ARGONNE NATIONAL LABORATORY ENERGY STORAGE AND TRANSFER EXPERIMENTAL PROGRAM*

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Introduction

Magnetic fusion reactor, equilibrium field, and ohmic heating (OH) coils require the coil energy to be cycled in relatively short periods of time. For large fusion reactor systems, the energy can be in the thousands of MJ range. These large amounts of energy cannot be removed from or returned to the power grid without having an adverse effect on the grid.

Several schemes have been proposed which can minimize the amount of energy required from the power grid over a fusion-reactor cycle. They include the flying capacitor,[1] the inductor-convertor bridge,[2,3] the homopolar generator,[4] and the motor-generator flywheel (MGF). The MGF is best understood and has been in use for this purpose for many years. It requires the least amount of development. The other schemes have not been applied to the energy buffering problem and require considerable development. Of the three remaining schemes, the homopolar generator and the inductor-convertor bridge seem to be the most desirable.

Each system has certain advantages and disadvantages. The homopolar generator is best suited for application where the system element can be allowed to operate in a passive sense that is operating at their natural frequency. An example would be the cycling of the OH coil current. The inductor-convertor bridge is a bit more complicated in its operation, but it has the advantage of being controllable, that is, it allows the transfer of energy at a controlled and variable rate.

Inductor-Convertor Bridge

Two superconducting solenoids, each storing 45 kJ at 150 A and capable of being charged at 150 V, along with an inductor-convertor bridge, were constructed. This circuit models the mechanism whereby energy can be extracted from one inductor and transferred, at a controlled rate, to the other inductor. A three-phase bridge circuit is shown in Fig. 1, and a block diagram of the digital controller providing the proper thyristor firing sequence is shown in Fig. 2. By controlling the phase delay between the switching sequences of the two sides of the bridge, net average voltage across the capacitor network can charge and discharge the inductors at controlled rates.

The energy the capacitors are allowed to accumulate is limited to a small fraction of the total energy in the system. An important feature of the bridge circuit is that if the energy stored in the capacitors is not removed by the load coil it goes back into the storage coil. Experiments were performed on this system and pictures of the voltage across the load coils at various times are shown in Fig. 3. The results obtained from these experiments agree nicely with the predicted theory.

An analysis of the bridge circuit is simplified when the theory of superposition is applied. Each inductor acting alone will, when provided with a proper switching sequence to the thyristors, generate a trapezoidal voltage across the capacitors. The summation of these two voltage waveforms will produce the correct voltage waveform appearing across the capacitors at any instant in time. From these waveforms, the voltage across the individual inductors can be obtained. The resulting capacitor waveforms in general will not be trapezoidal, but will depend on the relative magnitude of the currents in each coil and the phase displacement between the waveforms. Analysis shows that a phase displacement of from 0 to 90° will produce energy transfer in one direction, and 0 to -90° will produce energy transfer in the opposite direction.

At zero degrees, no net energy transfer takes place, and as the phase angles are increased, net energy transfer increases and reaches a maximum when the phase angles are at ± 90°. Computer analysis of the circuit has produced graphs which relate the voltage across the inductors as a function of coil current ratios and phase angles. These graphs are shown in Fig. 4.

If the energy transfer rate is to be variable during a transfer cycle, computer analysis shows that large capacitor voltage unbalances will be created, depending on the magnitude of the phase change. To minimize and eliminate any unbalance occurring, the phase change should be made to the bridge side containing the least current. Also, the phase change should be applied in at least two equal steps at 180° intervals. Figure 5 shows the unbalances created by changes in relative phase and the elimination of the unbalances by making the change at the proper time.

A microprocessor has been obtained to function as the controller for the inductor-convertor bridge. The microprocessor will examine the coil currents and, with information about the desired coil voltage, determine the proper operating phase angle. It will then make any necessary phase angle adjustments to the proper bridge thyristors at the proper interval. It will also function as a watch dog over the entire system and take appropriate action upon a system failure.

Homopolar Generator

A 40 kJ, 2500 A model of an air-supported aluminum drum-type homopolar generator has been constructed. The switching circuits for the system are installed and a schematic of the entire system is shown in Fig. 6. A photograph of the generator system is shown in Fig. 7.

A conventional magnet has been modified with special pole tips to provide a radial magnetic field through the surface of a central iron column. An aluminum (6061-T6) cylinder and air-bearing system is mounted on the iron column. The dimensions of the drum are scaled from the full-sized machine required by the TEPR OH coils. With a magnetic field of 1.5 T, the drum will have a capacitance of 21.3 F; and with a peak excitation of 2340 radians per second angular velocity, the drum will develop 61 V. A load inductor of 13.6 mH storing 40 kJ at 2425 A can be switched to the terminals of the generator which will reverse this load current in 1.7 s.

This model system will permit the study of the mechanical feasibility of a cylindrical rotor energy storage device, equipped with an air-bearing support structure in the presence of considerable radial expansion of the rotating cylinder. The air-bearing system is simpler than that required by a horizontal axis machine since the weight of the drum acts only axially and need not be supported radially. Conventional copper-carbon brushes bear onto the copper-plated upper and lower edges of the aluminum cylinder. The brushes are loaded against the cylinder with an air jet system for uniform electrical contact.

Referring to Fig. 6, in the sequence of operation, with the power supply set to deliver a certain current, S1 is turned on causing the 13.6 mH inductor to charge. Turning on S2 disconnects the power supply from the circuit and turning on S3 allows the energy to be transferred to the generator. S2 and S3 must be turned on simultaneously. When all the energy is in the generator and S4 is switched on, the energy returns to the magnet. Turning S3 and S4 on alternately causes the energy to cycle between the magnet and the homopolar generator.

The first tests performed on the homopolar generator were designed to measure the brush voltage drop. A 10 V, 100 A power supply was connected across the cylindrical drum and brush support structure. The radial field was set at approximately 0.93 T. The air-bearing pressure was set at 10 psi and the brush pressure had to be set to 30 psi before we were fairly confident that the brushes were making electrical contact. With the high brush pressure, we were unable to rotate the drum by hand. The power supply was turned on and after several seconds the drum reached an angular velocity of 3500 rpm the current through the drum was 70 A. The voltage drop across the brushes was calculated at 2.3 to 2.4 V. Because of the high brush pressure and large voltage drops, the brush support structure is to be modified, but before disassembly energy transfer was attempted. The 13.6 mH inductor was energized to 500 A and the current was switched through the homopolar generator. These tests were performed several times and pictures taken of the magnet current and drum voltage are shown in Fig. 8.

The current waveform of Fig. 8 is of the shape expected, however, the voltage waveform for the homopolar has some discontinuities which are not easily explained. The trailing edge of the drum voltage waveform shows that energy was stored in the homopolar and that large losses are present. The system was dismantled and modification to the brush support structures are under way.

Following the testing and evaluation of the demonstration generator, a conceptual design will be made for a 100 MJ homopolar system. This machine will interface to the 100 MJ pulsed coil developed in the pulsed coil program. This prototype system will achieve tokamak level operation in all important aspects and serve as an engineering test facility for the TEPR OH coil power supply design effort.

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References

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