} = \frac{1}{\varepsilon} \cdot I_{\text{nominal}} \tag{2}$$

The determined $I_{\text{fault current}}$ are 345.2 A and 25.27 A respectively.

4.2 Decoupling primary and secondary sides by normal transition of YBCO loops

If the secondary current in the S-S becomes higher (for example, in the case of short circuit) than the trigger level current of the protection, the superconducting current in YBCO tapes will increase to reach to the quench state, then the superconducting coupling between primary and secondary sides breaks.

On the other hand, the primary voltage is gradually increased, the superconducting YBCO loops / windings also goes to the normal state because of quenching. The quench breaks the coupling between primary and secondary sides as experimentally shown in Fig.5 at a frequency of 50 Hz. The result in Fig.5 has been obtained for a single phase transformer to demonstrate the quenching of a three-turn closed loops of YBCO tapes without resistive joint [see more details in ref. 8]. This functionality of the superconductive property has a promising potential to be used in an electrical protective system of a grid. Note that the secondary voltage is substantially reduced as a result of the quench, but not to zero. Because some metallic layers in the coated conductor contribute to the partial coupling even after the quench.

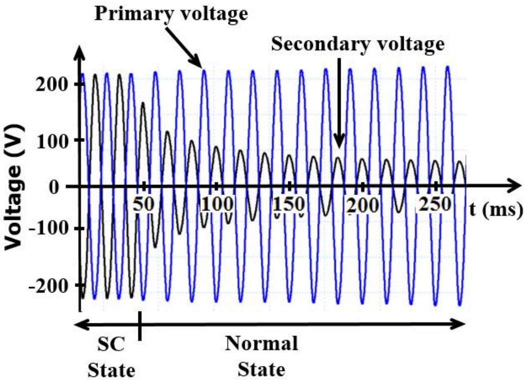

Fig. 5 The change of coupling between primary and secondary sides because of superconductor to normal state transition in the superconducting windings. Voltage drop in the S-S first occurs suddenly then becomes gradually decreased, while the current in the superconducting loop exceeds the critical current, as a result of the quench in the loop. However, the voltage drop does not reach to zero because of the metal conducting layers of 2G coated conductor as explained before.

Fig. 6 and Fig. 7 show the measured voltages on the primary and secondary sides for the set-up of Fig.4 without any load, respectively. The optimized number of turns for primary and secondary coils ensures a strong coupling being observed, and this results in almost identical induced voltages on both sides in magnitude with 180 degrees phase shift.

In addition, Fig. 8 shows the currents of primary and secondary circuits with identical loads on both sides. It can be seen that, the primary and secondary sides, such as 10.5 Arms, have the same current values with 180° phase shift. We note that the same number of turns were wound on both secondary coils.

When a short circuit applied artificially on the secondary coils to mimic fault conditions, the current on the secondary coil of the secondary side initially tends to increase and then immediately becomes limited within a few periods and the current reduces to a smaller value. The short of the secondary circuit does not influence the operational current in the reference secondary winding on the P-S iron core (in red) as shown in Fig. 9. In Fig.9, the green cycle is the measured secondary voltage. The inset in Fig.9 shows the same measurement on a much longer time-scale.

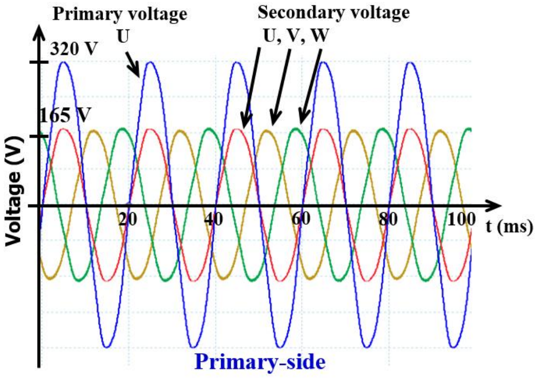

Fig. 6 Voltages of reference secondary windings on P-S iron core without load. YBCO loops with joints were used.

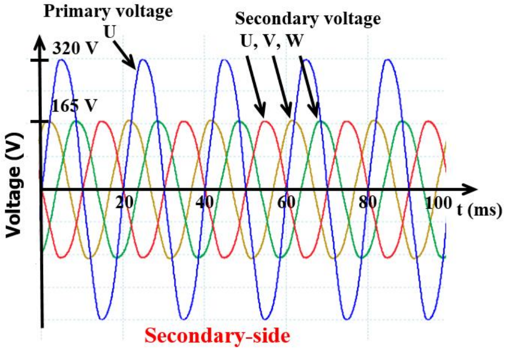

Fig. 7 Voltages of secondary windings on S-S iron core without load. YBCO loops with joints were used.

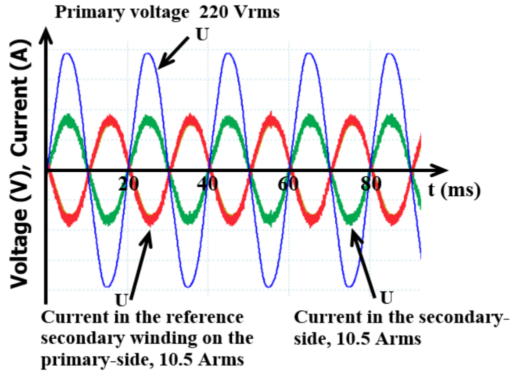

Fig. 8 Current in secondary winding on S-S iron core and that in reference secondary winding on P-S iron core, together with primary voltage. YBCO loops with joints were used.

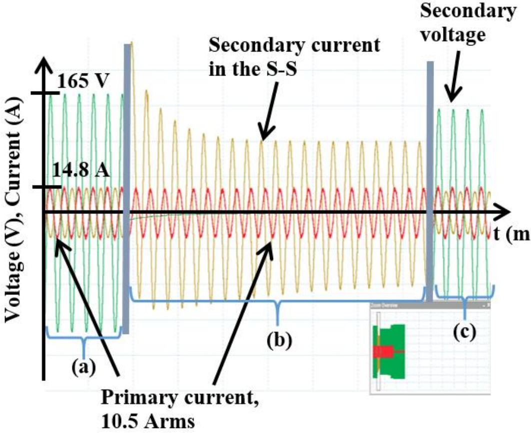

Fig. 9 **(a)** Yellow is the secondary current before shorting the load. Green is the secondary voltage on the S-S. Red is the primary current. **(b)** Yellow is the secondary current during shorting the load. Red is the primary current. **(c)** Yellow is the secondary current after shorting the load. Green is the secondary voltage. Red is the primary current.

In Fig. 9, the short circuit introduced artificially, at a calculated value of 27.3 Arms for a specific case, as experimentally observed to be approximately 3x$I_{nominal}$. This reduced short circuit current can then be removed by the conventional protection by a possible use of a circuit breaker after 4-5 periods (80-100 ms). As a conclusion, this type of a transformer can be very important for setting the conventional protection in an energy system. Space limits discussion to an only case of practical example, implications of the artificial load will be made to mimic the case of actual application in a grid and further results will be given elsewhere.

5 Conclusion

In summary, a 6 kVA 3-phase model of the flux-transfer type current-limiting transformer has been successfully developed. The sufficient magnetic coupling between the primary-side and secondary-side iron cores, on each of which the primary coil and the secondary coil was wound and confirmed experimentally. By applying a fault condition into the secondary coil by shorting the artificial load, the YBCO loops have become normal (quenched), and, then, the current in the secondary circuit was limited successfully within 3-4 periods of ac current. In addition a fault of more than 1 s, superconducting wire and the transformer could operate continuously without any damage. On the S-S, the fault energy is much lowered compared to the P-S. Therefore, substantially reduced energy can be transferred to the fault place which may be more useful with less risk in areas sensitive to potential hazards. It may also be possible that, circuit breaker lifetimes can be extended if a scale-up can be made possible for potential applications in the grid. Furthermore, use of expensive YBCO coated conductors can be reduced to have lower initial costs of such a system applicable in the grid protection. On the other hand, lower powered cooling system may become more advantageous for a system proposed. We have shown that a transformer with 2 iron cores coupled/decoupled by use of superconducting properties of YBCO loops / windings can have a successful function of fault current limitation.

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