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Transformation of the DC and AC Magnetic Field with Novel Application of the YBCO HTS ring

J. Kosa, I. Vajda *Member IEEE*

***Abstract*—With the new arrangement to be presented we can transfer the magnetic energy of DC or AC magnetic fields inductively between two independent iron cores from one closed iron core to the other one. Thus, DC magnetic field can be transformed in a controlled way. This method can result in novel applications in the field of transferring both the energy of DC magnetic field and AC electrical energy. The paper presents preliminary results of experiments with showing leading idea. The successful results of experiment open new advanced applications of superconducting regardless type of superconductors.**

***Index Terms*—Superconducting device, transformer, YBCO**

I. INTRODUCTION

WITH the method described in the paper we can generate DC magnetic field between two independent iron cores. The value of the magnetic flux of the secondary iron core is independent of the changing speed of the flux of the primary iron core. We set up the model and it works. 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 the magnetic flux conservation in the time in a closed loop. With this method unexpected short circuit in electrical machines are also calculated [1]. The aim of this article is not to examine higher frequencies. The measured results are relevant in the case of static and also low frequencies operating domain. The possibilities of AC application mentioned in the article are just few examples without detailed evaluation.

We used YBCO superconductor rings. Superconductor bulks were produced at IPHT in Jena, Germany. The first measurements were carried out at the Budapest University of Technology and Economics, the measurements were reproduced at IPHT Research Institute in Jena, Germany and at the Technical Faculty of Kecskemet College. The applied YBCO rings were drilled in some minutes with a technology we had elaborated [2]. The temporal constancy of magnetic flux in the case of YBCO superconductor rings is made possible by the “inter-granular current” inside the closed ring. We can apply other kinds of superconductors like MgB_2.

Fig. 1 shows the scheme of transformation of DC magnetic field. The cross-section of both the primary and the secondary iron cores is 100 – 100 mm^2.

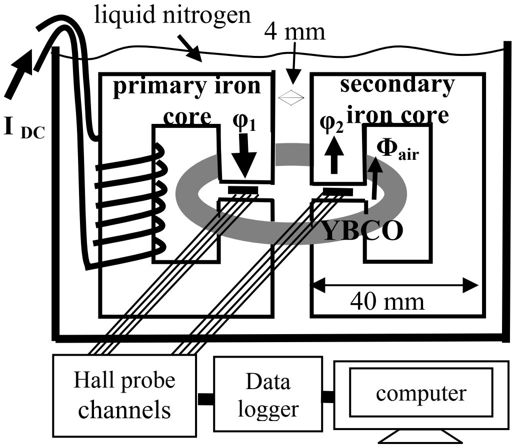

Fig. 1. Scheme of the measurement of the transformation of DC magnetic field.

II. DC FLUX TRANSFORMER WITH YBCO HTS RING

Orlando and Delin described a DC flux transformer with two coils in their book [3]. In our case we describe a different solution. Our DC flux transformer is implemented by using one YBCO ring.

With this solution the controlled flux change of one of the iron cores generates flux change of the opposite direction inside the other iron core.

As the ring is in superconducting state, the changed flux can remain stable inside the secondary iron core. The measurements are related to these examinations.

The critical current density of the applied superconductor is $Jc = 10^4$ A/cm^2 at 77 K. Its geometric data of the ring: D = 39 mm, d = 28 mm, h = 9 mm. The air gap of the iron core: 1.5 mm, $A_{iron\ core}$= 100 mm^2.

A. Measurement experiments with ZFC method

We changed the primer flux first with rapid switches and then slowly from 0 up to 0.2 Hz. We have continuously measured secondary flux. It can be seen in Fig. 2 that the magnetic flux of the secondary iron core is independent of the changing speed of the primary magnetic flux. It depends only on its magnitude.

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J. Kosa. I. and I. Vajda are with the Department of Electric Power Engineering, Budapest University of Technology and Economics, Egry Jozsef utca 18, H-1111 Budapest, Hungary (phone: +36-1-463-2904, fax: +36-1-463-3600; e-mail: kosa.janos@gamf.kefo.hu)

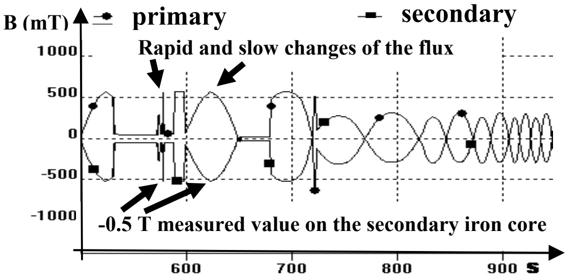

Fig. 2. The independence of the changing speed of primary flux.

The magnetic flux density of the secondary iron core does not decrease in a 2000 second interval (Fig.3).

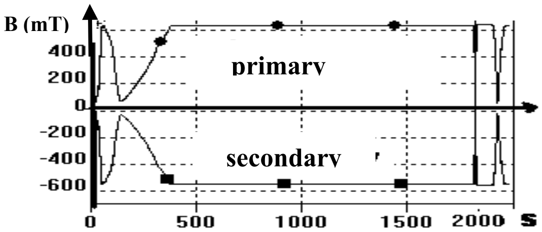

Fig. 3. Measurement results in long interval of time.

B. *Measurement results with FC method*

During the experiment we have generated magnetic flux only in the primary iron core when the ring was not yet in superconducting state. Then we cooled it down to 77 K and reduced electrical excitation on the primary iron core to 0 ampere. In parallel in the secondary iron core the flux increased in the opposite direction. After this we changed the polarity of the primary electrical excitation and the flux increased in the secondary iron core. This resulted in 1100 mT (Fig. 4).

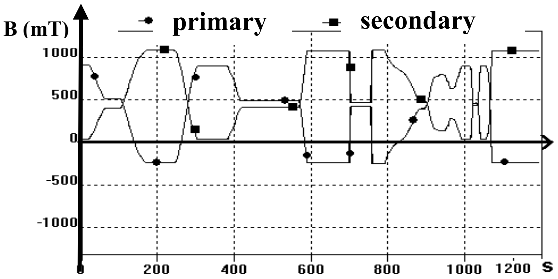

Fig. 4. Excitation on the primary iron core. FC method.

In the next experiment we 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 we decreased the flux of the primary iron core, and changed polarity of the primary electrical excitation. The system is also stable. We can see this case in Fig. 5.

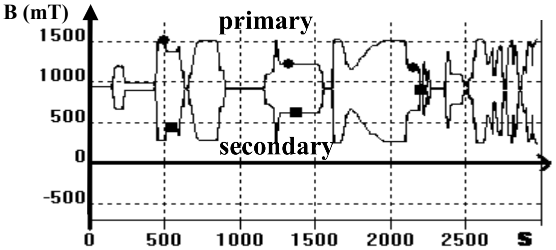

Fig. 5. Excitation on both iron cores and changing the polarity of the primary iron core.

III. AC FLUX TRANSFORMER WITH YBCO HTS RING

Fukuoka and Hashimoto have examined one-iron core transformer with HTS bulk in higher frequencies [4]. In our case we give application possibilities for double iron core systems. The principles of the two systems are different.

A. *Measurement result with a special transformer*

In Fig. 6 we can see a new example of application without technical evaluation. We show just the measured results.
$f = 50$ Hz; $N_1 = 80$; $N_2 = 20$.

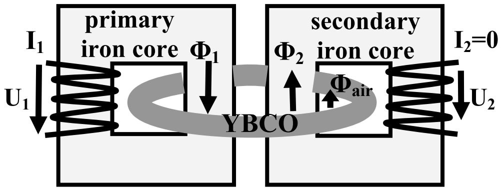

Fig. 6. Transformer option for current limiter.

We can see in Fig. 7 the dependence between the primary voltage and the secondary voltage.

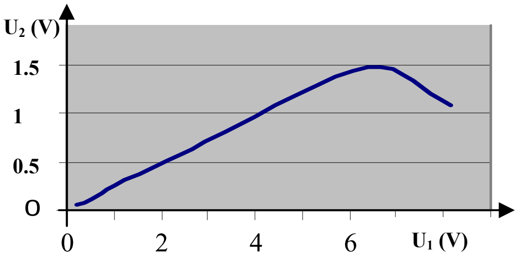

Fig. 7. $U_1 - U_2$ characteristic.

From Fig. 7 we can deduce that the coupling between the primary and the secondary coils is proportional to the number of turns.

$$\text{If } I_2 = 0 \text{ then } \frac{N_2}{N_1} = \frac{U_2}{U_1} \tag{1}$$

From these results we can see the saturation process of the iron core. If the current of the superconductor ring is bigger than the critical current, then the coupling between the primary and secondary coils is broken.

B. *Measurement results with passive control of current limiter using secondary iron core*

The current limiters and self-limiting transformer have nowadays more and more application possibilities [5]. The electric current of the superconductor can be influenced with the parameters of the passive secondary iron core (Fig. 8).

Naturally, this means loss depending on the geometry.

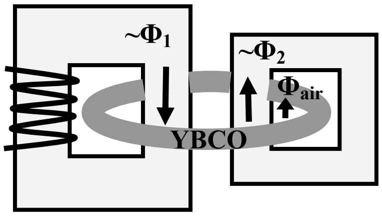

Fig. 8. Passive control of current limiter.

We can see in Fig. 9 the dependence between the primary voltage and the current of the primary coil in the case of different cross section of the secondary iron core. We can see also, that the limit current is reached by different primary currents. By increasing the cross section of secondary iron core increases also the impedance of the primary coil.

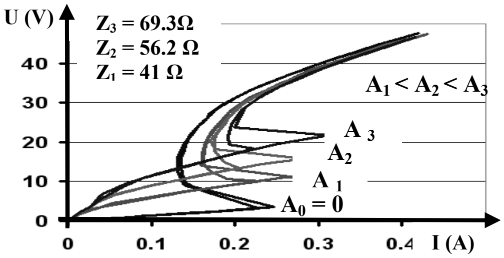

Fig. 9. I – U characteristic with secondary iron core.

IV. THEORETICAL JUSTIFICATION

We applied the well-known physical phenomenon when an electrically conductive ring wants to keep its flux (the principle of flux constancy). When the resistance of the ring is R=0 the principle of shielding occurs. Our application realizes the principle of flux constancy with two iron cores. The change of the flux of the primary and secondary iron cores has opposite directions inside the superconductor ring.

A. The change of flux inside the closed loop

When $\varphi_{app}(t)$ changes, the electric current, generated inside the closed loop by $\varphi_{app}(t)/dt$ voltage, decreases exponentially according to equation (2), as in [3].

$$i(t) = I_0 \cdot \exp(-\frac{R}{L} \cdot t) \tag{2}$$

So, if R →0, then $I(t) = I_{t=0}$ for $t \geq 0$
In the case of superconductors flux coupling is described with equation (3), as in [6].

$$-A \cdot \frac{dB_{app}}{dt} = L \cdot \frac{dI}{dt} \tag{3}$$

After integrating equation (3) we get:

$$-\varphi_{app}(t) = L \cdot i(t) + \varphi_{CONS} = \varphi_{SUP}(t) + \varphi_{CONS} \ . \tag{4}$$

In the system with two iron cores, we can change $\varphi_{app}(t)$, that is the flux in the primary iron core, with electrical excitation. The current of the superconductor ring in the secondary iron core leads to the change of the flux in the opposite direction. This ensures the constancy of the resultant flux in the ring. The temporal constancy of the flux in the secondary iron core after the flux has changed depends on the resistance of the ring which is determined by E-J characteristics of the superconductor ring.

B. Modeling

In modeling we use the following approach:

1) The exciting coil has no stray magnetic field.
2) There is no stray magnetic field of the iron core.
3) The flux is evenly dispersed inside the iron core.
4) The iron cores are operated on the linear section of B-H characteristic curve.
5) The current of the superconductor is less than the critical current. ($I < I_c$).
6) We neglect the loss deriving from the alternating flux of the superconductor (ring with thin wall thickness).
7) We leave the relaxation of the YBCO ring out of account.

In the system with two iron cores within the ring the magnetic flux of current of the superconducting ring and the flux of the exciting coil have opposite directions. Their resultant value is constant at each moment. This means we can regulate the electric current of the superconductor with controllable flux that supplies the system with the necessary flux for the continuance of the magnetic flux in the ring.

Let us call primary the iron core that receives the external electrical excitation and secondary the other (Fig. 10).

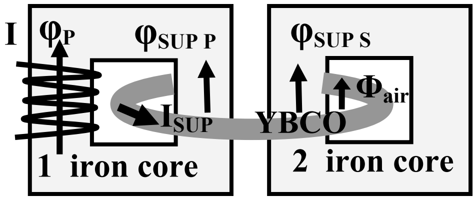

Fig. 10. The scheme of the model showing the direction of flux components.

After placing the secondary iron core into the ring, the value of flux in the primary iron core increases because the flux can develop in the secondary iron core in the opposite direction. This state needs less electric current in ring. The less electric current creates lower contra-flux in the primary iron core. The flux created in air is insignificant compared to that of the secondary iron core due to the differences in permeability.

$$\varphi_P = \varphi_{SUP\ P} + \varphi_{SUP\ S} + \varphi_{SUP\ air} \tag{5}$$

$$\begin{gathered} B_{P.} \cdot A_P = B_{SUP\ P} \cdot A_P + B_{SUP\ S} \cdot A_S + B_{SUP\ air} \cdot A_{air} \\ B_{1.} \cdot A_1 = B_2 \cdot A_2 + B_{air} \cdot A_{air} \\ where\ \ B_1 = B_P - B_{SUP\ P}; \qquad B_2 = B_{SUP\ S} \\ A_1 + A_2 + A_{air} = r^2\pi, \quad A_1 = A_P; \quad A_2 = A_S \end{gathered} \tag{6}$$

$$\begin{gathered} R_{magnetic} = \frac{l_1}{\mu_0\mu_1 A_1} + \frac{l_2}{\mu_0\mu_2 A_2} \times \frac{l_{air}}{\mu_0 A_{air}} \\ \varphi_1 = \varphi_P - \varphi_{SUPP} = \frac{N \cdot I_P}{\frac{l_1}{\mu_0\mu_1 A_1} + \frac{l_2}{\mu_0\mu_2 A_2} \times \frac{l_{air}}{\mu_0 A_{air}}} \end{gathered} \tag{7}$$

Where l_1, l_2, l_{air} = effective long; A = cross section;
μ = permeability.
Consequently, the primary electrical excitation generates flux through $R_{magnetic}$ resistance.
Its value depends on the value of the primary excitation and magnetic resistance of the primary and secondary iron cores.

C. Determining the current of the superconductor ring

The electric current of the superconductor is influenced by the geometric data and magnetic permeability of the primary and secondary iron cores both in AC and DC applications.

In this way the current of the superconductor ring can be planned ahead.

$$\frac{\Theta_P}{R_P} = \Theta_{SUP}\left(\frac{1}{R_P} + \frac{1}{R_S} + \frac{1}{R_{air}}\right)$$
$$I_{SUP} = \frac{N \cdot I_P \cdot R_S \cdot R_{air}}{R_S R_{air} + R_P R_{air} + R_P R_S}. \tag{8}$$

If $R_S \to \infty$, i.e there is no secondary iron core, then

$$I_{SUP} = \lim_{R_S \to \infty} \frac{N I_P R_S R_{air}}{R_S R_{air} + R_P R_{air} + R_P R_S} = \frac{N I_P R_{air}}{R_{air} + R_P}. \tag{9}$$

If $R_S \to \infty$, and $R_{air} \to \infty$, then

$$I_{SUP} = \lim_{R_{air} \to \infty} \frac{N I_P R_{air}}{R_{air} + R_P} = \lim_{R_{air} \to \infty} \frac{N I_P}{\frac{R_{air}}{R_{air}} + \frac{R_P}{R_{air}}} = N I_P. \tag{10}$$

If we use the approach where $R_{air} \to \infty$, and there is secondary iron core

$$I_{SUP} = \lim_{Rair \to \infty} \frac{N I_P R_S R_{air}}{R_S R_{air} + R_P R_{air} + R_P R_S} = \frac{N I_P R_S}{R_S + R_P}. \tag{11}$$

The temporary constancy of the resultant flux of the superconductor ring is realized with less ring electric current when we use the secondary iron core. This happens because magnetization M of the secondary iron core also enhances the flux because $\mu_{secondary} > \mu_{air}$, so lower superconductor current is sufficient for keeping the flux constancy. When switching on or changing primary excitation very slowly, electric field intensity depends on the changing speed of the magnetic field according to Maxwell II equation. But according to Bean postulate it is indifferent how great this electrical field intensity is, as there is critical current density due to the electrical field. The principle of the constancy of flux defines the size of the cross-section of the current necessary to have the contra-excitation.

Inside the superconductor ring the temporary constancy of flux does not depend on the material and this is an unquestionable fact. However, the value of electric current in the superconductor ring depends on the permeability of the primary and secondary iron core and its geometry. If there is no secondary iron core, the flux of opposite direction can be generated in the air only between the primary iron core and the inner side of the ring. In the case there is greater electric current in the superconductor ring and it decreases the flux of the primary iron core with a higher degree.

V. COMPARISON OF THEORETICAL EXAMINATIONS AND MEASURED RESULTS

Starting from equation (2) if $R=0$, we can see from equation (4) that the value of the current in the superconductor ring does not depend on the speed of the change of the applied flux (differential quotient of the flux), as it only shows the momentary values. Thus the magnetic flux of the secondary iron core is independent of the changing speed of the primary magnetic flux. This case can be seen in Fig. 2.

The flux stability of the secondary iron core depends on the decrease of the electric current of the superconductor according to equation (2). In Fig. 3 we can see that in the case of the applied superconductor ring, the secondary flux does not decrease within the interval of 2000 seconds. However, the decrease of the electric current of the superconductor depends on the resistance of the ring defined by E-J characteristics of the superconductor. If there is R resistance, the electric current of the ring should decrease exponentially and so should the flux of the secondary iron core.

In the case of FC method integrating constant represents the trapped flux of the superconductor ring before cooling. These cases shown in Fig. 4 and 5 are also proved by equation (4) as the resultant flux of the primary and secondary iron cores is constant φ_{CONS}.

Starting from equation (8) we can see from equation (10) the case of the typical current limiter.

VI. CONCLUSIONS

1) Numerous new applications can be developed with this arrangement. For example we can change the existing static magnetic field of an YBCO ring with DC applications. In this case, it is not necessary again to trap magnetic field with a new value into the superconductor ring. We can control it.
2) We can develop a new version of current limiter. Currently we are attempting to develop it.
3) Probably with this method the DC and AC magnetic field can be transformed independently of the type of the superconductor.

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