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Novel Application of YBCO Ring and Closed Loop with DC and AC Magnetic Flux Transformation

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1. Introduction

The chapter presents the theoretical and experimental results of DC and AC magnetic flux transfer with one closed superconducting loop. This method may open a new path for advanced applications by using superconducting ring and perfect closed superconducting loops. I examined a novel arrangement of YBCO ring and continuous loops made of HTS wire. With this solution we can develop a self-limiting transformer. At the same time I also tested the operation of the YBCO ring made from bulk and continuous YBCO loop developed with my own technology. I could carry out these experiments because earlier I had elaborated the machining of the YBCO bulk and wire.

In the first experiment I used YBCO superconducting rings made from a bulk because I managed to drill the YBCO bulk just in some minutes. This technology is low price (Kosa & Vajda, 2007; Kosa et al., 2009). Fig. 1 shows one bulk and two rings drilled from the same bulk. The used YBCO bulk was produced at IPHT Jena, Germany.

Fig. 1. Rings from YBCO bulk with economical and fast technology

Later I applied superconducting wire because the diameter of the superconducting ring from bulk is small. It is a positive fact there is possibility to soft-solder the YBCO wires to create closed loop, but this method is not optimal solution.

- For the beginning the transfer of the magnetic flux is impossible with DC current between independent iron cores.
- Secondly it is established fact we can use the soldered wire with AC current in different applications but with soldering we cannot ensure appropriate uniform temperature in the superconducting wire when the YBCO loop will change to normal state from superconducting state. In soldered spot the Joule loss is considerably higher than in the wire itself.

This is the reason why I did not apply the closed loops with soldering for my applications. However, we must consider the fact, that even in the case of a really good soldering, the superconducting join will not exist.

A Korean group produced 100 % BSCCO loops for the first time (Hee-Gyoun Lee et al.,2006). In 2009 the other Korean group wrote that the perfectly closed YBCO wire making process needs further development. I modified their technology and managed to develop a different cutting method (Kosa et al., 2010). After development of the technology of the cut I examine the arrangement of the continuous YBCO superconducting ring and loop (100% YBCO join). Fig. 2 shows the photograph of an eleven-turn serial loop. The advantage of this winding is that there is no twist along the longitudinal axis that could cause cracks in the YBCO layer at operating temperature, i.e. at 77 K or a lower temperature. It must be mentioned that with this method we can only produce coils with odd number of turns. The odd number comes from topology of the surface of the cut wire. The applied superconductor wire (2G HTS wire) was produced by SuperPower, Inc., New York, USA. Type: SF 12050.
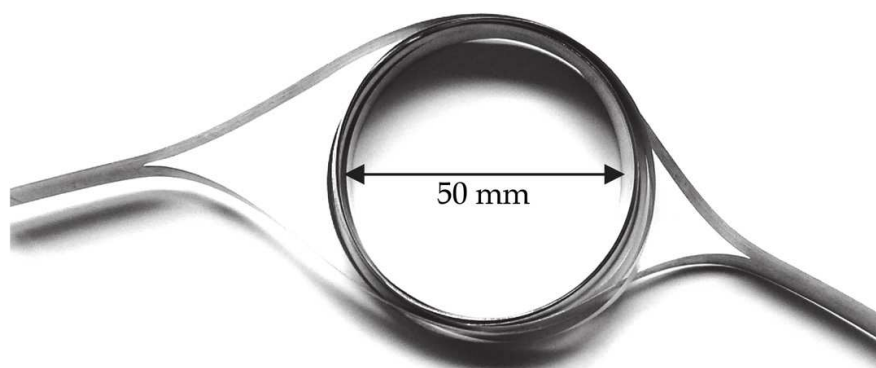

Fig. 2. Eleven-turn serial loop from YBCO wire without soldering and twists along its longitudinal axis (loops with layering)

With used technology we can create parallel and serial loops. This is the task of planning yet. We can apply the cut wires in DC and AC developments.

For example:

- DC flux transformer with one loop (Kosa & Vajda, 2009)
- self-limiting transformer and inductive fault current limiter (AC application)
- different solutions with active magnetic short circuit (DC and AC applications), etc.

With these rings and loops we can transfer the magnetic flux between two independent iron cores inductively from one closed iron core to the other one. This method gives a new

possibility to transform the DC and AC magnetic field. This arrangement can result in novel applications in the field of transfer both the energy of DC magnetic field and AC electrical energy. In Fig . 3 we can see the scheme of the connection of the theory and applications in this chapter.
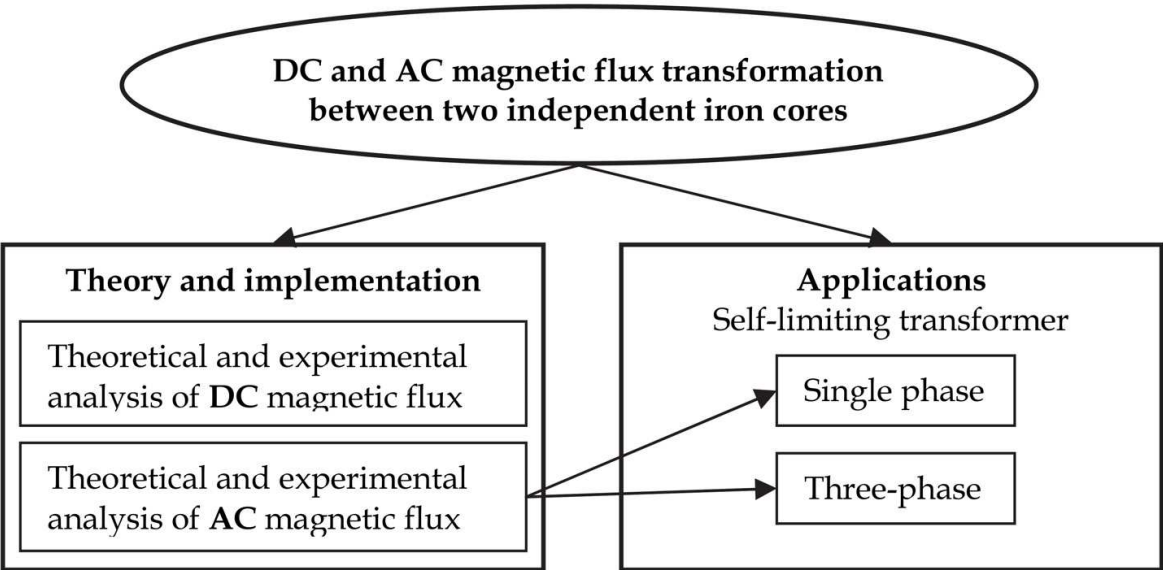

Fig. 3. The scheme of the connection of the theory and applications in this chapter

2. Theoretical and measurement examination of the transfer of the DC magnetic flux with one loop

We can see the experimental arrangement in Fig. 4.
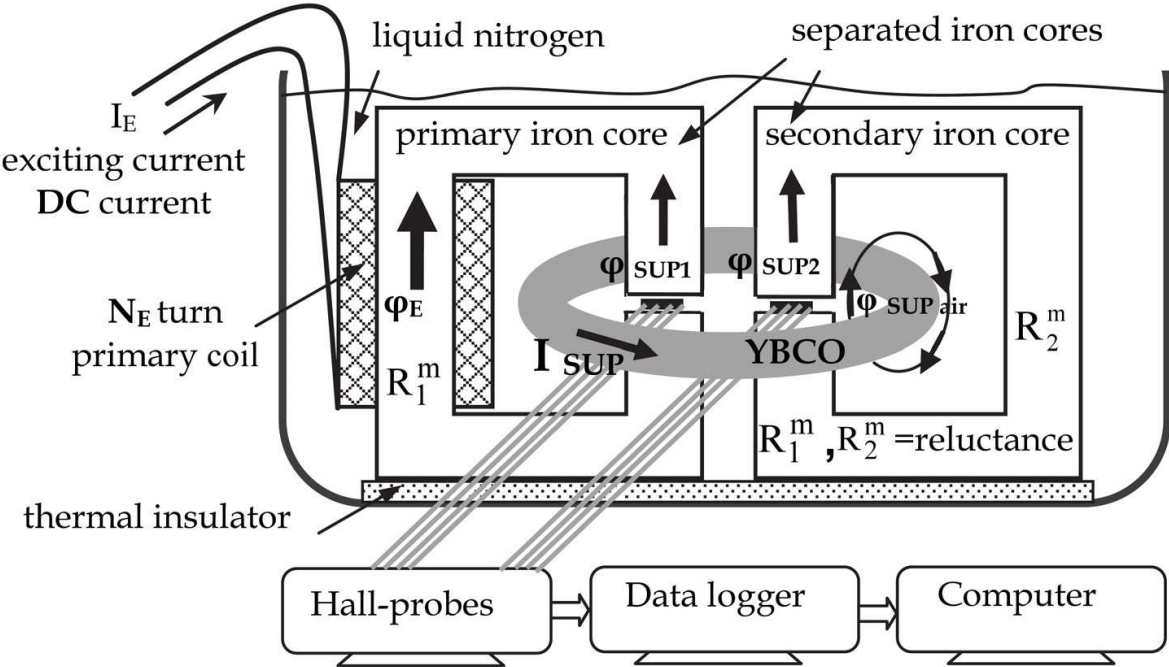
Fig. 4. Scheme of the transformation of the DC magnetic flux with one loop

2.1 Mathematical description of DC flux transfer

We can find a detailed theoretical description of the DC flux transformer with two coils (Orlando & Delin, 1990). In my case I describe a different solution. My DC flux transformer is implemented by using one YBCO ring. First I describe the theoretical examination. The Table 1 shows the nomenclature.

Parameters	Nomenclature
N_E	number of the primary turn (exciter coil)
φ_E	magnetic flux of the exciter coil in the primary iron core without superconductor loop
φ_{SUP1}; φ_{SUP2}	magnetic flux of the superconducting loop in the primary and secondary iron cores
$\varphi_{SUP\ air}$	magnetic flux of the superconducting loop inside the closed superconducting loop in air
R_1^m; R_2^m	reluctance (magnetic resistance) of the primary and secondary iron cores
R_{air}^m	reluctance (magnetic resistance) of the air around superconducting loop
I_{SUP}	current of the superconducting loop
I_E	exciting current

Table 1. Nomenclature

$$\varphi_E = \varphi_{SUP\ 1} + \varphi_{SUP\ 2} + \varphi_{SUP\ air} \tag{1}$$

$$\frac{N_E I_E}{R_1^m} = I_{SUP}\left(\frac{1}{R_1^m} + \frac{1}{R_2^m} + \frac{1}{R_{air}^m}\right), \quad \text{where} \quad R = \text{reluctance} \tag{2}$$

$$I_{SUP} = \frac{N_E I_E R_2^m R_{air}^m}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m} \tag{3}$$

If $R_2^m \to \infty$, there is not secondary iron core, then:

$$I_{SUP} = \lim_{R_2^m \to \infty} \frac{N_E I_E R_2^m R_{air}^m}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m} = \frac{N_E I_E R_{air}^m}{R_{air}^m + R_1^m} \tag{4}$$

If $R_2^m \to \infty$ and $R_{air}^m \to \infty$, then

$$I_{SUP} = \lim_{R_{air}^m \to \infty} \frac{N_E I_E R_{air}^m}{R_{air}^m + R_1^m} = \lim_{R_{air}^m \to \infty} \frac{N_E I_E}{\dfrac{R_{air}}{R_{air}^m} + \dfrac{R_1^m}{R_{air}^m}} = N_E I_E \tag{5}$$

If $R_{air}^m \to \infty$ and és $R_2^m \neq \infty$ then

$$I_{SUP} = \lim_{R_{air}^m \to \infty} \frac{N_E I_E R_2^m R_{air}^m}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m} = \frac{N_E I_E R_2^m}{R_2^m + R_1^m} \tag{6}$$

The operation is based on well known physical law. The possibility of the DC and AC flux transformation with single loop is based on the principle of the magnetic flux constancy in the time in a superconducting closed loop. The mentioned arrangement gives possibilities for the realization of novel industrial applications. The temporary constancy of the resultant flux of the superconductor ring is realized with less ring electrical current if we use secondary iron core.

We can see from Eq. 6 that the current of the superconducting ring decreases if there is a secondary iron core. We can see from equation (6), that the electrical current of the superconductor depends on the geometric data and magnetic permeability.

If the current of superconducting ring is bigger than the critical current of superconductor, there is not magnetic flux in the secondary iron core. In this case the coupling ends between the iron cores. The magnetic flux constancy depends on the current of the superconducting ring or loop because the characteristic (voltage–current) of superconductor. Non-linear effect of the characteristic is bigger in the case of the DC current, than at application of AC current.

2.2 Determination of the equivalent reluctance on the secondary side

The starting equation

$$\varphi_2 = \frac{I_{SUP}}{R_2^m} \tag{7}$$

$$\varphi_2 = \frac{N_E I_E R_2^m R_{air}^m}{\dfrac{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m}{R_2^m}} \tag{8}$$

$$\varphi_2 = \frac{N_E I_E R_{air}^m}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m} \tag{9}$$

$$\varphi_2 = \frac{N_E I_E}{R_1^m + R_2^m + \dfrac{R_1^m R_2^m}{R_{air}^m}} \tag{10}$$

$$\varphi_2 = \frac{N_E I_E}{R_{eq\,2}^m} \tag{11}$$

The result is as follows

$$R_{eq\,2}^m = R_1^m + R_2^m + \frac{R_1^m R_2^m}{R_{air}^m} \tag{12}$$

If $\quad R_1^m + R_2^m \gg \dfrac{R_1^m R_2^m}{R_{air}^m}$, then

$$R_{eq\,2}^m \rightarrow R_1^m + R_2^m \tag{13}$$

In Fig. 5 we can see the equivalent circuit. Consequently so the magnetic flux in the secondary side is with ease definable.
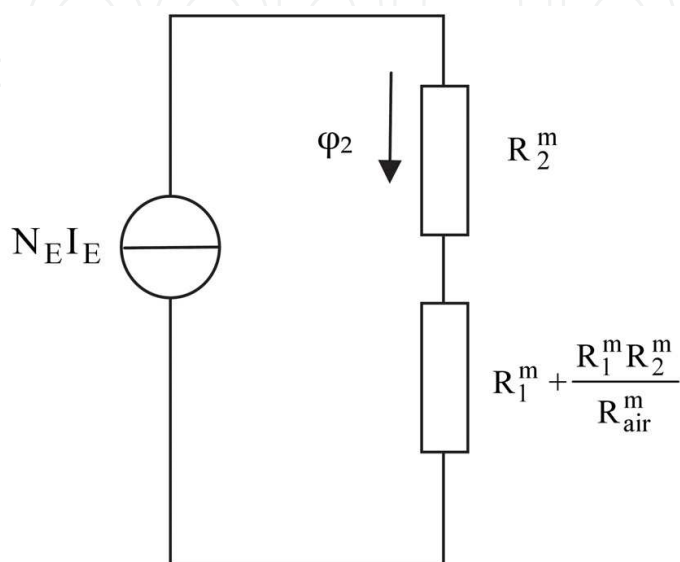

Fig. 5. Equivalent magnetic circuit on the secondary side

The scheme shows importance of proportion of the reluctances for the calculus of the magnetic flux in the secondary side.

2.3 Determination of the equivalent reluctance on the primary side

$$\varphi_1 = \frac{N_E I_E - I_{SUP}}{R_1^m} \tag{14}$$

$$\varphi_1 = \frac{N_E I_E - \dfrac{N_E I_E R_2^m R_{air}^m}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m}}{R_1^m} \tag{15}$$

$$\varphi_1 = \frac{\dfrac{N_E I_E R_2^m R_{air}^m + N_E I_E R_1^m R_{air}^m + N_E I_E R_1^m R_2^m}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m} - \dfrac{N_E I_E R_2^m R_{air}^m}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m}}{R_1^m} \tag{16}$$

$$\varphi_1 = \frac{\dfrac{N_E I_E R_1^m R_{air}^m + N_E I_E R_1^m R_2^m}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m}}{R_1^m} \tag{17}$$

$$\varphi_1 = \frac{N_E I_E (R_{air}^m + R_2^m)}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m} \tag{18}$$

$$\varphi_1 = \frac{N_E I_E}{R_1^m + R_2^m \times R_{air}^m} \tag{19}$$

$$\varphi_1 = \frac{N_E I_E}{R_{eq1}^m} \tag{20}$$

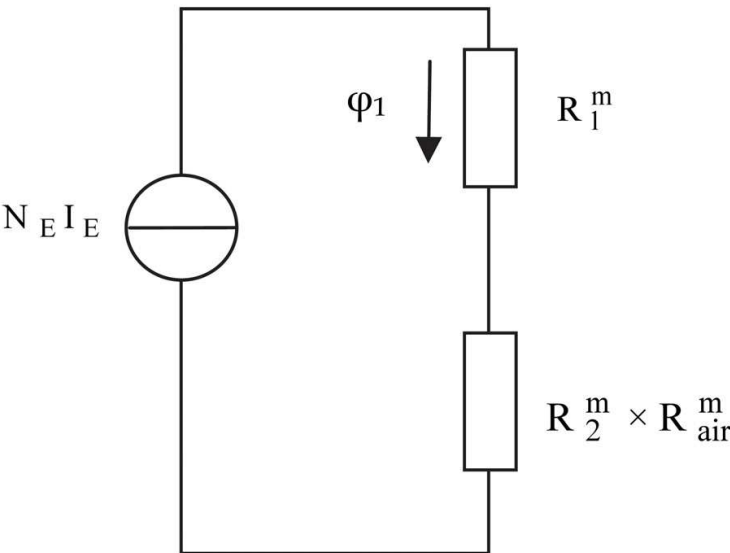$$R_{eq1}^m = R_1^m + R_2^m \times R_{air}^m \tag{21}$$

Fig. 6. Equivalent magnetic circuit on the primary side

If $R_{air}^m \gg R_2^m$, then

$$R_{eq1}^m \rightarrow R_1^m + R_2^m \tag{22}$$

We can see, if $R_1^m + R_2^m \gg \frac{R_1^m R_2^m}{R_{air}^m}$ and $R_{air}^m \gg R_2^m$ then

$$R_{eq1}^m = R_{eq2}^m = R_1^m + R_2^m \tag{23}$$

$$R_{eq1}^m = R_{eq2}^m = R_{EQ}^m \tag{24}$$

In this case

$$\varphi_1 = \varphi_2 = \frac{N_E I_E}{R_1^m + R_2^m} = \frac{N_E I_E}{R_{EQ}^m} \tag{25}$$

2.4 General solution in the case of "M" pieces of closed iron core

As long as M pieces of iron core loops the superconductor ring and number of the electrical excitation are K pieces then we can describe the current of the superconducting ring. Fig. 6 shows the arrangement.
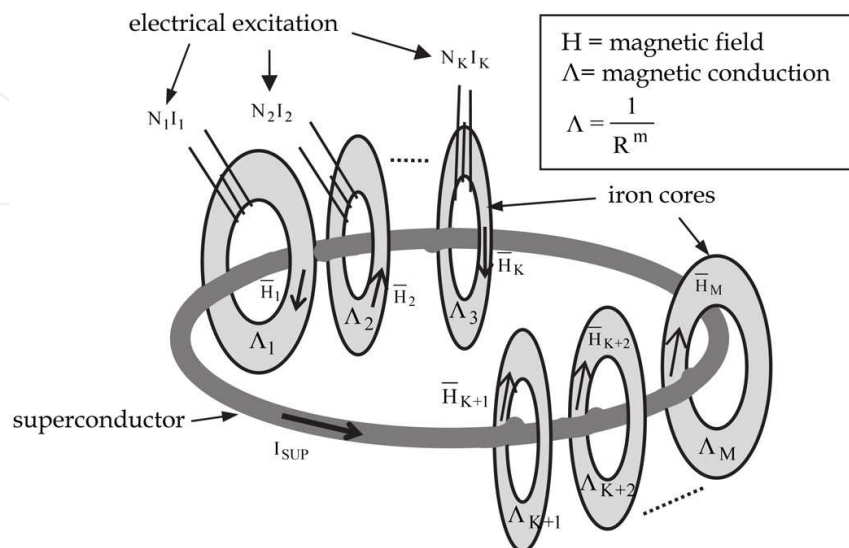
Fig. 7. The arrangement in the case of general solution

We can define numerically the magnetic flux in the iron cores from Ampere's Law.

$$\sum_{i=1}^{K} N_i I_i \Lambda_i = I_{SUP}(\sum_{1}^{M} \Lambda_i) \quad \text{where} \quad \Lambda_i = \frac{1}{R_i^m} \quad \text{and} \quad K \leq M \tag{26}$$

$$I_{SUP} = \frac{\sum\limits_{i=1}^{K} N_i I_i \Lambda_i}{\sum\limits_{i=1}^{M} \Lambda_i} = \frac{\sum\limits_{i=1}^{M} N_i I_i \Lambda_i}{\sum\limits_{i=1}^{M} \Lambda_i} \quad , \text{as} \quad I_{K+1} = 0 \tag{27}$$

In optional iron core where there is not exciting current:

$$\varphi_X = I_{SUP}\Lambda_X = \frac{\sum\limits_{i=1}^{M} N_i I_i \Lambda_i}{\sum\limits_{i=1}^{M} \Lambda_i} \Lambda_X \tag{28}$$

In optional iron core where there is exciting current:

$$\varphi_y = (N_y I_y - I_{SUP})\Lambda_y = (N_y I_y - \frac{\sum\limits_{i=1}^{M} N_i I_i \Lambda_i}{\sum\limits_{i=1}^{M} \Lambda_i})\Lambda_y \tag{29}$$

Equation (29) is the general solution.

2.5 Experimental results of DC magnetic flux transfer with one loop

First I changed the DC current of the coil of the primary side with rapid switches and then slowly. I measured the flux density in the primary and secondary iron core.

2.5.1 Measurement experiments with ZFC method

It can be seen in Fig. 8 that with this solution the change of the magnetic flux of the primary iron core generates opposed flux in the secondary iron core. This is natural because the resultant flux of a closed superconducting loop does not change.

In Fig. 9 and 10 we can see the magnetic flux density of the secondary iron core does not decrease during 2200 seconds.
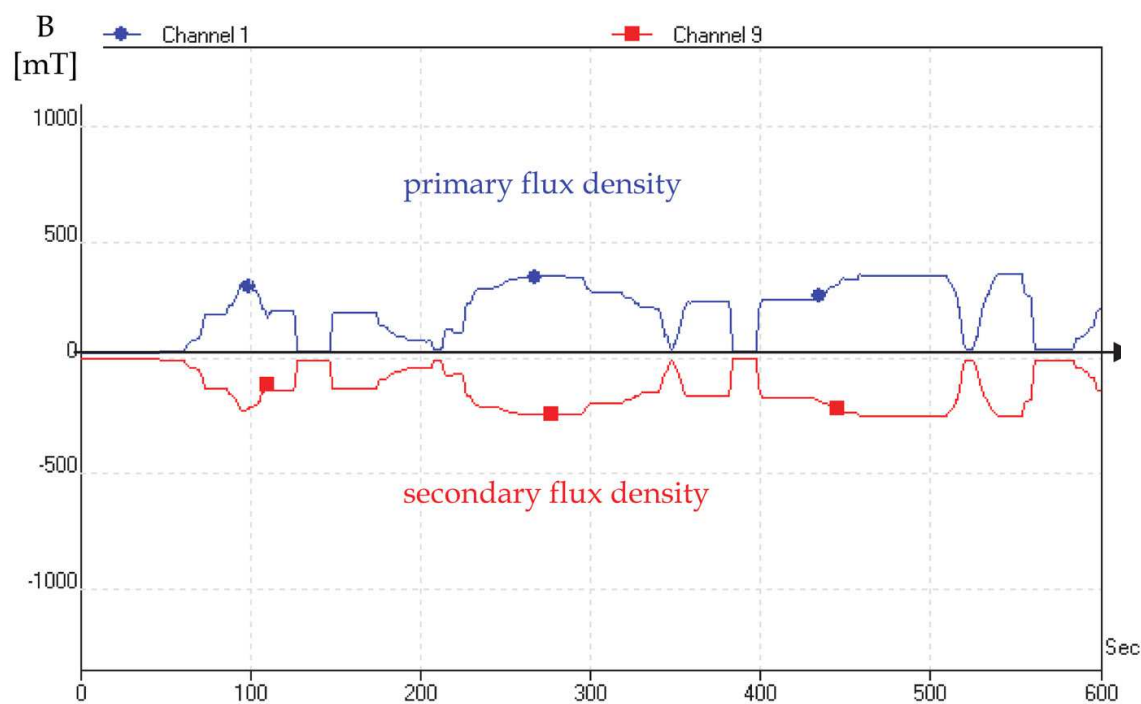
Fig. 8. DC results with one loop
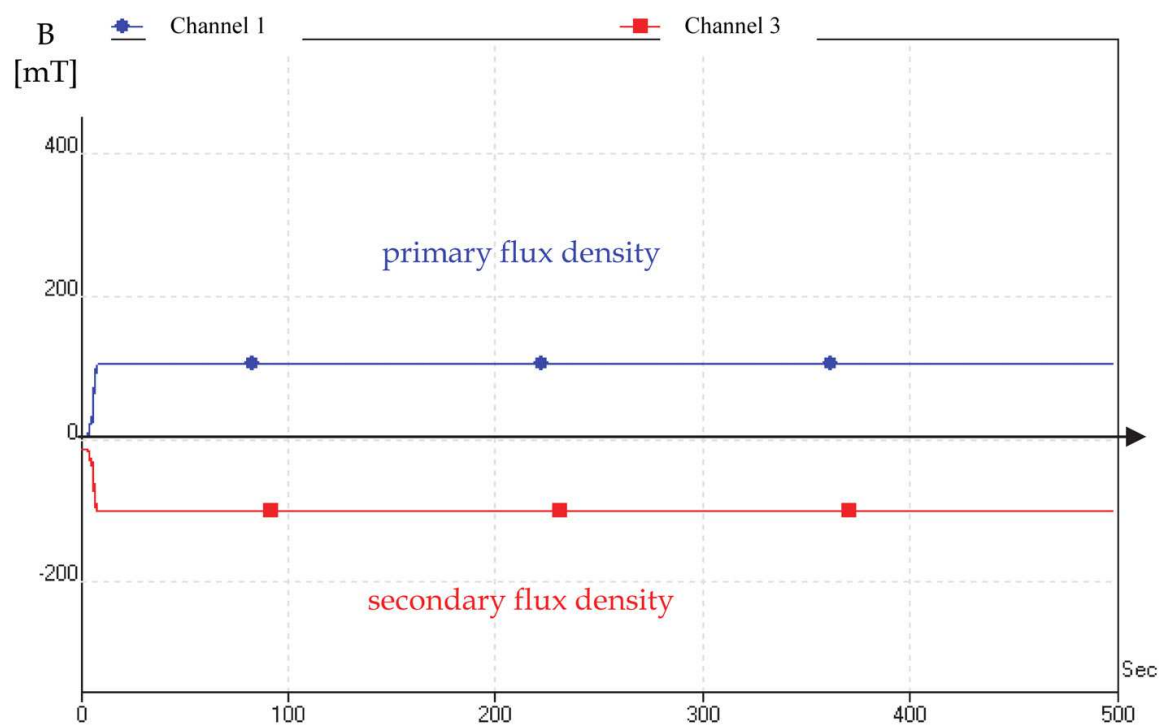
Fig. 9. Measurement result during 2000 seconds I.
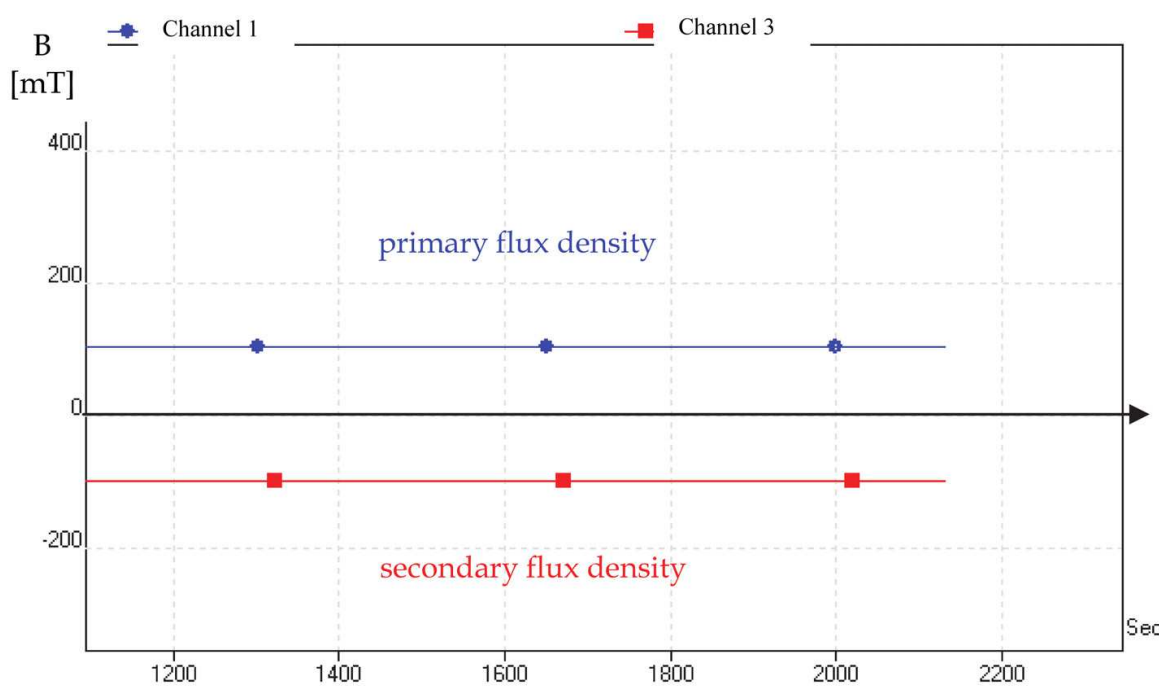
Fig. 10. Measurement result during 2000 seconds II.

The practical application of the transformation of DC magnetic field cannot be carried out with the critical current of superconductor during long time. We have to use a lower superconducting current.

The value of the critical current depends on definitions and even the producers give different definitions. One of the producers gives $1\dfrac{\mu V}{cm}$; another one gives $0.5\dfrac{\mu V}{cm}$ as the critical value. This is also influenced by business purposes.
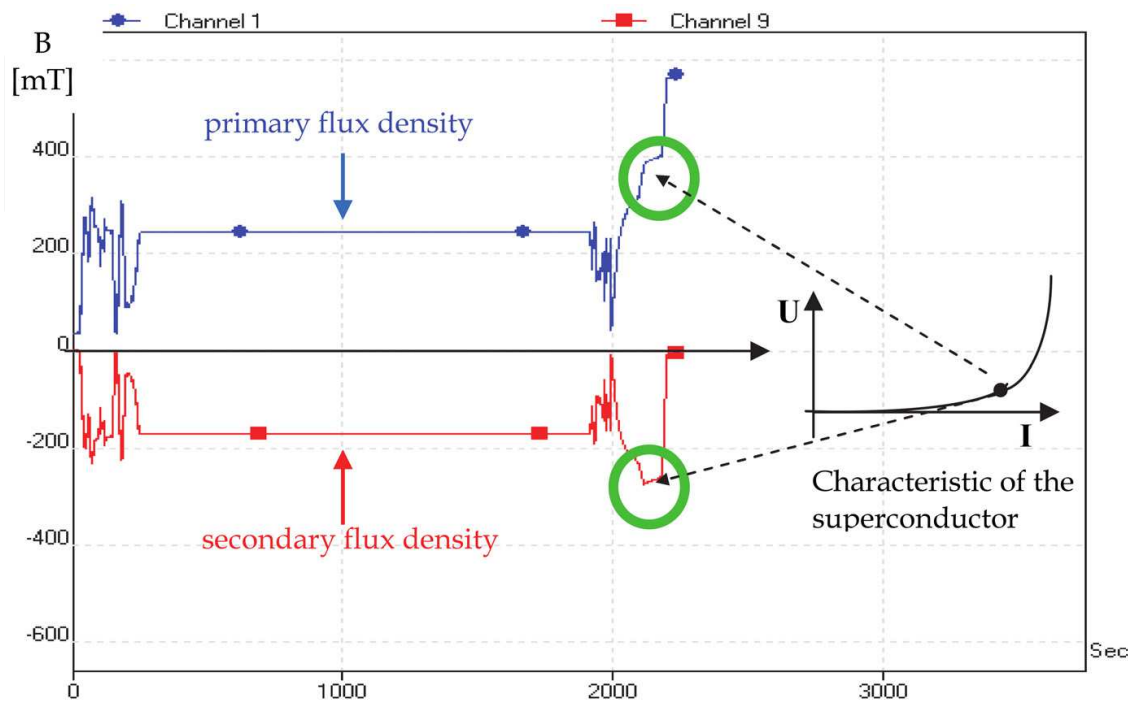
Fig. 11. The decrease of the current of the ring (effect of the non-linear characteristic)

In Fig. 12 we can see a measuring result with a thick copper-ring (instead of superconductor) in liquid nitrogen. Surface of ring was 1.5 cm². The flux density of the secondary side decreases very fast.
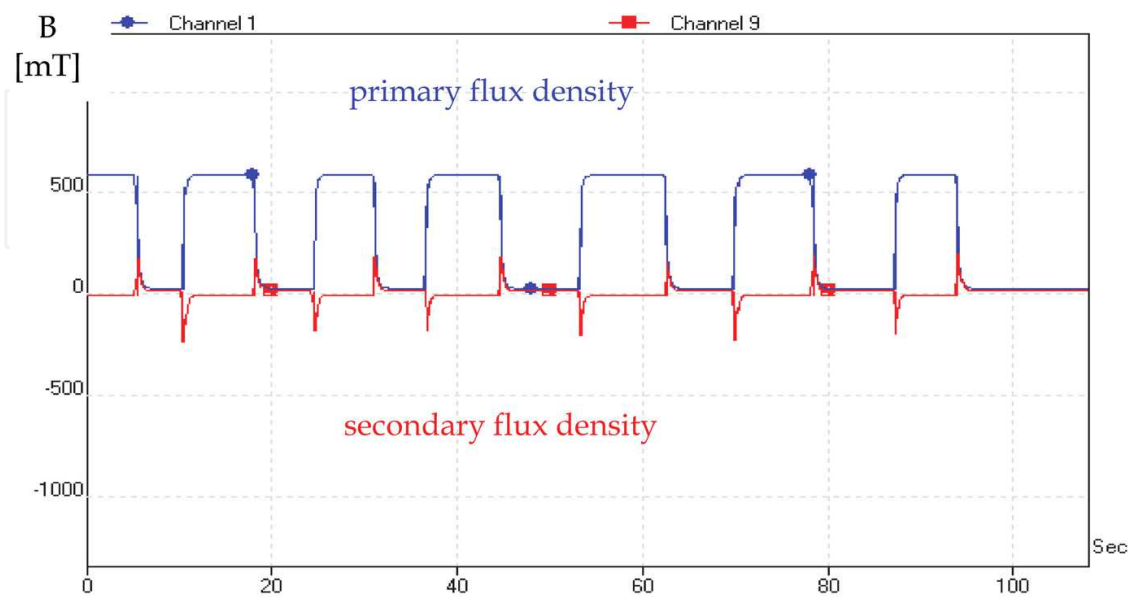
Fig. 12. Measuring result with a thick copper-ring in liquid nitrogen

2.5.2 Measurement experiments with FC method

In the next experiment I have generated magnetic flux only in the primary iron core when the ring was not yet in superconducting state. Then I cooled it down to 77 K and reduced exciting current on the primary iron core to 0 ampere. In parallel in the secondary iron core the flux increased in the opposite direction. After this I changed the polarity of the primary exciting current and the flux increased in the secondary iron core. We can see a measurement result in Fig. 13.
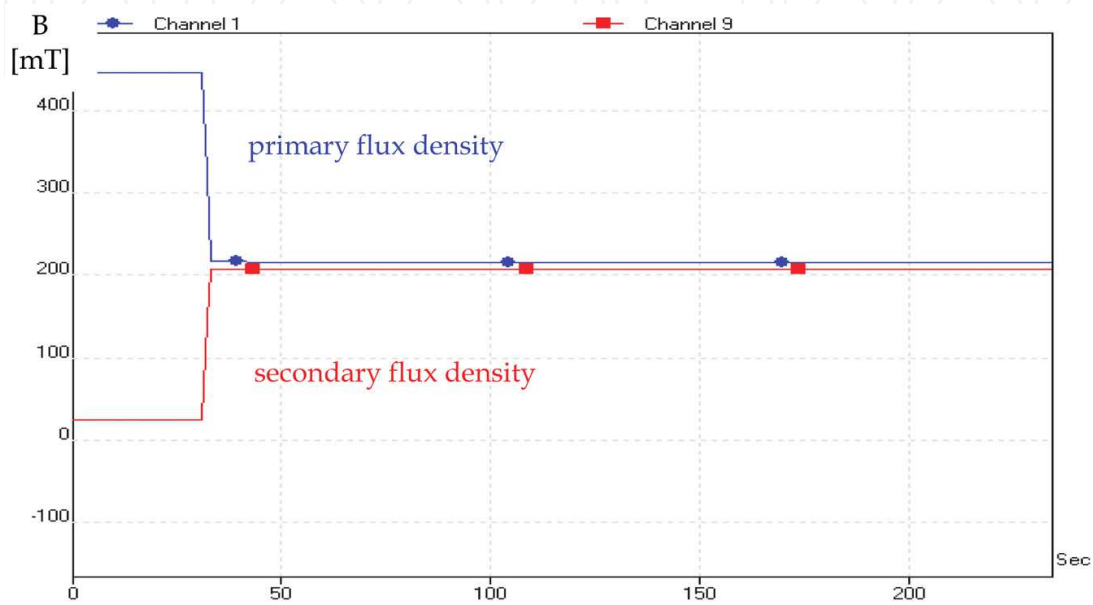
Fig. 13. Measurement result with FC method

Fig. 14 shows a measurement during 5200 seconds.
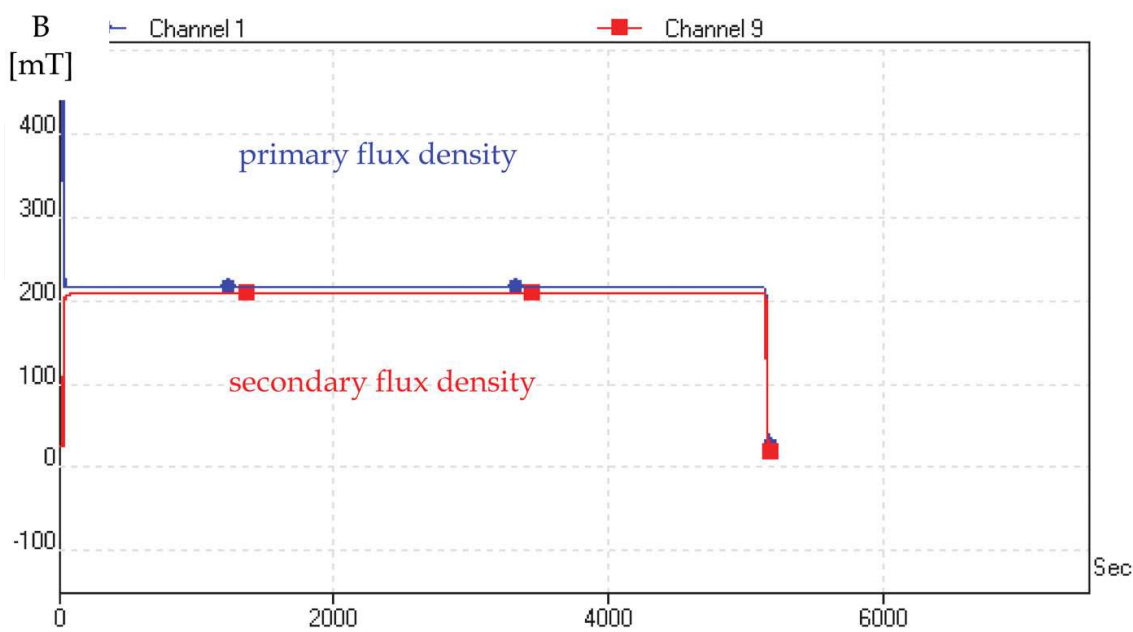
Fig. 14. Measurement result with FC method during 5200 seconds

In the next experiment I have generated magnetic flux in primary and secondary iron core with the same direction when the ring was not yet in superconducting state. The flux density of both iron cores was 0.9 T. After cooling I changed the flux of the primary iron core. We can see the result in Fig. 15. The system is also stable.
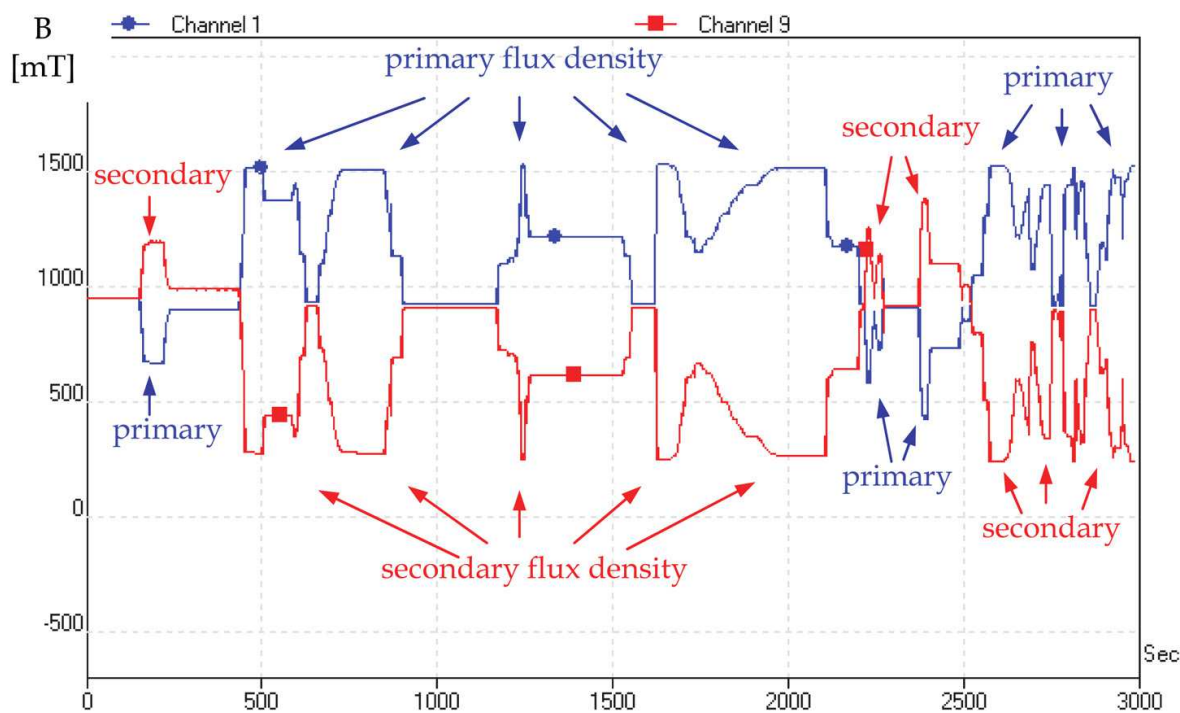

Fig. 15. Exciting current is on both iron cores and after this is cooling (77 K). After this is decrease and increase of the primary current.

3. Theoretical and measurement examination of the transfer of the AC magnetic flux with one loop for single-phase self-limiting transformer

We can see the experimental arrangement in Fig. 16.
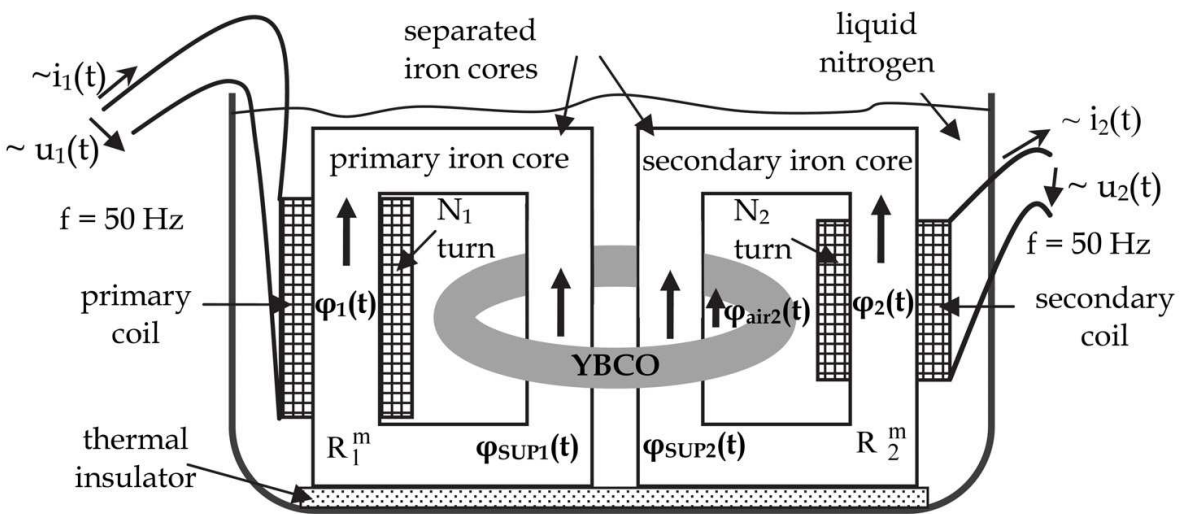
Fig. 16. Scheme of the single-phase self-limiting transformer using by AC flux transformer

The experimental arrangement is a single-phase self-limiting transformer by using AC flux transformer (Kosa et al.) In the case of AC application we can use closed YBCO wire. The superconducting YBCO loop creates the coupling between the primary and secondary coils. This case occurs if the current of superconducting loop is bigger than the critical current of the superconducting loop. The advantage of this solution is that the transformer is able to break the coupling between the primary and secondary coils even if there is not load current in the secondary side, only the primary current increases.

3.1 Mathematical description of single-phase AC flux transfer

$$\varphi_1(t) + \varphi_2(t) = \varphi_{SUP1}(t) + \varphi_{SUP2}(t) + \varphi_{air}(t)$$

$$\frac{N_1 i_1(t)}{R_1^m} + \frac{N_2 i_2(t)}{R_2^m} = \frac{i_{SUP}(t)}{R_1^m} + \frac{i_{SUP}(t)}{R_2^m} + \frac{i_{SUP}(t)}{R_{air}} = (i_{SUP}(t))(\frac{1}{R_1^m} + \frac{1}{R_2^m} + \frac{1}{R_{air}}) \quad (30)$$

The following functions contain the effect of the inductivities of all transformer elements: $i_{SUP}(t)$, $i_1(t)$, $i_2(t)$.

$$i_{SUP}(t) = \frac{N_1 i_1(t)}{R_1^m(\frac{1}{R_1^m} + \frac{1}{R_2^m} + \frac{1}{R_{air}^m})} + \frac{N_2 i_2(t)}{R_2(\frac{1}{R_1^m} + \frac{1}{R_2^m} + \frac{1}{R_{air}^m})} \quad (31)$$

$$i_{SUP}(t) = \frac{N_1 i_1(t)}{1 + \frac{R_1^m}{R_2^m} + \frac{R_1}{R_{air}^m}} + \frac{N_2 i_2(t)}{1 + \frac{R_2^m}{R_1^m} + \frac{R_2^m}{R_{air}^m}} \quad (32)$$

$$i_3(t) = \frac{N_1 i_1(t)}{1 + \frac{R_1^m}{R_2^m} + \frac{R_1^m}{R_{air}^m}} + \frac{N_2 I_2 i_2(t)}{1 + \frac{R_2^m}{R_1^m} + \frac{R_2^m}{R_{air}^m}} = \quad (33)$$

$$i_{SUP}(t) = \frac{N_1 i_1(t)}{\frac{R_2^m R_{air} + R_1^m R_{air}^m + R_1^m R_2^m}{R_2^m R_{air}^m}} + \frac{N_2 i_2(t)}{\frac{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m}{R_1^m R_{air}^m}} \quad (34)$$

$$i_{SUP}(t) = \frac{N_1 i_1(t)\ R_2^m R_{air}^m}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m} + \frac{N_2 i_2(t)\ R_1^m R_{air}^m}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m} \quad (35)$$

If $R_{air}^m \to \infty$, then

$$i_{SUP}(t) = \frac{N_1 i_1(t)\ R_2^m}{R_2^m + R_1^m} + \frac{N_2 i_2(t)\ R_1^m}{R_2^m + R_1^m} \quad (36)$$

If there is not current in the secondary side, then

$$i_{SUP}(t) = \frac{N_1 i_1(t)\ R_2^m}{R_2^m + R_1^m}$$ (37)

3.2 Measurement results of single-phase self-limiting transformer using by flux transformer

Fig. 17 shows a static characteristic of the single-phase self-limiting transformer. This was my first experiment in the case of self-limiting transformer using by flux transformer (Kosa et. al., 2010). I have measured the primary and secondary voltages.
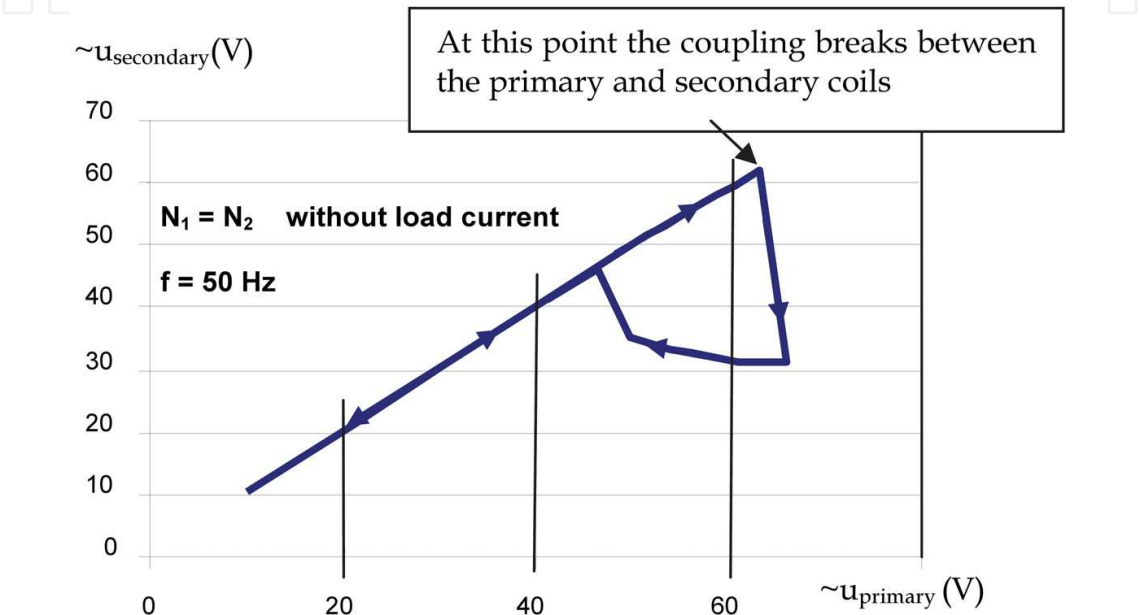

Fig. 17. Static characteristic

We can see a theoretical scheme of the arrangement for dynamic examination in Fig 18.
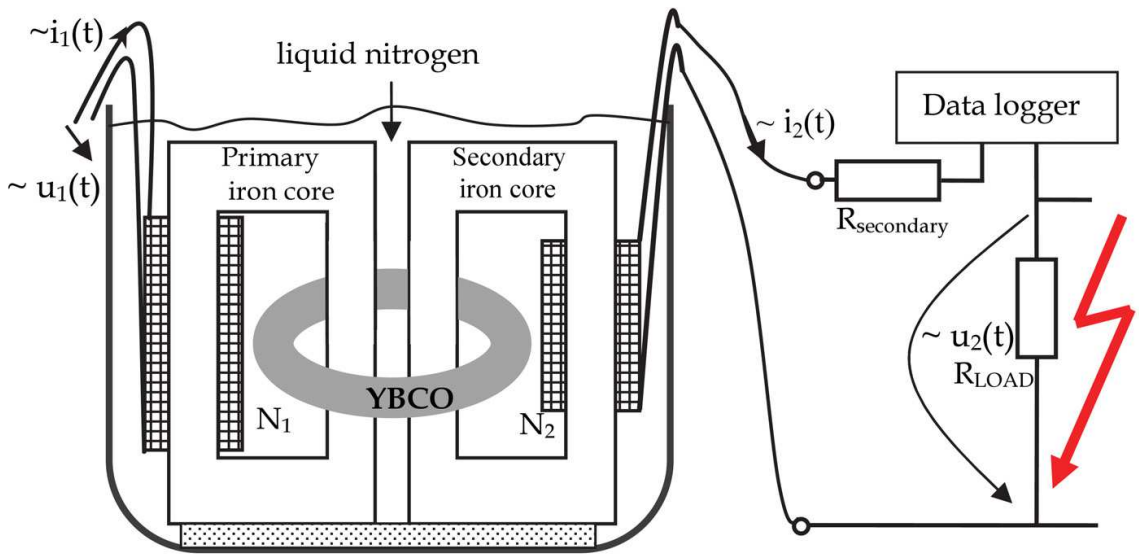
Fig. 18. Measurement arrangement

I generated artificial fault from the operating current of the secondary coil and measured its current. In the experiment, the fault time was 5 periods. The sample rate was 10 kHz.

The current limitation occurs within 3.3 ms (Kosa et al.). This time is less than a quarter of a period (Fig. 19).
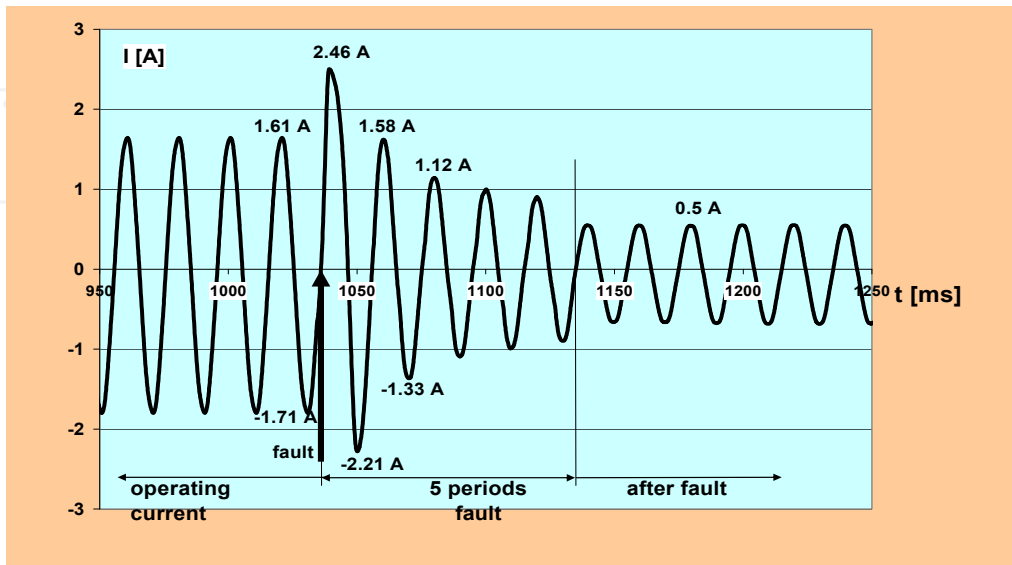

Fig. 19. Dynamic characteristic

3.3 Arrangement of the three-phase self-limiting transformer with flux transfer

The possibility of three-phase application is also based on the principle of magnetic flux constancy in the closed superconducting loop. The solution includes two independent iron cores (Kosa & Vajda, 2011). As I used two iron cores, consequently the loss, the weight, the size, and the price are higher compared to the conventional transformers but this solution has several advantages. For example, the fault power is less, switching is fast. In the case, when there is no load current on the secondary coil and primary voltage increases, the arrangement is able to break coupling between the primary and secondary sides. The developed new type three-phase self-limiting transformer was 400 VA. I realised the primary and secondary windings of the three-phase transformer for this experiment with copper wires. I used SF 12050 wire. This wire (2G HTS wire) was produced 2G HTS wire) was produced by SuperPower, Inc., New York, USA. We can see a photo from device during fitting (Fig. 20).
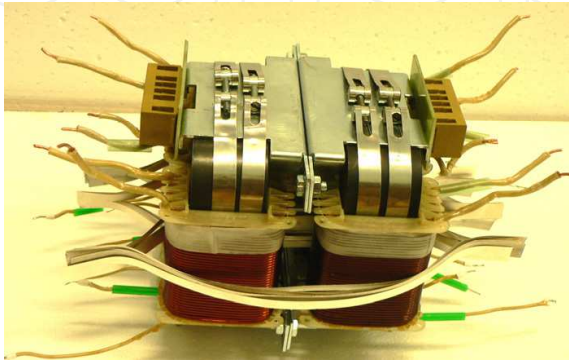

Fig. 20. Photo from the self-limiting transformer during fitting

Table 2 shows the parameters of the experimental arrangement.

Parameters	Data
S_{rated}	400 VA
$U_{primary}$	3 x 400/230 V
$U_{secondary}$	3 x 42/24 V
$N_{primary}$	697
$N_{secondary}$	73
YBCO loops	3 x 7 loops

Table 2. Parameters of transformer

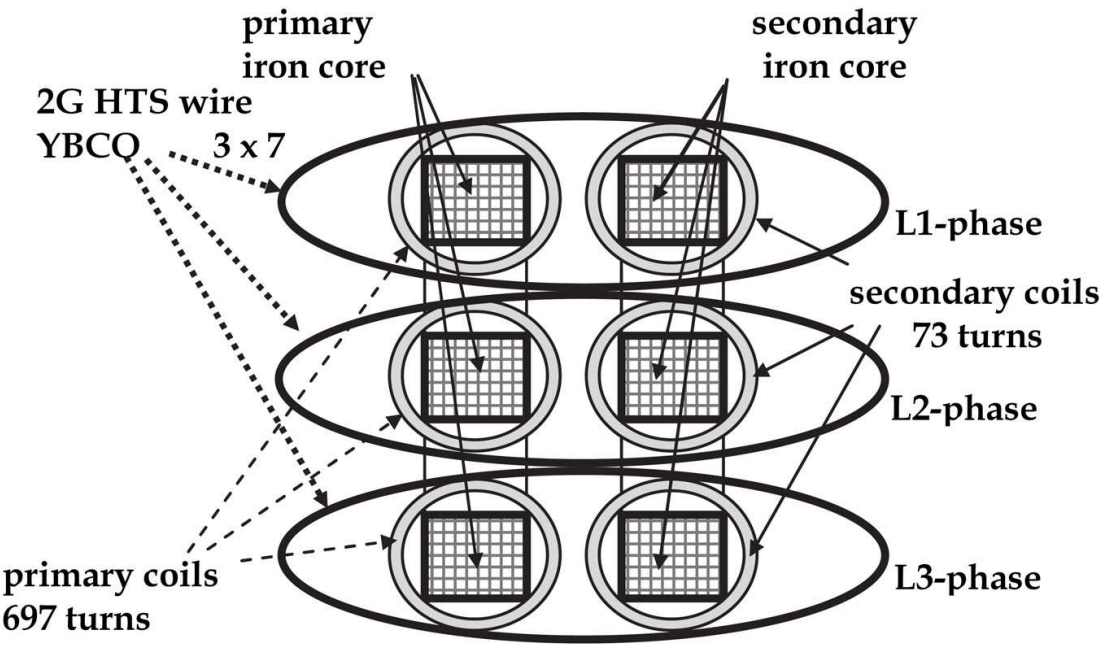We can see the cutaway view of the device (Fig. 21) and the electrical connection (Fig. 22).
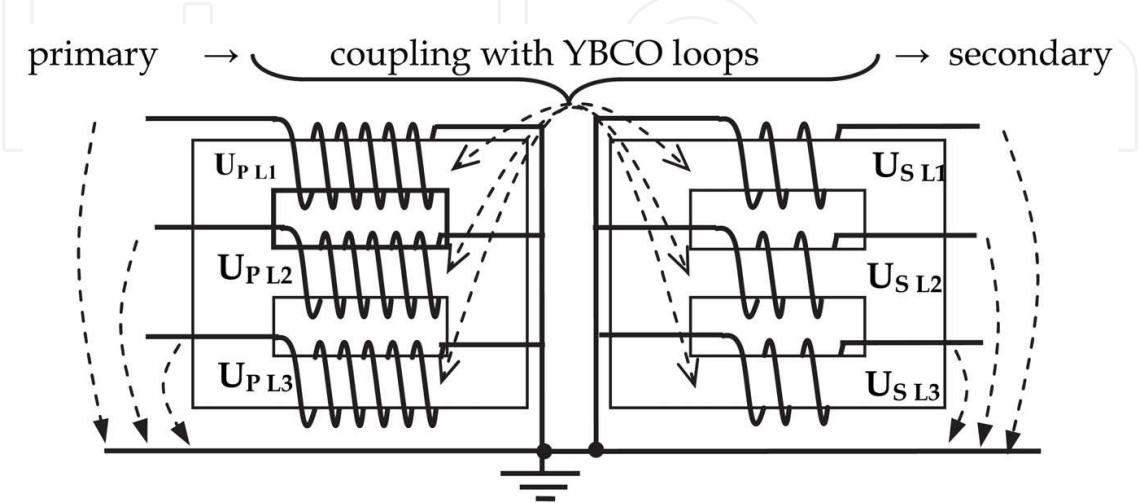

Fig. 21. Cutaway view of arrangement

Fig. 22. Electrical connection

3.4 Measurement results

Measurements were carried out using 4-channel data logger. Sample rate = 50 kS/s.

You can see in Fig. 23 and Fig. 24 the secondary voltage of the self-limiting transformer without load-current and with maximum load-current. What is the difference? Hardly anything.
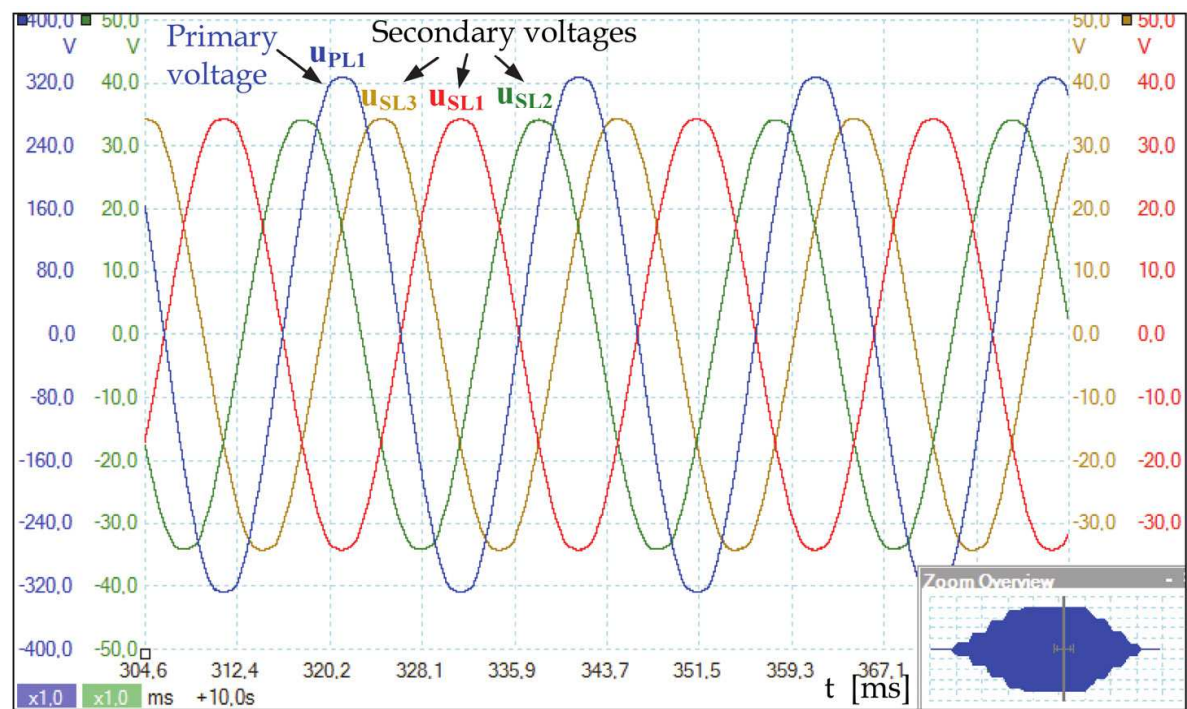

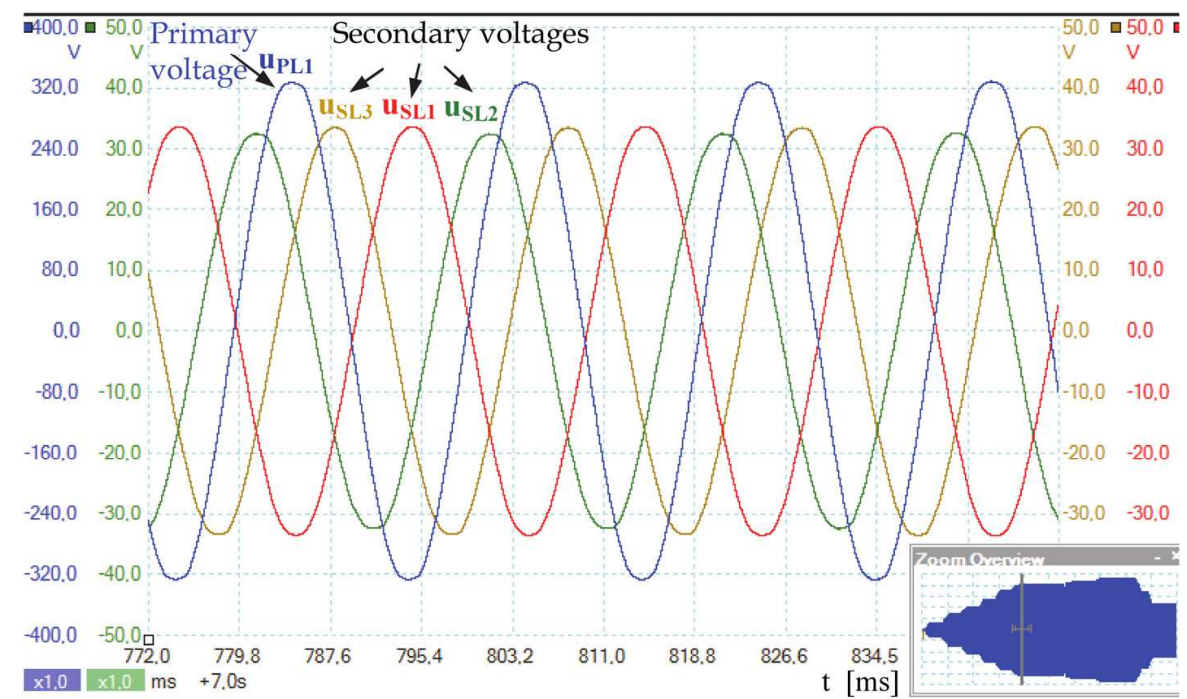Fig. 23. Measurement result without load-current

Fig. 24. Measurement result with maximum load-current (3 x 4.5 Ω, P = 400 Watt)

In Fig. 25 we can see a fault. There is load-current on the secondary side (R_{load} = 3 x 4.5 Ω) and single-phase short circuit in L_1 phase.
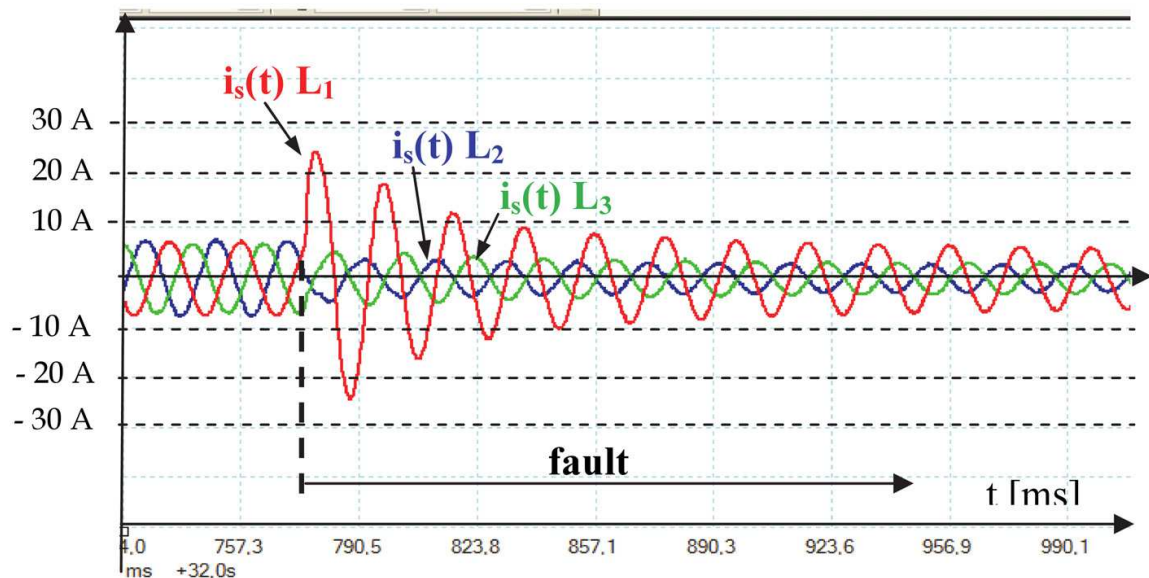

Fig. 25. Single-phase short circuit in L_1 phase

The advantage of the arrangement is that in the case of single-phase short circuit the current will decrease in all the three phases. This can be an appropriate solution for high power machines. In the case of high-power electric motor if there is a single-phase breaking or a single phase short circuit, we can decrease the current in the three phases with this solution.

4. Conclusion

The continuous closed loop made from YBCO tape is suitable for use in such equipment. It is possible to create the novel type 3-phase self-limiting transformer with flux transfer. The short circuit current is less than the operational current within some periods. This is very advantageous for high-power machines (motor). It seems that the arrangement is good also in the case of the single-phase breaking of high-power electric motor. If there is a breaking in one phase, the current increases in both the other phases. And the superconductor will be in the normal state. This means that the current will decrease in an electric motor. The two iron cores' greater size, cost and loss compared to the conventional transformers are facts but the transformer has several advantages e. g. fast switching, the ability of limiting even if the primary current is increased without loading the secondary side.

5. Acknowledgment

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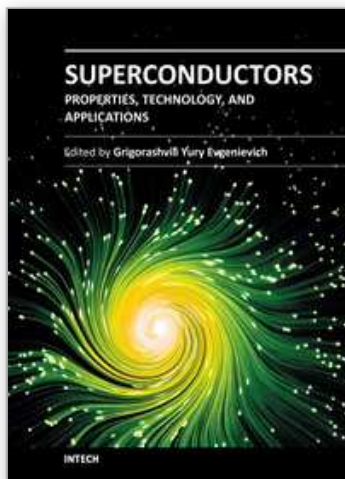
Superconductors - Properties, Technology, and Applications

Edited by Dr. Yury Grigorashvili

Book "Superconductors - Properties, Technology, and Applications" gives an overview of major problems encountered in this field of study. Most of the material presented in this book is the result of authors' own research that has been carried out over a long period of time. A number of chapters thoroughly describe the fundamental electrical and structural properties of the superconductors as well as the methods researching those properties. The sourcebook comprehensively covers the advanced techniques and concepts of superconductivity. It's intended for a wide range of readers.

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