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# PLAYING CATCH WITH ENERGY BETWEEN TWO SUPERCONDUCTING COILS

by

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## Abstract

The first performance of playing catch with energy between two 100 kJ superconducting magnets has been presented. The mechanism of the energy transfer as an interface between the superconducting coils is a thyristorized DC-AC-DC converter. The obtained experimental efficiency of energy transfer has been compared with the theory and good agreement has been obtained. The method will offer a versatile extension of superconductive technique in energy problems.

## 1. Introduction

Magnetic fusion reactors, equilibrium coils and ohmic heating coils, require large pulsed energy which is cycled in relatively short period of time. The operation of accelerator magnets which are made of normal conductors or superconductors has similar situation, the same period of time and almost the same amount of energy that is from hundreds to thousands of MJ range. These large amount of pulsed energies can move a power grid with an adverse effect.

As far as the accelerator concerned, many schemes have been proposed on this problem and some of them have been constructed successfully. One is reactive power control by thyristors[1] for a proton synchrotron. No matter how precisely the reactive power is controlled by the thyristor device, the active power has never been controlled.

For the fusion reactors, the necessity of some devices of energy storages is not only for suppression of the adverse effect to the power grid but also includes the improvement of operation efficiency by saving energy losses over an operation cycle. Some schemes have been also proposed for the fusion reactors. They are a homopolar generator, a flywheel motor-generator and a superconductive energy storage.

The flywheel motor-generator had been employed in old accelerators. But for a past decade, the flywheel machine has never been employed in the modern accelerators because of the mechanical failure of the generator pole. Now the static machine is conventional rather than the rotating machine. Thus the fusion reactors and the big accelerators have the common problems and should prepare the same devices to minimize the amount of energy required from the power grid. The pulsed superconductive energy storage is one of the solutions of the above mentioned problems.

The purpose of the paper is to introduce the connected technique to the superconductive energy storage that is the energy transfer between two superconducting coils, imaging that one is the storage coil and the other is the accelerator magnet or the poloidal coil in Tokamak for example.

## 2. Experimental Procedure

Two superconducting coils, each storing 100 kJ, have been set in a same dewar. The similar experiment has been already carried out by Argonne group[2] and one shot energy transfer has been tried.

The present experiment has been done not only for one-shot energy transfer from one coil to the other but also done for energy catch between the two superconducting coils.

Photograph 1 shows the overview of setting of the two 100 kJ superconducting coils. The interface of the two superconducting coils that is the energy transmitter is the thyristor inverter which had been proposed by Wisconsin group.[3] The description of the detail of the circuit and the logic controller to fire the thyristors sequentially is out of the scope of the present paper but is roughly done in Fig. 1.

The experimental procedure for each run has been done as follows. A DC power source, 50 amperes and 100 volts, drove the thyristor bridge 1 and generated AC voltage of 400 to 500 Hz between terminals of commutating capacitors. The generated AC voltage was rectified and the coil 2 was charged up to the maximum by the thyristor bridge 2. This is the charging cycle. After that, the system was isolated from the DC power source by a switch and immediately the stored energy in the coil 2 was transferred to the coil 1 with the inverse operation of the bridges 1 and 2.

When the whole energy was transferred to the coil 1 by the thyristor bridges, once again the energy was transferred back to the coil 2 with just the inverse operation of the thyristor bridges.

The feature of the experiment was likely as a catch of energy but the repetition could not be continued as playing catch with a ball. The total energy decayed mainly by the thyristor loss and the cycles could be really continued only 5 to 7 times. Figs.2 and 3 show the recorded sheets for one shot energy transfer and the catch of energy.

## 3. Estimation of Loss

The estimation of losses which is one of the most important factors to evaluate the system of the energy transfer has been tried on one-shot scheme. The schematic diagrams of the circuit and the current forms of the two coils for calculation are shown in Figs.4 and 5, respectively. The energy is transferred from $I_p$ to $I_s$ in a period of time $\tau$. The two superconducting coils are identical and therefore both nominal rated currents are the same. By the energy transfer the accepted current is about 10 to 30 % smaller than the transmitted current because of losses.

The losses are mainly caused by the thyristor forward voltage drops, the protection resistors and the circuit cables. The forward drop voltage and the resistances of the resistors and the cables are denoted $\Delta V$, R and r, respectively. The energy loss per one shot energy transfer can be estimated as follows.

$$\Delta W \cong \int_0^\tau [nI_p\frac{t}{\tau}\Delta V + r(I_p\frac{t}{\tau})^2 + nI_s\frac{t}{\tau}\Delta V + r(I_s\frac{t}{\tau})^2]dt,$$

$$\cong \frac{1}{2} LI_p^2 - \frac{1}{2} LI_s^2 \qquad (1)$$

where $I_p$ and $I_s$ are the primary and the secondary currents flowing into the commutation capacitors, and n is the number of thyristors carrying the current. The current ratio, $I_s/I_p = \alpha$, is given from a solution of Eq.1. In the present case, L, r and ΔV are assumed as 0.22 H, 10 mΩ and 2.0 V, respectively. Then Eq.1 is transferred to the following equation.

$$(0.11 + \frac{1}{3}\cdot 10^{-2}\tau)\alpha^2 + 3\tau\frac{1}{I_p}\alpha - (0.11 - 2\tau\frac{1}{I_p} - \frac{1}{3}\cdot 10^{-2}\tau) = 0. \qquad (2)$$

Thus the $\alpha$ is obtained as a solution of the equation.

$$\alpha \approx 1 - 23\frac{\tau}{I_p} - 0.03\tau \ . \qquad (3)$$

On the other hand, $I_p$ and $I_s$ are shared by the coils and the protection resistors as shown in Fig.4. The sharing ratio, $\beta$, is given as follows.

$$\beta = I_p/I_p^L = \frac{1}{1 + \frac{T_0}{\tau}} \qquad (4)$$

where $T_0$ is the time constant between the superconducting coil and the protection resistor, L/R. Thus the total efficiency of transfer, $\eta = (I_s^L/I_p^L)^2$ is obtained as follows.

$$\eta = [\beta^2\{1 - 23\tau\frac{1}{I_p^L\beta} - 0.03\tau\}]^2. \qquad (5)$$

The calculations have been done for three different currents of the coil and for both cases of with and without the protection resistors. The results are summarized in Fig.6.

## 4. Experimental Results and Discussions

More than thirty experimental runs have been carried out. The typical pen-recorded sheets are shown in Figs.2 and 3. From these recorded sheets the transfer efficiencies, $\eta$, have been obtained as shown in Fig.7. The good agreements were obtained with the calculated results as shown in Fig.7. The shorter the transfer time is, the better the transfer efficiency is without the protection resistors. In the case with the protection resistors, the quick transfer was difficult. Anyway one of the main reasons to deteriorate the transfer efficiency might be the protection resistors. Even if the varistors are employed for protection purpose, these might give an adverse effect on the quick transfer.

One more main loss in the present circuit is the thyristor loss. The thyristor loss comes from the forward voltage drop which is constant value for any types of and any sizes of thyristors. Therefore, the thyristor loss is in linear proportion to the current. On the other hand, the stored energy is always proportional to the square of the current. Thus the thyristor loss for a bigger system, that is more than 100 MJ for example, will play a minor role in the losses of the system of the superconductive energy storage.

## References


1) M. Masuda, S. Matsumoto and T. Shintomi: "Flicker Suppressor by Thyristor", IEEE Trans. on Nucl. Sci., NS-24, 1306, 1977.
2) R.L. Kustom, R. Fuja, R.P. Smith, J. DeOlivares, A. Kellman and T.J. Bauer: "The Use of Multiphase Inductor-Converter Bridges as Actively Controlled Power Supplies for Tokamak Coils", Argonne National Laboratory Report, ANL/FPP/TM-78, 1977.

3) H.A. Peterson, N.Mohan, W.C. Young and R.W. Boom: "Superconductive Inductor-Converter Units for Pulsed Power Loads", Proceedings of International Conference on Energy Storage, Compression, and Switching, Asti-Torino, Italy, November 5-7, 1974, Plenum Press, N.Y., pp.309.

Appendix

No load AC voltage of a capacitor commutated inverter

## Star connection of capacitors

The star connection of the inverter is shown in Fig.A-1. The sequence of triggering the thyristors is just like one in a Graetz bridge. The voltage wave form of both terminals of a capacitor is shown in Fig.A-2.

$$V_c \cong \frac{1}{\sqrt{2}} \int_0^{\frac{1}{6f}} \frac{I_0}{C}\, dt$$

$$V_c = \frac{1}{6\sqrt{2}} \frac{I_0}{Cf}$$

where $V_c = V_{c1} = V_{c2} = V_{c3}$ = the rms voltage on the capacitor,

$C = C_1 = C_2 = C_3$ = the value of the capacitors,

$I_0$ = the constant source current, and

$f$ = the frequency.

## Delta connection of capacitors

The delta connection of the capacitors is shown in Fig.A-3. The voltage wave form of both terminals of a capacitor is shown in Fig.A-4.

$$V_c \cong \frac{1}{\sqrt{2}} \left[ \int_0^{\frac{1}{12f}} \frac{2}{3} \frac{I_0}{C}\, dt + \int_0^{\frac{1}{6f}} \frac{1}{3} \frac{I_0}{C}\, dt \right]$$

$$= \frac{1}{9\sqrt{2}} \frac{I_0}{Cf}$$

where the notations are the same as the delta connection.


Photograph 1. The setting of the two 100 kJ Superconducting coils.

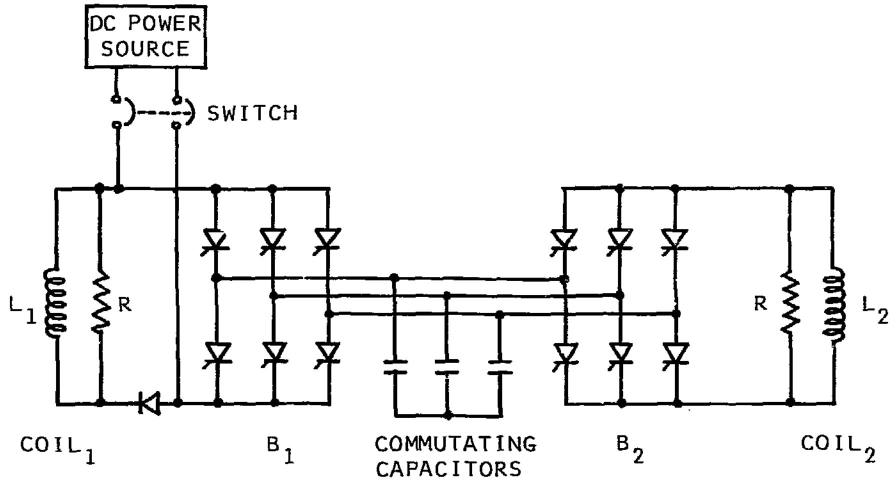


Fig. 1. The schematic diagram of the experiment. L and B are superconducting coils and thyristor bridges respectively. R means the resistance of protection resistors.

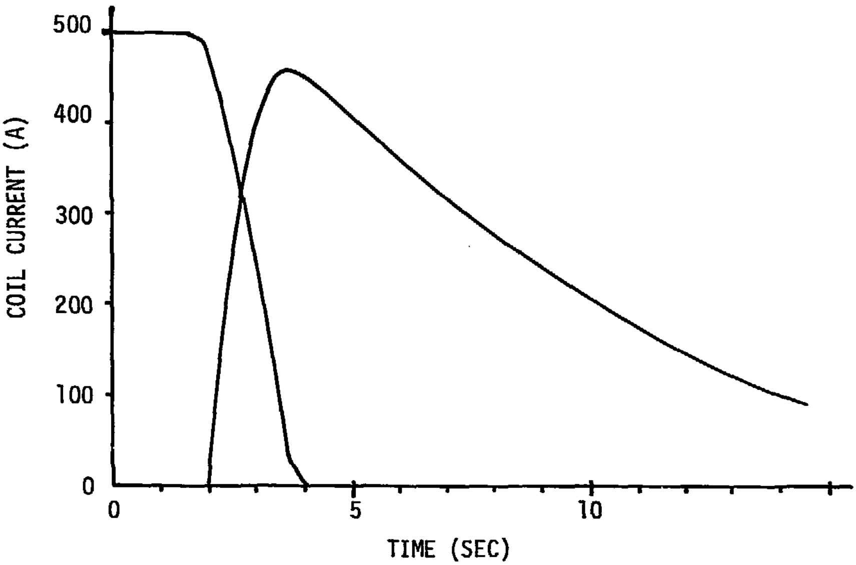


Fig.2 Recorded currents in one-shot energy transfer. between the two coils.

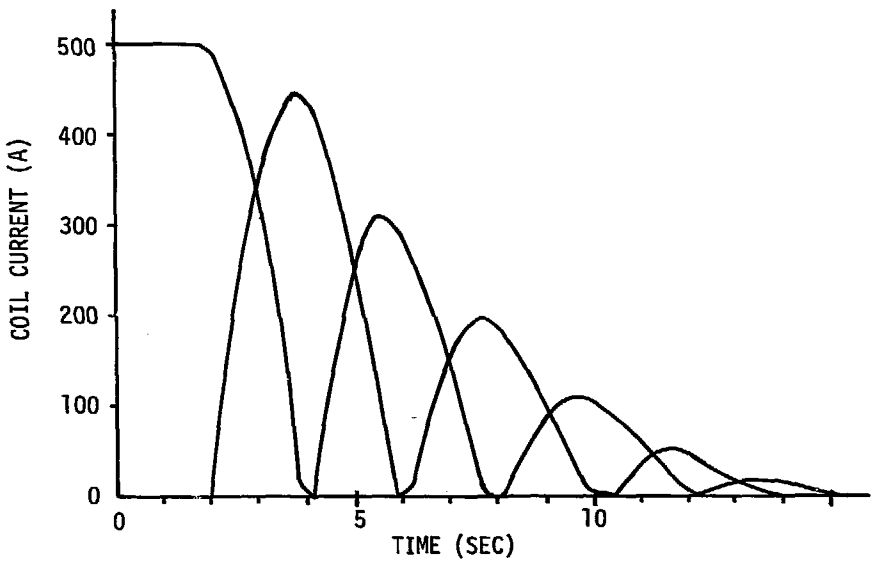


Fig.3 Recorded currents in the catch of energy between the two coils.

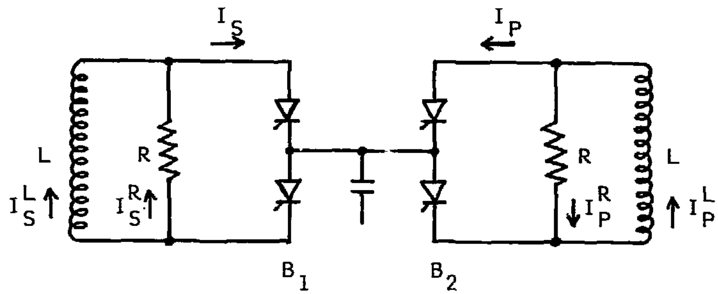


Fig. 4. The circuit of the energy transfer

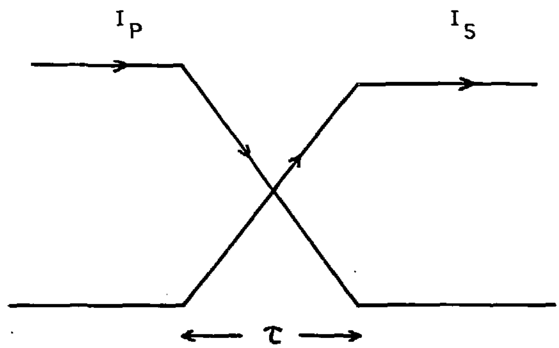


Fig. 5. The assumed current forms of the two superconducting coils. $\tau$ is the transfer time.

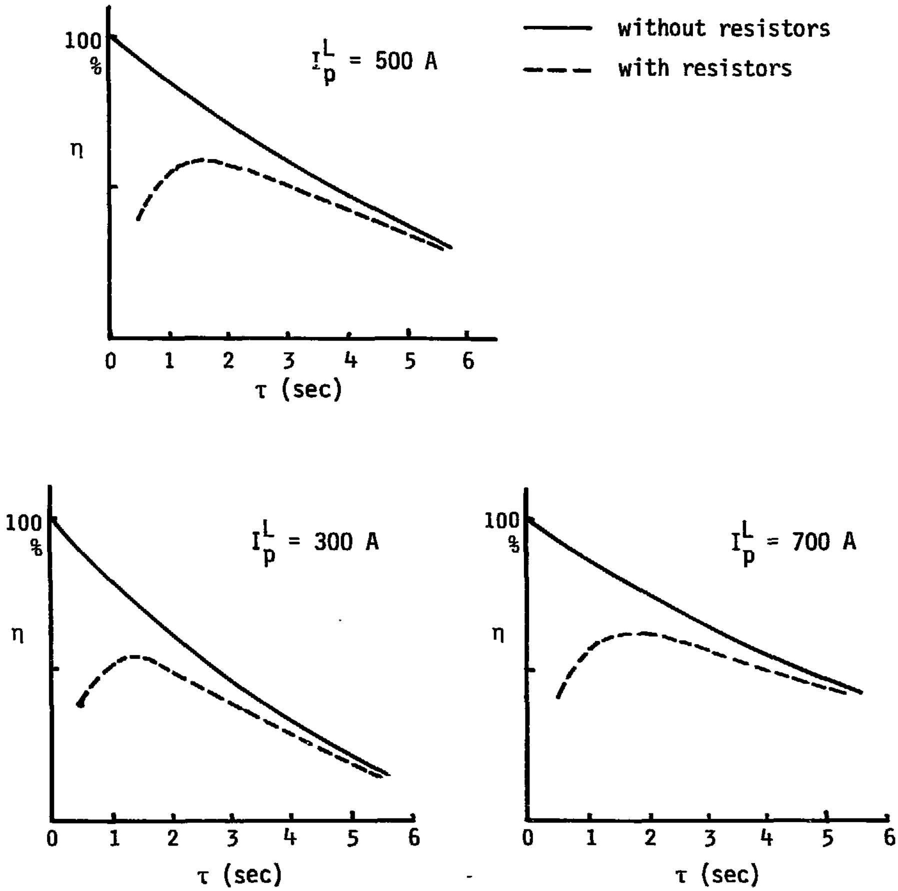


Fig. 6. Calculated efficiencies of one-shot energy transfer for three different amperes of the current and for with and without the protection resistors.

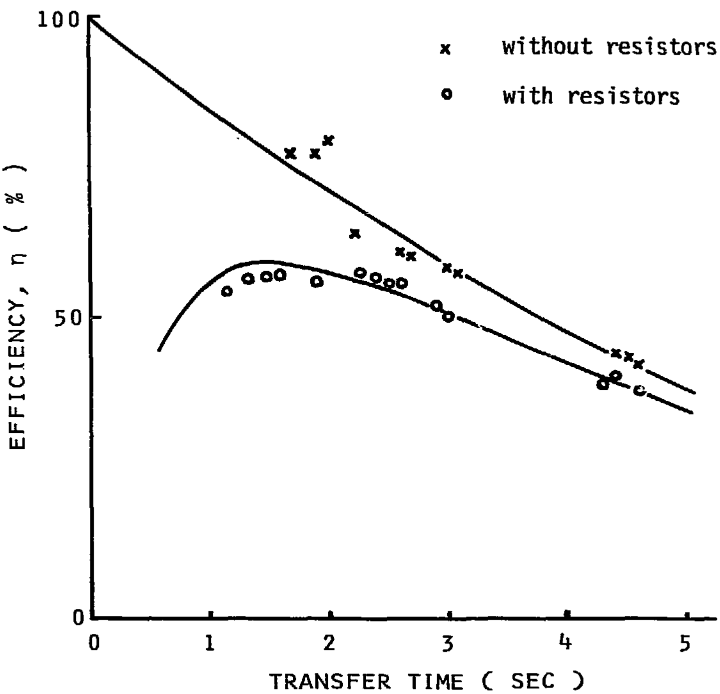


Fig. 7. The experimental results of efficiencies of one-shot energy transfer with and without the protection resistors. The solid lines are the calculated efficiencies.

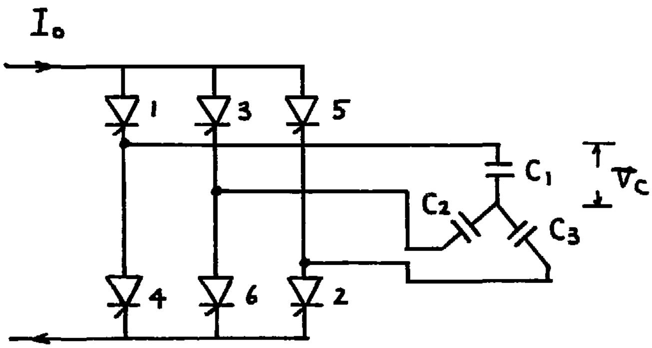


Fig. A-1. Star connection of capacitors.

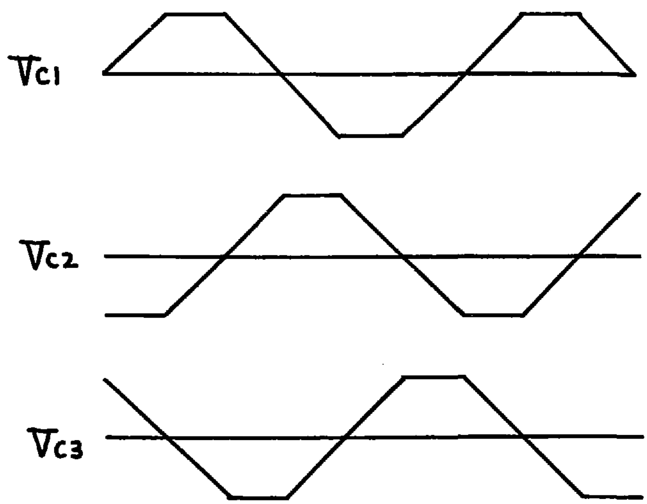


Fig. A-2. Capacitor voltage waveforms of the star connection.

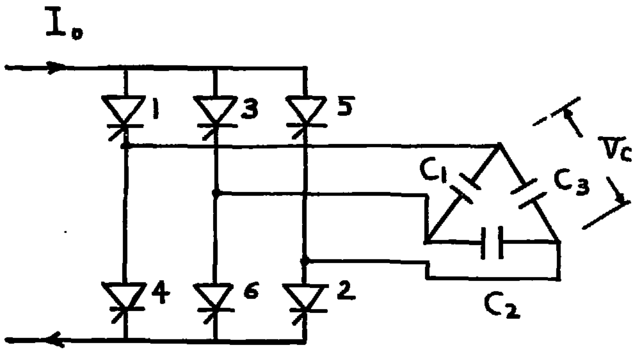


Fig. A-3. Delta connection of capacitor.

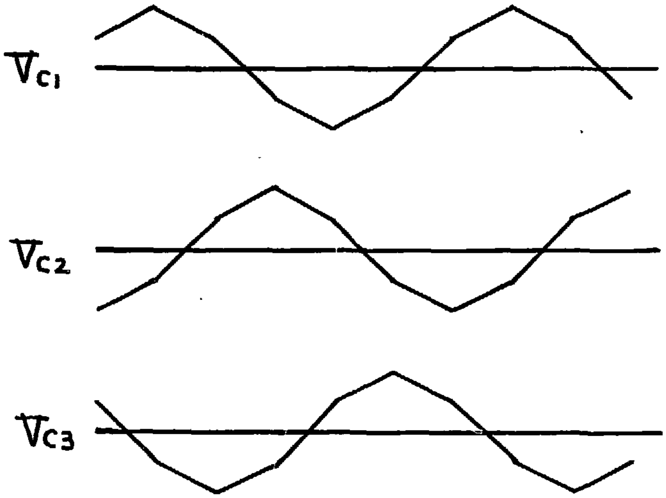


Fig. A-4. Capacitor voltage waveforms of the delta connection.