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RESULTS FROM A MODEL SYSTEM OF SUPERCONDUCTING SOLENOIDS AND PHASE SHIFTING BRIDGE FOR PULSED POWER STUDIES FOR PROPOSED TOKAMAK EF COILS*

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Summary

A matched pair of superconducting solenoids and a phase-shifting bridge circuit has been constructed to study energy storage and transfer for application to tokamak EF coils. The intrinsically stable solenoids, each with 4 H self-inductance, incorporate sufficient cooling to allow charging at several hundred volts, corresponding to $\dot{B}$ = 1 T/sec. The three-phase inductor-convertor capacitive bridge network operating at up to 150 V rms transfers energy reversibly and at controllable rates from the storage coil to the load coil.

1. - Introduction

Superconducting energy storage inductors have been proposed [1] for storing the energy of the OH and EF coils of tokamak power reactors between plasma burn cycles. Because the EF coils of a tokamak must be excited dynamically in response to plasma current, temperature and position during the burn cycle of the reactor, unique requirements are made of the EF coil power supply system. An energy transfer circuit suggested by Peterson et al.,[2] promises to meet the power transfer and control requirements of the EF coil excitation circuit supplied from a storage inductor.

2. - Model System

Two superconducting solenoids and a dc-ac-dc Inductor-Convertor (IC) Bridge circuit (Fig. 1) have been constructed to model the mechanism whereby energy can be extracted from a storage inductor and transferred at a variable and controllable rate to an EF coil.

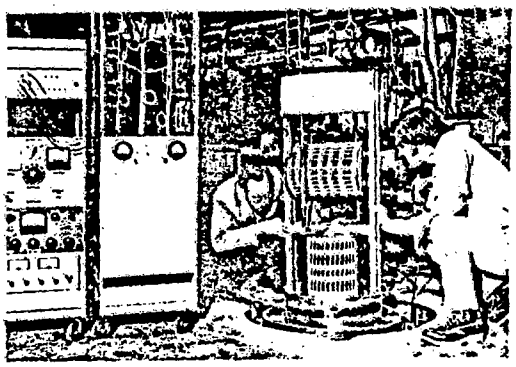

Figure 1. Model IC Bridge and Superconducting Solenoids

2.1. - Superconducting Coils. The two identical solenoids store 125 kJ each at 250 A and are designed to permit charging at voltages corresponding to $\dot{B}$ = 1 T/sec without degrading the ultimate quench limit of the superconductor. The coils each contain 6000 turns of a 1 mm diameter copper-stabilized filamentary Nbti conductor, and each coil reaches the short sample limit of 4.2 T when charged at 150 V. This charging voltage was the highest available during the magnet tests and corresponds to $\dot{B}$ = 0.6 T/sec. The two 34 kg coils are each wound on an epoxy-fiberglas bobbin and are suspended with their axes mutually perpendicular in a single large cryostat for ease of cryogenic operations. The orientation of the coils ensures no inductive coupling, and a rigid frame resists the torque tending to align the coils when both carry current.

The coil parameters are given in Table I.

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The coil bobbins are made of epoxy-fiberglas cylinders of 0.8 cm wall thickness with 1.3 cm thick G10 end flanges epoxied to the cylinders. Interlayer cooling passages are formed by 0.025 cm thick mylar "pickets" laid across each level-wound layer. The pickets are 0.3 cm wide and separated by 0.3 cm; a 0.008 cm thick continuous sheet of mylar was laid on the layer after the pickets were in place to provide inter-layer dielectric insulation. A total of 16 layers of conductor, each of 373 turns, completed the coil. The winding tension was approximately 60 N, and epoxy-fiberglas bands and 1.0 cm thick micarta pickets banded the outer layer of the coil firmly in place.

Table 1. Solenoid Parameters

Inner Diameter	22.0 cm
Outer Diameter	26.6 cm
Length	40.6 cm
Number of Turns	5969
Self-Inductance	4.0 Hy
I_c	265 A
Peak Field at I_c	4.3 T
λ (packing fraction)	0.51
λJ_c	1.69×10^8 A/m2

The eddy current losses in the conductor matrix for a linear rise and fall of the external field, are given[3] by:

$$Q_m = \frac{4 \dot{B} \hat{B} r^2}{3\pi \rho m} \text{ Joules/m}^3 \text{ per cycle.} \quad (1)$$

For $\dot{B}$ = 1 T/sec and $\hat{B}$ = 4 T, $Q_m = 8.5 \times 10^4$ J/m^3 per cycle. The hysteresis losses in the superconductor are given[3] by:

$$Q_h = \frac{4 J_o B_o d_f}{3\pi} \ln \frac{B_o + B}{B_o} \text{ Joules/m}^3 \quad (2)$$

per cycle. With $d_f = 25 \times 10^{-6}$ m, and $\beta = 0.25$, $Q_h = 3.8 \times 10^4$ J/m^3 per cycle. Enough cooling space was provided such that less than one-fourth of the helium in the cooling channels will vaporize in a cycle where the total heating is 12.3×10^4 J/m^3.

3. - Invertor-Convertor Bridge

The circuit diagram for an IC bridge which can extract energy from a storage inductor and transfer it to a load inductor at controllable rates is shown in Fig. 2. The switching sequence which commutates SCR's 15, 16, 26, 24, 34, and 35 into the conducting state generates a symmetrical multi-phase voltage on the capacitors. The right hand side of the bridge switches by the same sequence as the left hand side, although identical switching steps do not necessarily occur at the same instant in time. This difference in time is measured as a phase angle, ϕ, relative to a full switching cycle. The The phase angle, ϕ, can be varied so energy is transferred from one coil to another at a controllable rate.

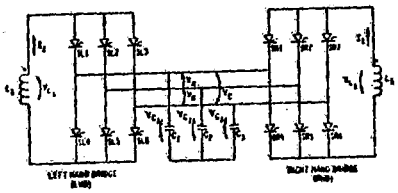

Figure 2. Circuit Diagram for the 3-Capacitor Model IC Bridge

If one considers the instant at which SR1 and SR5 both become conducting, then

$$I_s(t) = I_s^o \cos \omega t + \frac{V_{C_1}^o - V_{C_2}^o}{\omega L_s} \sin \omega t$$

$$V_{C_1}(t) = \frac{I_s^o}{\omega C} \sin \omega t - \frac{V_{C_1}^o - V_{C_2}^o}{2} \cos \omega t + \frac{3V_{C_1}^o}{2} - \frac{V_{C_2}^o}{2} \quad (3)$$

$$V_{C_1}(t) = -\frac{I_s^o}{\omega C} \sin \omega t + \frac{V_{C_1}^o - V_{C_2}^o}{2} \cos \omega t - \frac{V_{C_1}^o}{2} + \frac{3V_{C_2}^o}{2} .$$

The capacitors only store a small fraction of the total energy of the system so ωt is a small quantity. Thus to first order in ωt,

$$I_s(t) = I_s^o + \frac{V_{C_1} - V_{C_2}}{L} t$$

$$V_{C_1}(t) = \frac{I_s^o t}{C} + V_{C_1}^o \tag{4}$$

$$V_{C_2}(t) = \frac{I_s^o t}{C} + V_{C_2}^o .$$

The value of ω is $2/L_s C$.

At the beginning of the energy transfer cycle, when all the energy is stored in L_s, the capacitor voltages are given in Fig. 3. V_o is equal to $I_s t_s/C$, where t_s is the time between switching pulses. In Fig. 3 is also shown the voltage waveforms across the storage and load (EF) inductors for the choice of phase $\phi = 90°$. The voltage on the storage coil varies from V_o to $-V_o$ for which the average value is equal to or near zero, while the voltage on the load coil averages $-1.875\ V_o$.

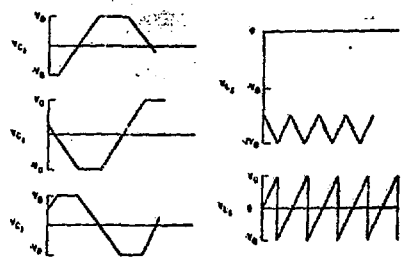

Figure 3. IC Bridge Capacitor and Coil Voltages When Load Coil Current is Zero and ϕ is 90°.

It is possible to analyze the behavior of the bridge for a variety of relative phases and relative coil currents. In all cases, the switching sequences must be such that the capacitors are properly charged relative to each other to succeed in force-commutating the current conduction from one bridge arm to the next. Acceptable phases, as function of current ratio I_L/I_s are shown in Fig. 4 for both the 3-capacitor model bridge and a 5-capacitor bridge. The forbidden regions correspond to a choice of phase which generates a switching failure; i.e., a bias condition on the SCR's which prevents current commutation.

The average values of load coil voltage normalized to $I_s t_s/C$ are shown in Fig. 5 for various choices of phase angle ϕ as a function of current ratio I_L/I_s. Not all phases are allowed for the entire range of current ratios, thus the voltage curves cannot be constructed across the entire graph for phases greater than 90°.

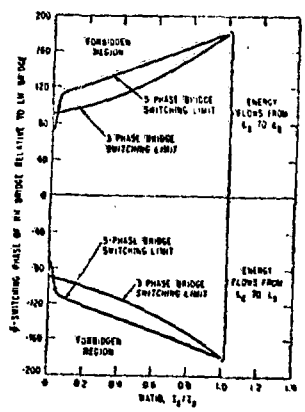

Fig. 4. Acceptable Switching Phase ϕ as a Function of I_L/I_s.

The three-capacitor bridge has a digital controller to provide switching pulses for a set of six SCR's on the supply side of the bridge and six SCR's on the load side of the bridge. With a choice of $C = 200\ \mu F$, $I_s^o = 150$ A and $V_{max} = 150$ V, the switching time is 200 μsec. The model bridge permits a choice of ϕ, and suitable initial conditions of the inductors and capacitors,

to be preset. The digital controller then switches the SCR's at a fixed frequency in a fixed sequence. Protection circuitry guards against overvoltages on the SCR's in the event of circuit failure.

4. - Experimental Results

Operation of the bridge has resulted in successful energy transfer from one inductor to the other with an efficiency exceeding 95%. Since the operation of the bridge is completely symmetric in ϕ, the phase angle can be reversed and the current transfers back from the load coil to the storage coil. In Fig. 6 are the oscillograms of the load coil voltage during the transfer half-cycle. It is seen that the waveforms evolve from the fully charged coil to the completely deenergized coil, just as calculated in Fig. 3.

Subsequent effort will be expanded to modify the digital controller to include dynamic variation of the phase and switching frequency, so that active control of the energy transfer rates can be achieved.

5. - References

(1) W. M. Stacey, Jr. et al., "EPR-77, A Revised Design for the Tokamak Experimental Power Reactor," ANL/FPP/TM-77, Argonne National Laboratory, Argonne, IL 60439, March 1977.

(2) H. A. Peterson et al., "Superconductive Inductor-Convertor Units for Pulsed Power Loads," Energy Storage, Compression, and Switching, p. 309, Plenum (1974).

(3) M. N. Wilson, "Filmentary Composite Superconductors for Pulsed Magnets," RPP/A89, Rutherford Laboratory Preprint.

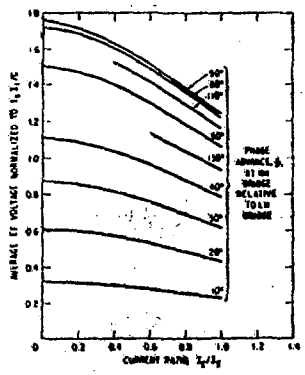

Fig. 5. *Average Coil Voltages on Load Coil as a Function of ϕ.*

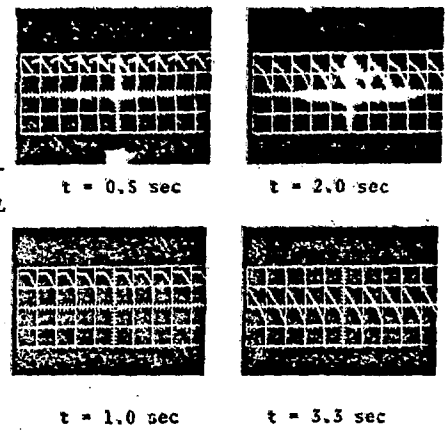

Fig. 6. Load Coil Voltages During Energy-Transfer Half-Cycle