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A 10-kA PULSED POWER SUPPLY FOR SUPERCONDUCTING COILS

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Abstract

A new 4-MW inductor-converter bridge (ICB) for supplying power to pulsed superconducting magnets is under construction at Argonne National Laboratory. This is a second-generation ICB built at Argonne Lab. The analytical, design, and control techniques developed for the first prototype have been used in the design of the new system.

The paper presents the important considerations in the design of the new ICB. A brief description of the operation of the circuit is also given.

Introduction

The inductor-converter bridge (ICB) is a solid state dc-ac-dc converter system for reversible energy transfer between two high Q inductors. Figure 1 shows a schematic diagram of a three-phase ICB circuit. The details of operation of the ICB may be found in Refs. 1 and 2. The operation of the three-phase ICB is summarized here. At a typical instant during the energy transfer in the circuit, dc currents i_S and i_L will be present in the storage and load coils, respectively. The storage side (left-hand) converter is fired in the normal Graetz bridge sequence.

SL1-SL5, SL1-SL6, SL2-SL6, SL2-SL4, SL3-SL4, SL3-SL5, SL1-SL5,...

The load side (right-hand) converter is fired in the same sequence but may be out of step with respect to the storage converter. The direction and level of power is controlled by this relative switching timing (phase difference) between the storage and the load converters. When the load bridge switching sequence leads the storage bridge sequence, the net power is into the load and vice versa. The y-connected capacitors serve as the intermediate energy storage between the two coils. They also provide the necessary reverse voltage to commutate the coil currents from one SCR to the next. The circuit is designed so that, in every converter cycle, a very small fraction of the magnetic energy is stored in these capacitors and then transferred.

The inherent efficiency and real time control of power in either direction makes these circuits specially suitable for pulsed superconducting magnets, requiring *several hundred megawatts and durations from a fraction* of a second to minutes. Two such applications are superconducting equilibrium field coils of the projected tokamak fusion reactors[3] and superconductive magnets needed in the future particle accelerators.[4] In such systems, the load constitutes one of the ICB coils, the other being the storage superconductive coils. After the initial charging of the storage coil, energy is delivered to the load coil according to the load requirements. The system losses are continuously supplied to the storage coil by the utility grid. Thus, large pulsed powers in the energy transfer process can be isolated from the utility power grid. The storage coil may be used to supply several such inductive loads.

The development of the ICB has been underway at Argonne National Laboratory (ANL) since 1977.[5] The first ICB prototype, which was a 125 kJ system, was built and tested at ANL. This prototype demonstrated the circuit operation and controllability of power. In addition, a time optimal, microcomputer based control system was developed for this system.[2] Thus, the load current was controlled in a closed loop.

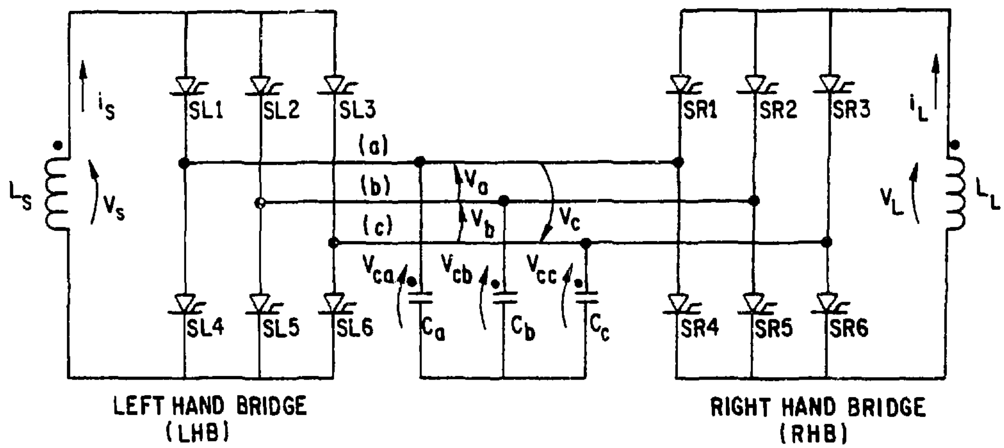

Fig. 1. Circuit Diagram for the 3-Capacitor Model IC Bridge.

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The construction of a second generation ICB prototype, capable of storing 3 MJ, is presently underway at ANL.

This paper presents the important design and construction aspects of the new ICB system.

The 10 kA ICB

The new ICB system was specifically designed for supplying power to experimental pulsed superconducting magnets. However, it will also provide design experience with higher power ICB's which require paralleling of the SCR's for each converter arm. Furthermore, it will provide opportunity to re-evaluate and expand the control concepts that were developed on the smaller ICB system.

Circuit Characteristics

The details of the superconducting storage and load coils is presented in a separate paper.[6] The electrical characteristics of the coils are listed below.

Storage Coil	Load Coil
L_S = 25 mH	L_L = 60 mH
I_{max} = 11 kA	I_{max} = 10 kA
E_{max} = 1.5 MJ	E_{max} = 3 MJ
B_{max} = 4.5 T at I_{max}	B_{max} = 6 T at I_{max}

A photograph of the load coil appears in Fig. 2.

Fig. 2. A 3 MJ, 10 kA superconducting pulsed coil

From the analysis published previously[2,7], the average coil voltages, currents, and power in the coils are

$$i_S(t) = 10{,}000 \cos \pi/2t \text{ A}$$
$$i_L(t) = 6455 \sin \pi/2t \text{ A}$$
$$v_S(t) = 392 \sin \pi/2t \text{ A}$$
$$v_L(t) = 608 \cos \pi/2t \text{ V}$$
$$p(t) = 1.96 \times 10^6 \sin \pi t \text{ W.}$$

The above behavior is for when the storage coil is charged to 10 kA initial current, the converters are operated at 1325 Hz, and the load converter leads the storage by 90° phase angle. For this operation, two of the 3.6 mF, y-connected, capacitors are precharged to 350 V.

To handle the 10 kA peak current, six SCR's will be connected in parallel for each arm of the converters. Thus, the ICB will contain 72 SCR's rated at 1400 V and 1600 A rms with di/dt rating of 800 A/μs. The current in the parallel SCR's of each converter arm is equalized inductively as shown in Fig. 3.

The SCR and capacitor voltage rating is based on the highest expectable voltage in the system. This will occur when the system is operating at zero phase difference and the sum of the storage and load currents is the maximum. It can be shown that the maximum total current happens when the ratio of the storage to load current is $i_S/i_L = L_L/L_S$. This total current is 11902 A and will produce a peak voltage of 415 V on the phase capacitor. The converter SCR's will see double the per phase voltage or 830 V. Therefore, the 1400 V rated SCR's are quite adequate for this purpose.

Special attention is paid to the SCR commutations. At the instants of switching on each converter, the correct capacitor voltage polarities must be present on the off going and on coming SCR's. The commutation condition is a function of the coil current ratios, operating phase angle and frequency, as well as the stray resistance and inductance in the commutation loop. In the new ICB system, the commutation is more complicated due to the six parallel SCR's that must switch together in each arm.

Control System

The load coil current in the ICB will be controlled in a microcomputer based closed loop configuration. A time optimal control strategy was developed and tested on the first ICB prototype. A similar control strategy, which modulates the operating phase angle, will be implemented in the new system. However, to further optimize the system, a combination of phase and frequency control[2] will be considered.

The new ICB system is substantially larger, faster, and more complicated in its behavior than the first prototype. Therefore, the expansion and adaptation of the mentioned control system to the new prototype will give additional experience and confidence in the developed control strategy for the future ICB's with much higher power ratings.

Conclusions

The experience in analysis, design, and control of the ICB has been applied to building a new 4 MW, 10 kA, 3 MJ pulsed power supply at ANL. The new system removes the circuit simplifications that were present in the first ICB prototype. The developments in the new ICB include; 1-parallel SCR in each converter arm, 2-unequal

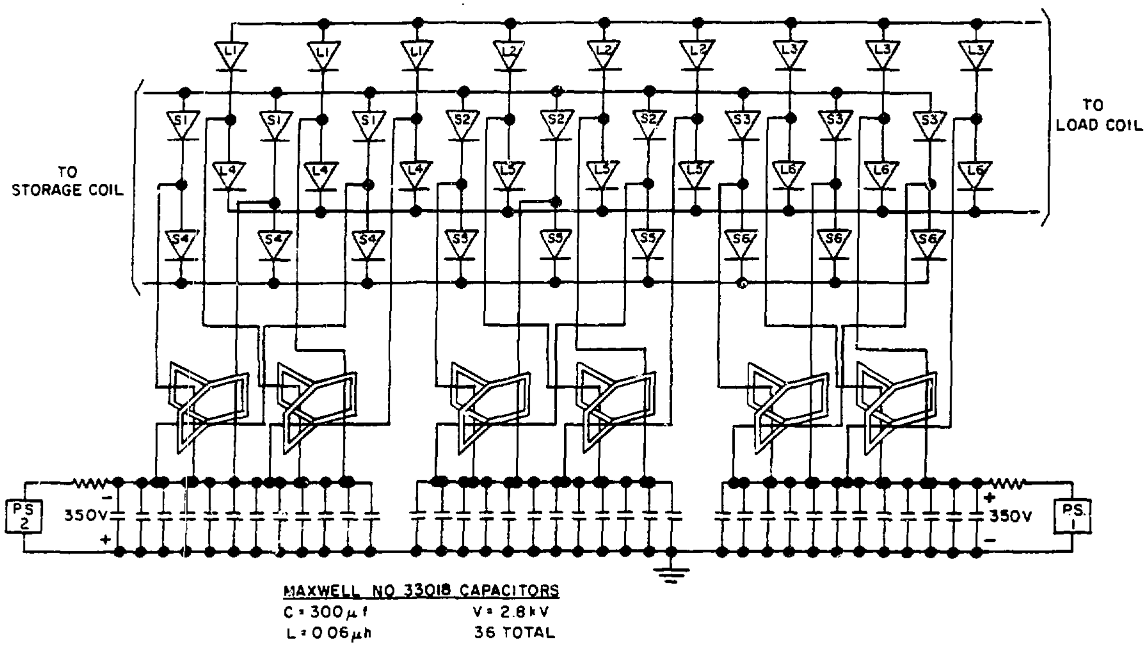

Fig. 3. Circuit diagram for a 5 kA ICB with thyristor current equalizing

storage and load inductors. 3-higher operating frequency, 4-higher power and other electrical ratings.

This ICB system will be used to supply power to experimental pulsed superconducting magnets.

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