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Application Possibilities with Continuous YBCO Loops Made of HTS Wire

J. Kosa[1], **I. Vajda**[2], **A. Gyore**[2]
[1] Kecskemet College, Fac. of Mech. Engineering and Automation, Kecskemet, Hungary
[2] Budapest University of Technology and Economics, Department of Electric Power Engineering, Budapest, Hungary

E-mail: kosa.janos@gamf.kefo.hu

Abstract. In our previous experiments we have produced YBCO rings machined from bulks for superconducting applications. In this work we examine the arrangement of the continuous superconducting loop made of HTS wire for advanced applications. A Korean group of researchers led by Hee-Gyoun Lee produced 100% BSCCO loops from tape for the first time in 2006 [1]. In our solutions we use parallel and serial turns from perfect YBCO loops made from HTS wire. Production of multi-serial turns is not the same as the "wind and flip" [1] method. In our case the twisting of the YBCO wire along its longitudinal axis can be avoided. We check the quality of the perfect YBCO loops with the transformation of the DC magnetic field [2]. In the case of the AC application we describe a new arrangement of the self-limiting transformer with using these loops. This self-limiting transformer can be a voltage or current restricting system. The paper presents the results of our experiments and opens new advanced applications of perfect YBCO loops made of HTS wire focusing on the efficiency and importance of the Korean team in creating the perfect closed loop.

1. Introduction

There is a growing demand for the application of superconductor rings to ensure permanent magnetic field for MRI, NMR and magnetic separation applications using YBCO loops. In the case of greater bulk rings BSCCO has been used so far. The size of YBCO bulks is restricted due to the production technology. In the case of closed loops 1G technology does not result in creating perfect superconductor connection. The 2G technology of the wire made it possible to produce perfect YBCO loops from HTS wire. A Korean group of researchers led by Hee-Gyoun Lee produced 100% coated loops from tape for the first time in 2006 [1]. Afterwards, on 28 August 2008 Gye-Won Hong and Hee-Gyoun Lee introduced "wind and flip" method as a patent [3]. Another group of Korean researchers led by Woo-Seok Kim also published the production possibilities of 100% YBCO loops from tape in 2009 [4]. The ideas described by him are really original, however, we decided to change the technology of cutting, because we think that this material can only be exposed to shear due to its layered structure as its structure gets the least damaged this way. Cutting with diamond wheel wears

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[1] Kecskemet College, Kecskemet, Izsaki ut 10. Hungary 6000.
[2] Budapest University of Technology and Economics, Department of Electric Power Engineering, Budapest, Egry Jozsef u. 18. Hungary 1111

the material abrasively causing loss of material and it can considerably lessen the value of the critical current. We developed a model of the new self-limiting transformer with continuous superconducting loop made of HTS wire.

2. Background to creating the new type self-limiting transformer containing continuous superconductor loops

2.1. Producing the continuous superconductor loops

We have modified the technology described by the Korean group of researchers led by Hee-Gyoun Lee [1] and by another Korean group of researchers led by Woo-Seok Kim [4]. Cutting with diamond wheel causes loss of material as wears the material abrasively, so it considerably reduces the value of the critical current. As the material is of layered structure, we used an industrial blade of appropriate thickness to slit the tape on a plastic sheet. In the case of a longer cut we applied the shearing force of scissors on the tape already slit with blade. This solution is considered just a temporary solution until producers elaborate the 100% superconductor joint as a routine.

- Type of blade No. 13610 INOX, MARTOR-Solingen, Germany.
- The superconductor wire (2G HTS wire) was produced at SuperPower, Inc. in New York, USA. Type: SF 12050.

Our opinion is that SF 12050 is perfectly suitable for the realization of the task we have carried out.
From one basic loop we can made serial loops when we slip them through each other. In these solutions we use parallel and serial turns without twisting. In our case coiling was made with slipping as it can be seen in Figure 1. Its advantage is over "wind and flip" solution is that there is no twist along its longitudinal axis that could be the source for cracks of the YBCO layer at operating temperature, i.e. 77 K or at a lower temperature. Figure 1 shows the photographs of a five-turn serial loop.

Figure 1. Side-view of five-turn serial loop.

2.2. DC flux transformer

Orlando and Delin described a DC flux transformer with two coils in their book [5]. We have also developed the transformation of the DC magnetic field with different solution [2]. Our DC flux transformer is implemented by using only one YBCO ring. So it gives possibilities for the realization of novel industrial applications. The operation is based on well-known physical laws but so far not applied yet in this manner. The possibility of applications is based on the principle of conservation of the magnetic flux in a closed loop ideally. First we used YBCO superconducting rings from bulk. The applied YBCO rings were drilled within some minutes with a new technology we had elaborated [6].

The quality of the drilled YBCO bulks and rings and the precision of the fitting of the YBCO rings joined together can be deduced with a new elaborated method [7]. Figure 2 shows the experimental scheme of the DC magnetic field. During the experiment between two independent iron cores we provide coupling of flux with superconductor ring. This is an efficient application of flux conservation.

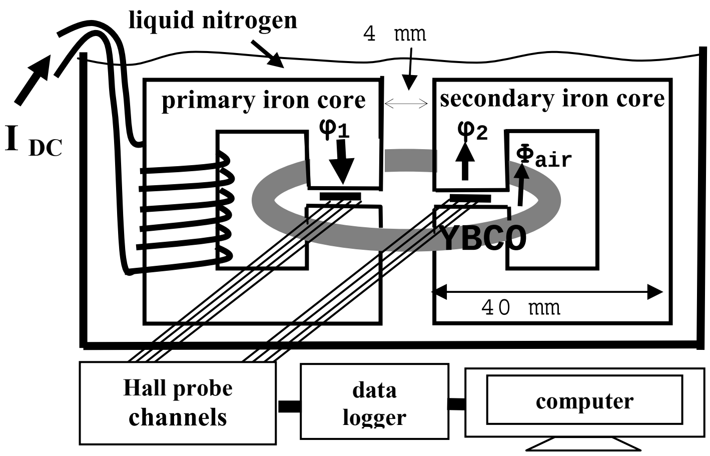

Figure 2. The experimental scheme of the DC magnetic field.

During the experiment we excited the primary iron core with DC current and measured the value of flux related to time on both iron cores. It can be seen in Figure 3 that the flux changes in the opposite direction within the closed loops in the primary and secondary iron cores and, as a superconductor ring was used for coupling, flux conservation was efficient for a longer time (2,000 sec).

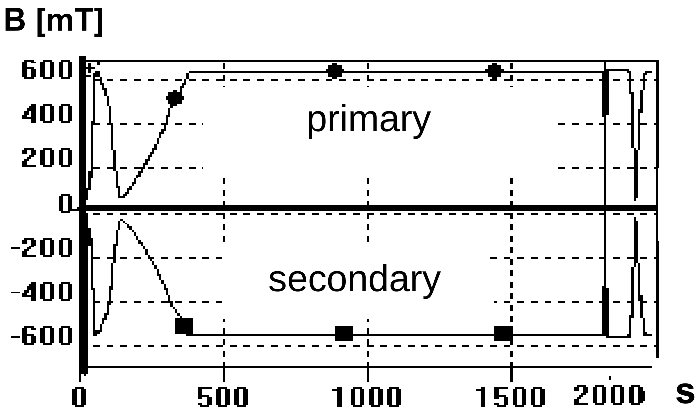

Figure 3. The measured result of the DC magnetic field.

2.3. AC application of the arrangement

In this experiment we used AC current and drilled the superconducting ring from a larger YBCO bulk. From the measured results we could deduce that the coupling between the primary and the secondary coil is proportional to the number of turns [2]. If $I_2 = 0$, then,

$$\frac{N_2}{N_1} = \frac{U_2}{U_1} \tag{1}$$

The limited size of the YBCO rings means the limit to this solution. This limit can be avoided due to the possibility of applying a continuous superconducting loop.

2.4. Theoretical examination of the current maintenance of closed YBCO loops in the air

We will examine the current of a closed loop depending on time related to the resistance and inductivity. ***L*** is the inductivity of the loop, ***R*** is the resistance of the loop. In our case, the resistance of superconductor tape is non-linear that makes the equation more difficult to solve. The non-linear feature of the loop can be defined with measurement results. The equation can be solved applying non-linear characteristics ($R_{nonlinear}(i_S)$).

$$L \cdot \frac{di_S}{dt} = -R_{nonlinear}(i_S) \cdot i_S \tag{2}$$

$$where: \; R_{nonlinear}(i_S) = f(E\text{–}J)$$

$$R_{nonlinear}(i_S) = R_C \cdot e^{\frac{i_S - I_C}{c \cdot I_C}} \tag{3}$$

where:

R_C *is the resistance at the critical current*

c *=consant, depending on the material.*

$$L \cdot \frac{di_S}{dt} = -R_C \cdot e^{\frac{i_S - I_C}{c \cdot I_C}} i_S \tag{4}$$

Solution giving inverse result:

$$\ln i_S - \frac{1}{c \cdot I_C} \cdot i_S + \frac{1}{2c^2 I_C^2} \cdot \frac{i_S^2}{2} - \ldots = -\frac{R_C}{L \cdot e^{\frac{1}{c}}} \cdot t + K \tag{5}$$

From Equation (5) we can calculate directly how long it takes the current of the superconductor ring or a closed loop to diminish to the given current value if the initial current was equal to the critical current.

Equation (4) can be solved applying Ei(x) integral exponent function integrated into mathematical software and a general solution can be obtained.

The general solution (6) of the differential Equation (4) can be carried out with the help of MatLab software. The requested function is I(t).

$$\begin{aligned} &dsolve('L \cdot Dy = -R \cdot \exp((y - c1)/(c1 \cdot c2)) \cdot y') \\ &The\ \ symbolic\ \ solution\ : \\ &t - 1/R \cdot L \cdot \exp(1/c2) \cdot Ei(1,1/c1/c2 \cdot y) + C1 = 0 \\ &where\ \ c1 = Ic,\ c2 = c,\ C1 = cons. \end{aligned} \tag{6}$$

In Figure 4 and Figure 5 we can see that how a superconductor ring with known parameters can conserve its current if the given initial current equals Ic and Ic/2.

$$R_C = 1.5 \cdot 10^{-7}\,\Omega,$$
$$L = 10^{-5}\,H,$$
$$I_C = 200\,A,$$
$$I_O = initial\ current$$

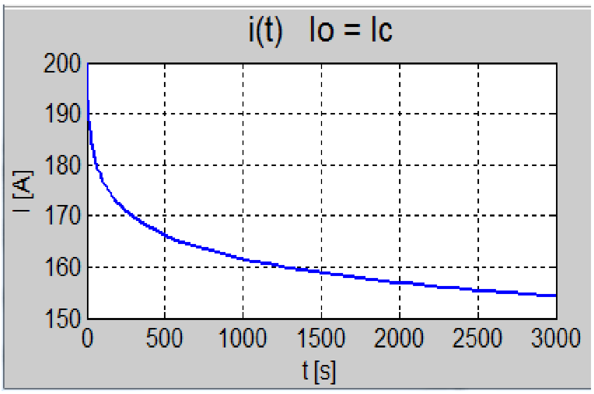

Figure 4. The function of the current-time of the ring, $I_O = I_C$.

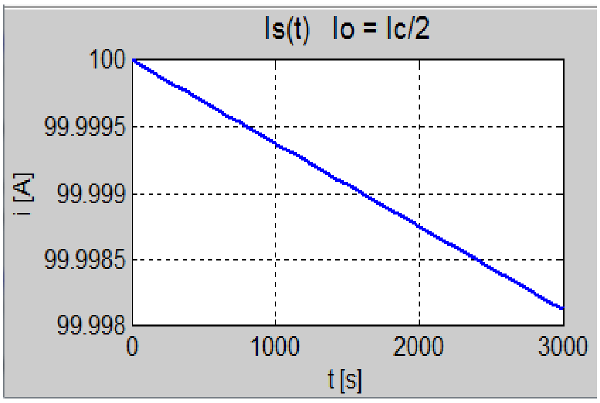

Figure 5. The function of the current-time of the ring, $I_O = I_C/2$.

3. New type self-limiting transformer

With this solution we wanted to examine whether it is possible to create a self-limiting transformer applying a new method never used before. Therefore we made a working model for testing. The primary and secondary coils were assembled as shown in Figure 6 and placed the YBCO loop on it to create the coupling between the primary and secondary coils.

The advantage of this solution is that the transformer is able to break the coupling so there is no current in the secondary coil. That is why we can use it to limit voltage unloaded or to limit the current.

Model data: $U_{primer\ effective\ maximum}$ (sinus) = 90 V
P_{max}: 70 W
A =7.78 cm^2 (cross section of the iron core)
B_{max}: 1.7 T (in iron core)
f= 50 Hz

The investigated scheme is in Figure 6.

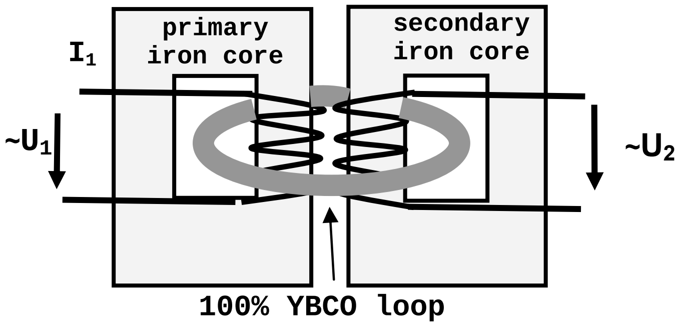

Figure 6. Scheme of the arrangement.

3.1. Self-limiting voltage transformer

With this arrangement we can limit voltage on the secondary side when $I_2 = 0$. If primary voltage increases, then flux in the primary iron core also grows and as a consequence, the current inside the superconductor increases in order to maintain the flux stability of the closed loop. With the arrangement in Figure 6 the stray of the magnetic field of the coils is low.

In modeling we use the following approach:

- There is no stray magnetic field of the iron core.
- The flux is evenly dispersed inside the iron core.
- The iron cores are operated on the linear section of B-H characteristic curve.
- The current of the superconductor is less than the critical current. ($I < I_c$).

The decrease of the temporary current of the superconductor ring – due to losses – can be neglected within the periodic time of AC frequency.

The magnetic resistance of the air is roughly infinite ($R_{air} \rightarrow \infty$), thus the current of the superconducting ring [2]:

$$I_{SUP} = \lim_{Rair \to \infty} \frac{NI_P R_S R_{air}}{R_S R_{air} + R_P R_{air} + R_P R_S} = \frac{NI_P R_S}{R_S + R_P}. \tag{7}$$

Where: N = number of primary turns
I_P = momentary value of the primary electrical excitation
R_S = magnetic resistance of the secondary iron core
R_P = magnetic resistance of the primary iron core.

It can be expected if the current of the superconductor ring is bigger than the quench current of the superconductor, then the coupling between the primary and secondary coil is broken. Thus no voltage arises in the secondary coil. We applied 50 Hz frequency. Later on this can be an advantage when producing unloaded high voltage on the secondary side. In Figure 7 we can see the coupling of one superconductor loop with N_1=N_2= 350 limited voltage, while in the case of transforming higher voltage two parallel YBCO loops have been applied with N_1 = 250, N_2 = 350 turns (Figure 8). Due to temperature rise within the superconductor we can observe hysteresis.

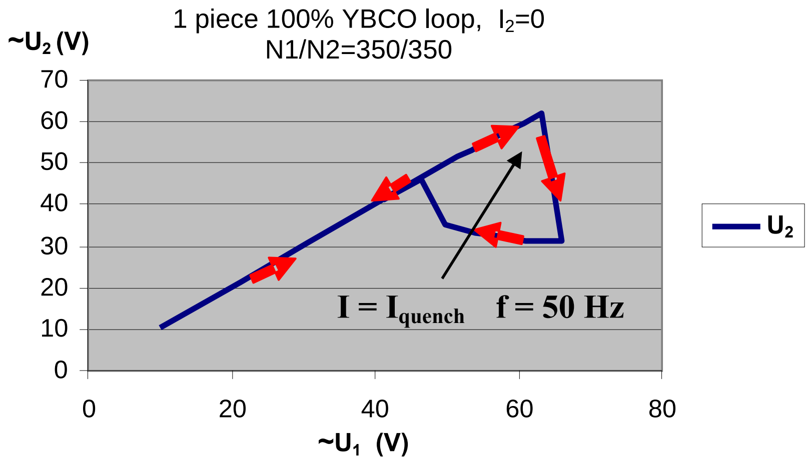

Figure 7. Coupling of 1 turn YBCO loop, unloaded N1/N2=350/350, $I_2 = 0$.

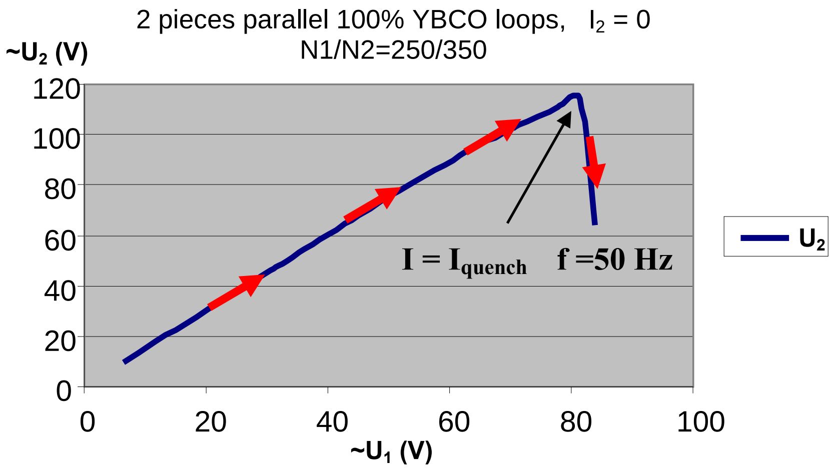

Figure 8. Coupling of 2 parallel turn YBCO loops, unloaded N1/N2=250/350, $I_2 = 0$.

3.2. Self-limiting current transformer

The secondary side is loaded (Figure 9). In this case R=50 Ohm, N1 = N2 = 350. Figure 10 shows the power relation between primary and secondary coils, 1 piece YBCO loop.

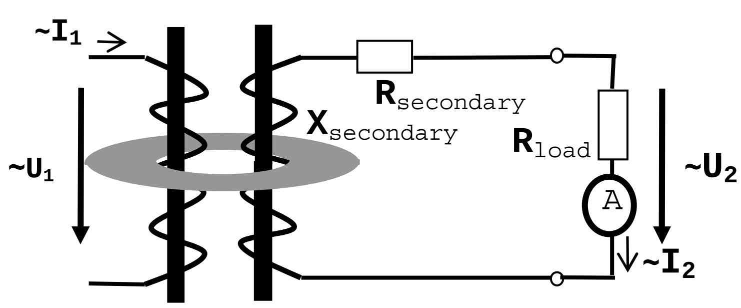

Figure 9. The secondary side is loaded.

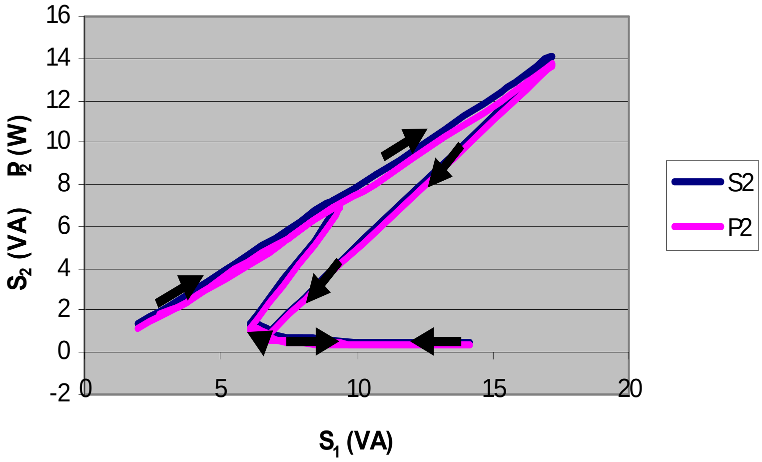

Figure 10. The power relation, 1 piece YBCO loop.

We have introduced a new factor (K) that shows the maximum effective electrical power that one closed superconductor loop can transfer. It depends on the geometry of the arrangement, the cross section of the iron core and the parameters of the superconductor, the number of turns and the load. This factor is represented by K. In our model the superconductor with one turn transfers 13.5 W effective electrical power (P_2) in secondary coil, when the load is 50 Ω. The maximum transfer capacity occurs at quench current. Primary apparent electric power (S_1) is 17 VA, secondary apparent electric power (S_2) is 13.8 VA. Thus: K = 13.5 W/turn. This can be a characteristic of the equipment.
With the application of several closed loops we can carry out sizing easily. The free choice of size is a definite advantage opposed to brittle YBCO and BSCCO bulks of restricted size.
In Figure 11 we can see the voltage transfer of a superconductor loop with 5 parallel turns at 30 Ω.

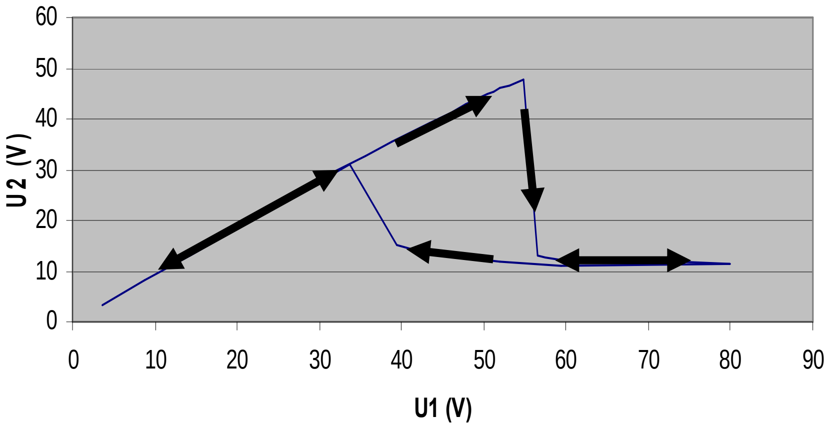

Figure 11. Voltage transfer with 5 parallel turns at 30 Ω.

4. Dynamic examination

We can see the scheme of the arrangement in Figure 12. We generated artificial fault from the operating current of the secondary coil and measured its current. In the experiment, the fault time was 5 periods. This time was enough for the operating current to decrease after the fifth period, when it was loaded. The sample rate was 10 kHz.

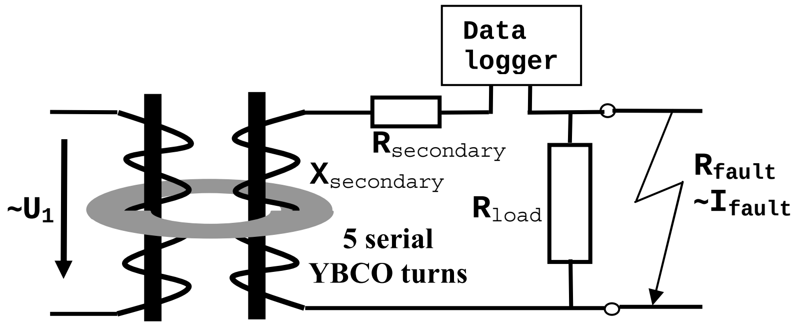

Figure 12. Scheme of the arrangement for dynamic examination.

Figure 13 shows the measured results. $R_{load} = 30\ \Omega$. We used 5 serial turns made of YBCO wire.

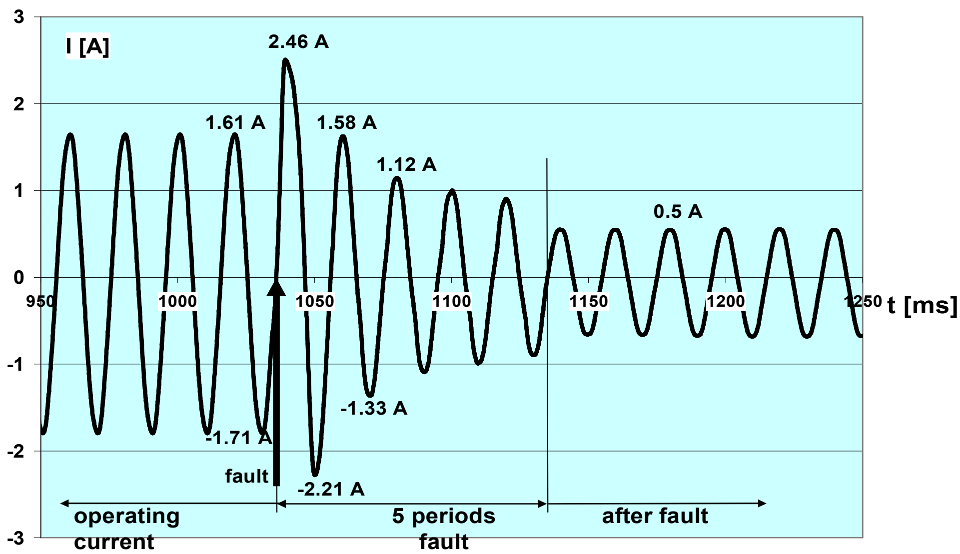

Figure 13. The fault time is five periods.

Figure 14 shows the moment of the fault enlarged. In this figure we can see the current limit occurs after 3.3 ms. This time is less than a quarter of a period.

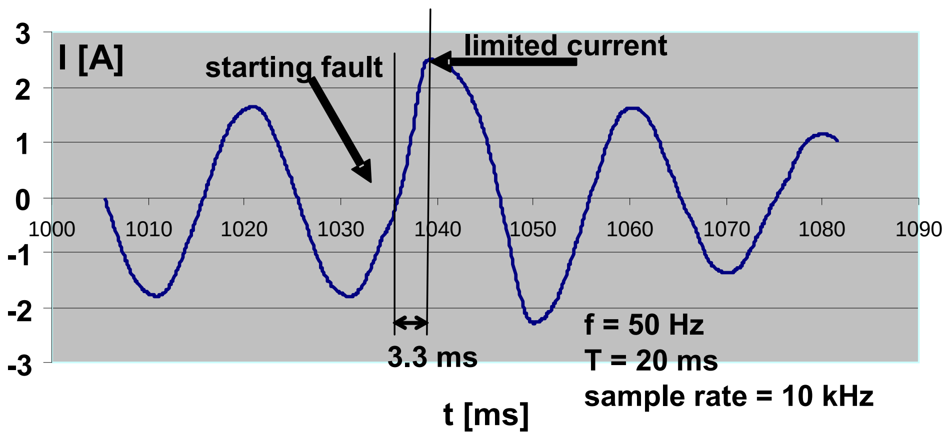

Figure 14. The limited current.

In the arrangement shown by Figure 15 we can see the emergence of the fault current in unloaded circuit. We chose 50 periods for the fault time, i.e. 1 second.

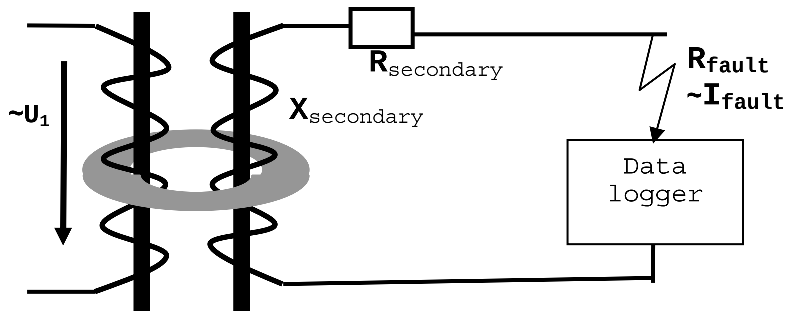

Figure 15. Scheme of the arrangement.

We can observe that right after the first period the current starts to decrease and stagnates at about 30% of the fault current. After the fault was over 10 ms later we caused a new fault and we could see that the new fault current could not develop due to the rise in temperature in the superconductor (Figure 16). In this case 10 ms is too short for the superconductor loop to achieve the superconductor state again.

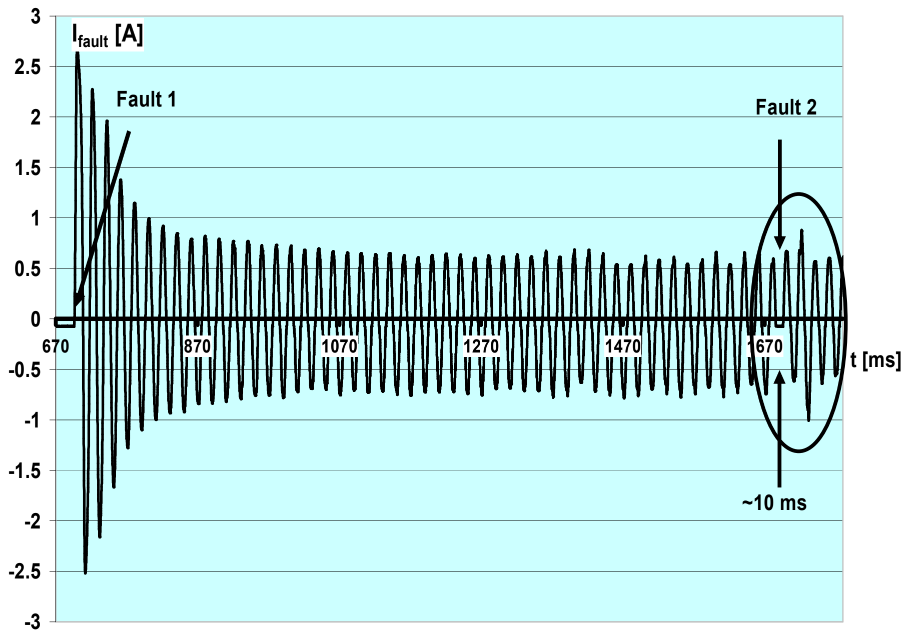

Figure 16. 50 periods for the fault time and again fast fault.

When there was a longer time between the two faults, the starting fault current was higher but did not reach the maximum of the first fault (Figure 17). When we caused a new fault in the unloaded circuit after 420 ms, after the first fault was cancelled, the fault current did not reach the value of the first fault current.

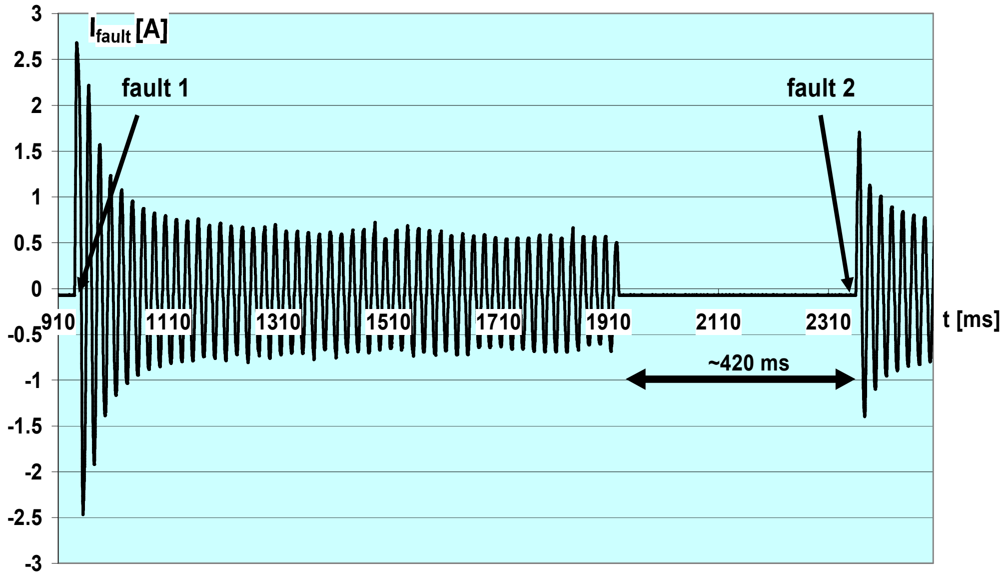

Figure 17. 50 periods for the fault time and a second fault.

When there was even longer time between the two faults, the starting maximum of the second fault did reach the maximum value of the first fault (Figure 18). By this time the superconductor loop cooled down to such a temperature when the loop achieved the superconductor state again.

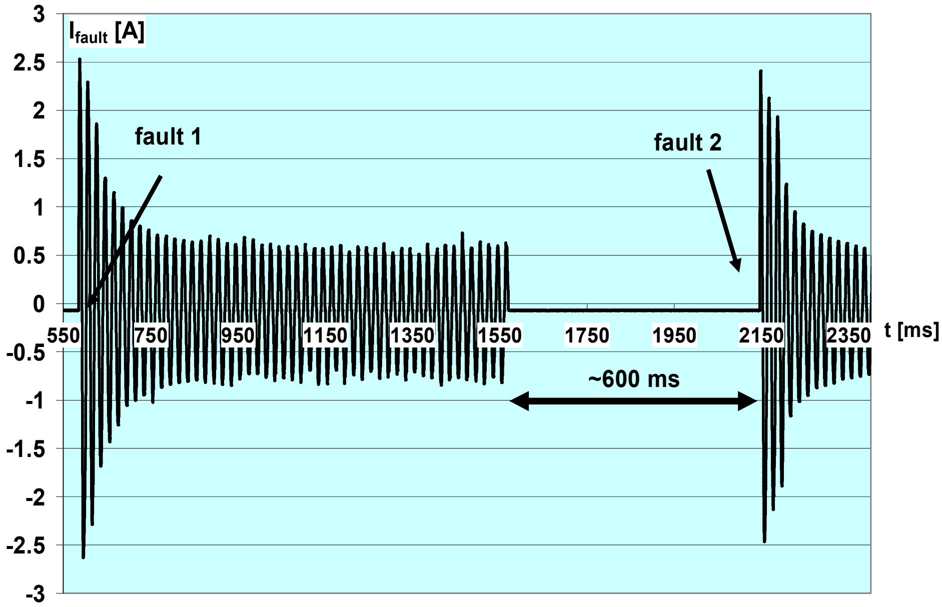

Figure 18. Longer time between two the faults.

5. Conclusions:

- The continuous closed loop made from YBCO tape is suitable for use in such equipment.
- Slitting with blade does not considerably influence critical current.
- Serial windings can be produced with slipped coiling.
- The self-limiting transformer described above can be produced in bigger size and used profitably due to the fast connection.

6. References

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