Switching and Decoupling Effects in a Single-Phase Transformer Using Extra DC Current

S. Gecer, E. Ertekin, E. Yanmaz, J. Kosa, S. Safran, R. Özgüzel, E. S. Kilicarslan, A. Kilic, and A. Gencer

***Abstract*—A single-phase current-limiting transformer has been developed based on flux transfer. The transformer consists of two independent iron cores, one primary coil, two separate secondary coils, and superconducting windings/loops. Two iron cores are in a mechanical contact and clamped. Superconducting windings/loops act as coupling/decoupling mechanism between two iron cores. The transformer has been made operational via a switchgear of the applied dc current for a potential use in the current limitation when the transition between the superconducting and normal (quench) states can be triggered. DC and ac currents can be applied simultaneously in fault and no-fault conditions to mimic the realistic cases of use. With decoupling ac energy transfer, we propose that conventional switching off may be replaced with the approach described.**

***Index Terms*—Self-limiting transformer, superconducting coils, superconducting transformer, superconducting wire.**

I. Introduction

It is worth nothing that, existing world-wide efforts of many research groups on REBCO transformers with current limiting functionalities have already resulted in some fruitful prototypes of self-limiting transformers for use as Superconducting Fault Current Limiters (SFCL) [1]–[5]. Significant achievements have been already made by applying YBCO wire in the case of self-limiting transformers for use as examples in refs. [6]–[10]. In the previous work, submitted to this issue, a hybrid transformer has been reported with promising features for the fault current limitation titled as “Test of 6 kVA 3-Phase Flux-Transfer Type Current-Limiting Transformer” [11].

In this paper, we focus on a single-phase transformer with the use of an adjustable extra DC current in addition to the induced AC current both affecting on the coupling mechanism. The extra DC current can be facilitated to trigger transition between superconducting and normal (quench) states of the YBCO windings/loops. This proposed method appears to provide some advantages for potential applications in the power systems.

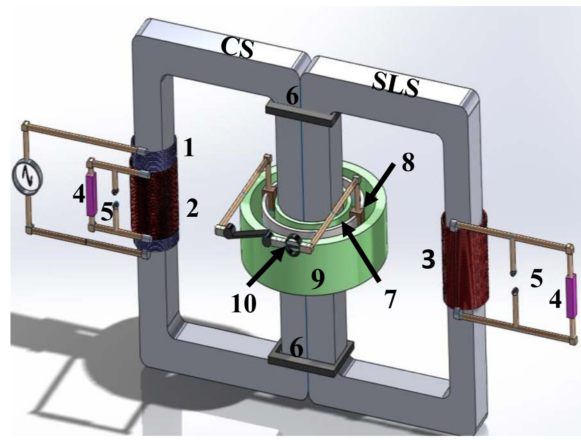

Fig. 1. Scheme of the arrangement of a self-limiting transformer using magnetic flux transfer: 1–primary coil; 2–secondary coil on CS; 3–secondary coil on SLS; 4–load; 5–short-circuit ports; 6–clamp; 7–superconducting loops; 8–mechanical contact; 9–LN2 container; 10–DC power supply.

In Fig. 1, a schematic representation of single-phase self-limiting transformer using magnetic flux transfer is given. Left hand side is called “Conventional Side (CS)” while right hand side is called “Self-Limiting (SLS)”. In the middle, the superconducting windings/loops are immersed in liquid nitrogen and are supposed to act as coupling/decoupling mechanism for flux transfer from primary coil to secondary coil on SLS.

The current in the superconducting windings/loops depends on the many parameters of arrangement (for example, primary and secondary currents, reluctance of iron cores, number of turns of the primary and secondary coils, operating temperature, etc.). It can be expected in this system that if the current of the superconductor windings/loops increases beyond the critical current, then the coupling between the primary and secondary coil on SLS is broken, which leads to the voltage drop in the secondary coil. This is called de-coupling between primary and secondary coil on SLS because it is able to cut off coupling between both sides. This can happen even when the primary voltage is increasing and even if the secondary side is not-loaded. The key point is that the flux subjecting to superconducting windings/loops can cause a quench. This actual property of a superconducting loop can be an important advantage when united with two separate limbs of iron cores associated with primary and secondary coil on SLS for potential use as a fault current limitation in a system to be protected. In this work, we developed a 2.5 kVA single-phase self-limiting

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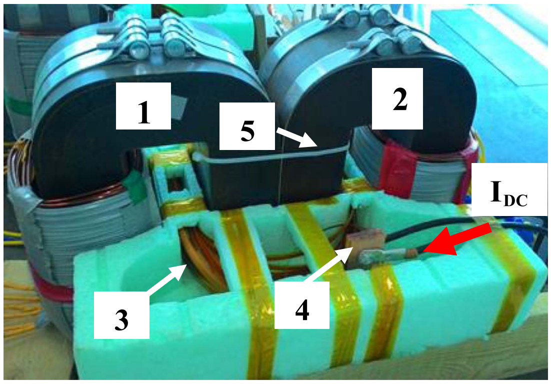

Fig. 2. Photo of the transformer top view.

transformer with a controllable extra DC current in the superconductor windings/loops in relation to the coupling between the voltages and currents of the primary and secondary coils.

II. The Method in the Construction

DC current can bring an additional functionality of switching off energy transfer and flux linkage between primary and secondary coils. With a controllable coupling/decoupling AC energy transfer, the conventional switching off may be replaced with this proposition.

Fig. 1 shows the arrangement of methodology in a schematic way for a single ring with no provision of external DC current. In the state with no DC current applied, it is only a typical self-limiting transformer with flux transfer at nominal voltage in the secondary coil given by the usual equation

$$V_S \cong \frac{N_S}{N_P} V_P. \tag{1}$$

Here V_S is secondary voltage; N_s is number of turns on secondary coil; V_P is primary voltage and N_p is number of turns on primary coil.

If we are to stop energy transfer for some reason, the DC current is switched and this leads to an increase to exceed the critical current of the ring at a given temperature, current and self-field. Note that quench state implies a transition from superconducting state to normal state. At the quench conditions, the superconducting coupling is broken leading to the secondary voltage dropping to a vanishingly small value. Remaining coupling is only associated with metallic coatings of the superconducting CC

$$V_S \cong 0. \tag{2}$$

With the provision of the DC current externally, the conventional protection can be reached with a smaller induced current in excess of I_c in the superconducting ring. In Fig. 2, we can see a photograph of the transformer at the top-view (see Table I for the notation). 3 pieces YBCO windings/loops joint in parallel in vertical direction. The superconducting windings/loops are used for

1) Coupling between the primary and secondary iron cores to provide electrical energy transfer from the CS to the SLS.

TABLE I
Explanation of the Notation in Fig. 2

Notation	Explanation
1	Conventional side
2	Self-limiting side
3	Superconducting loops
4	Mechanical contact
5	Mechanical clamp

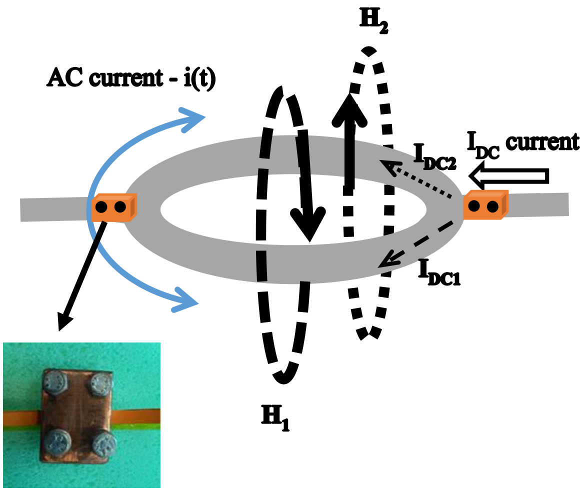

Fig. 3. Schematic of superconducting windings/loops connected to dc power supply via copper mechanical clamp. The current is supposed to be divided into two segments, which produces self-magnetic field. Ideally, the self-flux inside the loop is supposed to be zero in a way to cancel each other. The inset at the bottom left shown is the photo of the mechanical OFHC copper clamp.

2) The YBCO windings/loops break the coupling between the iron cores when the critical current is exceeded as a result of a fault either on the CS or on the SLS.
3) If the coupling is be broken without any fault in the system, it can be made by an extra DC current.

The DC current ideally does not affect the constancy of the flux in the loop, because the extra DC current branches into two parts and the magnetic field of these currents oppose each other inside the loop (see Fig. 3). Ideally, when two branches of the loop are made identical, i.e., both branches have the same inductance and associated flux creep/flow resistivity, magnetic fields of these two branches can cancel each other inside the loop. Hence, the magnetic flux inside loop does not change. Therefore, this additional DC current is not expected to have any influence for the AC energy transfer, on the condition that quench conditions are absent. However, when quench conditions are arrived, energy transfer is minimized. The DC current applied and the induced AC current at the same time can produce the expected quench current in superconductor to give rise to the decoupling effects

$$I_{\mathrm{DC}} = I_{\mathrm{DC1}} + I_{\mathrm{DC2}} \tag{3}$$

$$I_{\mathrm{DC1}} + I_{\mathrm{peak}} > I_{\mathrm{quench}} \text{ or} \tag{4}$$

$$I_{\mathrm{DC2}} + I_{\mathrm{peak}} > I_{\mathrm{quench}}. \tag{5}$$

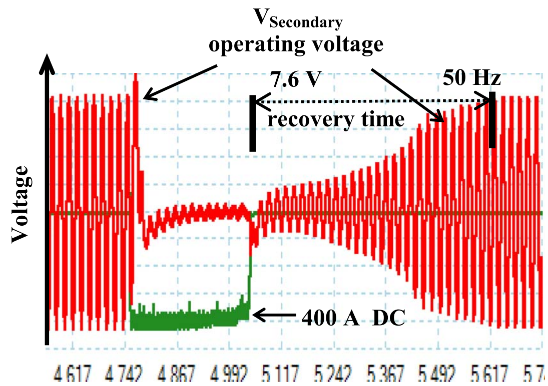

Fig. 4. Voltage of the secondary coil on SLS.

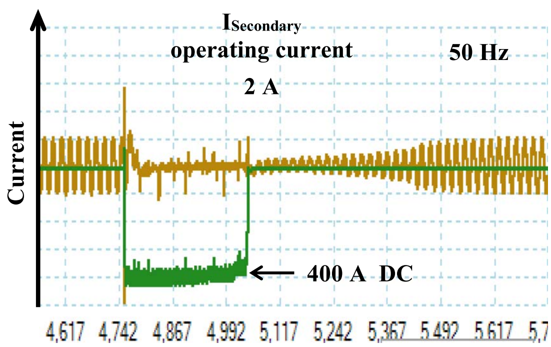

Fig. 5. Current of the secondary coil on SLS.

At these given conditions of equations (4) and (5), the coupling can break between the CS and the SLS.

In Fig. 3 we can see the schematic representation of the magnetic field of the extra DC current. The applied superconducting YBCO coated conductor used for the construction is a commercial SF 12050 closed loop in parallel connection with three loops. For each loop a single piece of tape that was cut in the middle, resulting in a single loop without mechanical junction. This was initial measurements and not repeated for the measurements and reported in this paper. This is to show working principle of the transformer.

III. Measurements

A. Initial Experimental Results

The arrangement has already been given as photo in Fig. 2. The voltage and current of the secondary coil on SLS are shown experimentally can be seen in Figs. 4 and 5 in the case of a load of 2.5 kVA.

In this experiment, operating voltage was 7.6 V (at peak) with operating current of 2 A (RMS). During the operation, an extra DC current of 400 A was applied using the mechanical contacts to the superconducting windings/loops. This can be seen at 4.742 s, in a period of 20 ms, the voltage drops very sharply to a diminishing value (Fig. 4).

A similar drastically drop is observed for the current in Fig. 5. When DC current is switched off, the voltage starts to increase and recovery time is also shown to be measured as around 697 ms.

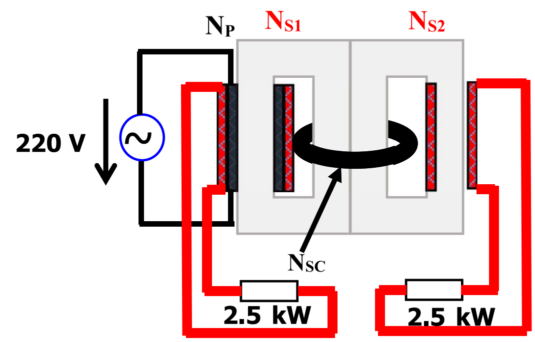

Fig. 6. Schematic of the arrangement for the transformer.

TABLE II
Interpretation of the Parameters

Parameters	Interpretation
N_P	Primary number of turns (115)
N_{S1}	Secondary number of turns on CS (115)
N_{S2}	Secondary number of turns on SLS (125)
N_{SC}	Number of superconducting turns (45)

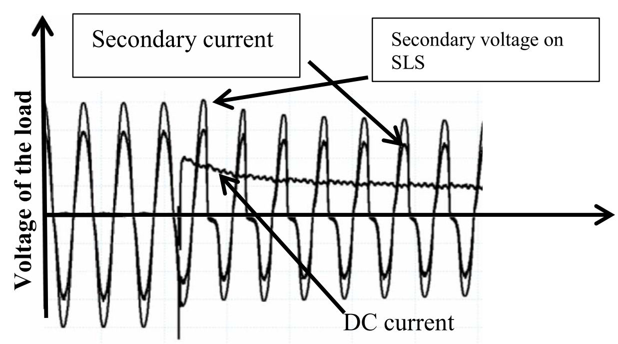

Fig. 7. Moment of the switching of DC current.

B. Operation of a 2.5 kVA Transformer via Flux Transfer and Extra DC Current

The hybrid transformer is shown in Fig. 6 as a complimentary for further explanation to Fig. 1 (see Table II for the interpretation of the parameters). This arrangement has a 5 kVA transformer with a 2.5 kVA self-limiting function on SLS and 2.5 kVA on CS. Both sides can give maximum 2.5 kVA power. The cross-sections are the same and that the transformer using by flux transfer poses more advantages. For example, the flux-transfer increases the drop of the SLS, fast working, decouples CS and SLS.

In the experiments, we tested this single-phase system and examined the effect of DC current in the superconducting windings/loops. The applied loop was SCS 4050 type in contradiction to first experiment when we used SF 12050 type and we did not use perfect closed loop. Fig. 7 shows the moment of the switching of DC.

We can see the secondary voltage and secondary current on SLS and the switching DC current. Note that, secondary voltage

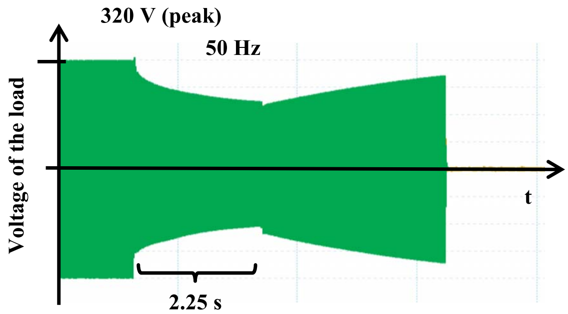

Fig. 8. Secondary voltage in the self-limiting side.

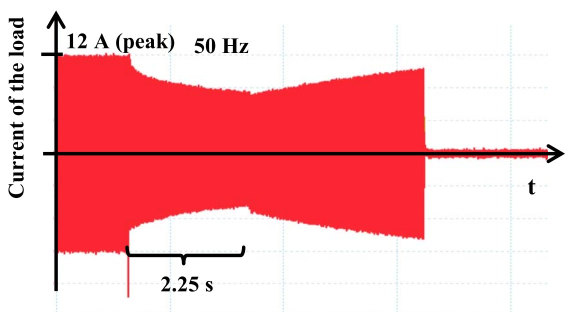

Fig. 9. Secondary current in the self-limiting side.

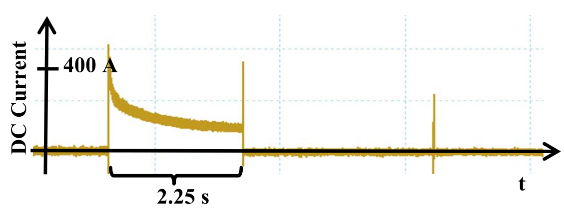

Fig. 10. Secondary current in the self-limiting side.

sustains the wave form before switching DC current. As soon as DC current applied, the voltage drops in a few periods as shown in Fig. 7.

Fig. 8 shows the graph of the secondary voltage on SLS. Primary voltage and secondary voltage were 225 V RMS. Additional 10 turns were added on secondary coil (SLS) to compensate the missing coupling. This was experimentally verified number of turns. Operational power was 1.9 kW at $f = 50$ Hz. The current (because there is load) of the secondary coil on SLS can be seen in Fig. 9. Fig. 10 shows the DC switching current. It is evident that DC current of 400 A is good enough to make a quench in the superconducting windings/loops and the decoupling is observed with decaying current during fault conditions of 2.25 s in Figs. 8–10.

IV. Conclusion

We have shown that applied extra DC current for decoupling in the case of self-limiting transformer using magnetic flux transfer has worked. The switch off the electrical energy between CS and SLS with favorable conditions are observed. In the case of higher power, a circuit breaker could be used with a reduced current at desirable conditions. This arrangement gives a possibility to control the quench current in the superconducting windings/loops. Once the conditions are satisfied with a robust cooling system and higher efficiencies achieved, the proposed transformer could be potentially usable for actual protection part of the system as a fault current limiter. Further study with larger power, robust cooling system and auto electronics are planning to be developed, which will be presented elsewhere.

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