APPLYING A HOMOPOLAR POWER SUPPLY TO A TOKAMAK

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APPLYING A HOMOPOLAR POWER SUPPLY TO A TOKAMAK

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ABSTRACT

The new Texas Experimental Tokamak (TEXT) will use homopolar generators as a pulsed power source. The high current, low voltage output of such a source calls for unusual solutions to achieve a proper match to toroidal coil system and ohmic heating system. The paper discusses several possible alternatives. The solutions chosen for both the toroidal and the heating coil system are described including some of the salient components such as switches and power electronics.

INTRODUCTION

The proposed Texas Fusion Plasma Research Tokamak will use homopolar generators to power both the toroidal and the ohmic heating coil systems. The homopolar machine is a high current low voltage source which for purposes of circuit analysis can be represented as a capacitance. Matching this source to toroidal coil system of the tokamak as well as using the same source to derive the power for the ohmic heating of the tokamak presents some unique engineering problems.

The bulk of the energy goes into supplying the toroidal field while a much smaller portion is used for ohmic heating. Available power at the site made some form of energy store for the toroidal field system necessary and for the ohmic heating supply desirable although it would have been marginally possible to supply the ohmic heating power directly from the laboratory power system.

POSSIBLE ALTERNATIVES

Free Discharge

The current of a homopolar generator discharging into an inductance such as toroidal coil system is a rapidly decaying and sinusoidal oscillation of the form.

$$i = I_0 e^{-\alpha t} \sin\omega t$$

The circuit elements can be chosen so that the current at the first maximum stays within a 2% band for the required .5 seconds. Such a circuit is very simple. The only controlling element is a making-switch. It has a drawback, however, that the homopolar store comes to a full standstill in every shot. Also the heat load into the coil is larger than necessary and since, at the time of the current crest, the terminal voltage of the machine is near zero; it precludes using this source to power ohmic heating supply.

Field Control of Homopolar Machines

Field control may be used to vary the output voltage. The main parameters determining a field control system are: the energy stored in magnetic circuit (airgaps and iron parts) and the eddy currents due to flux variation.

The average flux density over the active area in the TEXT homopolar is 1.5 T. The corresponding magnetic energy in the airgaps is 112 kJ and the magnetic energy in the iron parts is 9.5 kJ.

The evaluation of eddy-currents was performed by assuming (Ref. 4) a distribution of flux density in a large number of modes represented in the form of a double Fourier series:

$$B = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{B(m,n)}{mn} \cos\left(\frac{m\pi}{\alpha}x\right) \cos\left(\frac{n\pi}{\beta}y\right) e^{-\rho(m,n)t}$$

For the TEXT machine the calculated time constant of the fundamental is 2.88 s. The fundamental wave is 1.95 Wb of a total flux of 2.95 Wb. 1 Wb represents the amplitude of the higher harmonics. Flux modulation for periods short by comparison with the time constant of the fundamental will be performed through high harmonics. Together with the uncertainty of the position in the hysteresis loop this will require a complex control system. Losses in the homopolar machine due to eddy-currents represent a further disadvantage of this solution.

This calculation was confirmed by experiments in a similar machine (5 MJ, 42 V homopolar) with a calculated time constant of 1.35 s. The measured values were between 1.25 and 1.4 s depending on the remanent flux density and the position in the hysteresis loop.

Field Control by Modulation of Output Current

By inserting a variable resistor in the main current path and varying this resistor either by servo control or in a preprogrammed manner, it is possible to shape the current wave. The circuit then consists of a making-switch, a regulating resistor and a resistor switch bridging this resistor to permit the fastest possible current rise (Figure 1). This scheme permits a fast buildup of current thus minimizing heating of the coil, good control of the flat portion of the current wave and interruption of the current at the time when there is considerable energy retained in the inertial store. It also provides for a sufficient voltage to derive ohmic heating power at the time of the experiment.

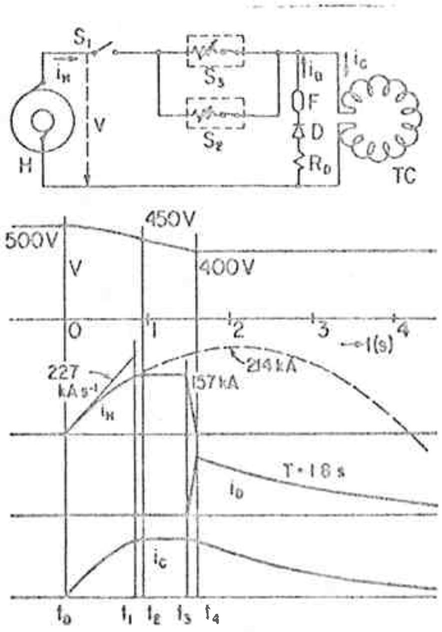

Figure 1. TEXT toroidal field circuit

S_1	Making switch
S_2	Insertion switch
S_3	Resistor/switch
D, F, R_D	Crowbar

This control method satisfies all requirements, the only difficulty is the choice of proper switching elements. The switches S_2 and S_3 have to interrupt direct currents in the order of 150 kA with recovery voltages ranging up to 500 V. Fortunately, the magnetic energy of the toroidal system can be shunted through a crowbar diode and need not be considered in the switching problem. However, the magnetic energy in the residual circuit consisting of homopolar machines, busbars, etc. amounts to approximately 100 kJ. Several solutions were considered and appear feasible:

a) use of a AC circuit breaker possibly with resistor step using an elevated arc voltage to interrupt the current;

b) use of a circuit breaker and a capacitive counter-pulse circuit.

c) use of thyristors in conjunction with a counter-pulse circuit;

d) use of a resistor serving both for current modulation and as a switching element.

Solution d) was finally adopted mostly on economical and practical considerations.

TOROIDAL COIL FIELD SUPPLY

Toroidal Coil Circuit

The toroidal coil consists of sixteen segments, each having six turns for a total of 96 turns. Coil inductance is 2 mH, coil resistance, 1.2mΩ. The coil is machined from solid copper stock.

The main elements of the circuit as well as operating sequence are shown in Figure 1.

Components

Making switch. The making switch, a cross-section of which is shown in Figure 2, has to withstand the machine voltage up to the time of the experiment, then close the circuit without arcing and carry the current for the time of the experiment. The design (Ref. 1) consists of two sets of stationary contact fingers which are bridged by a pneumatically driven movable contact. Prior to switch transfer, the pneumatic cylinder is biased in a closing direction but restrained from moving by a quick release latch. Since this scheme does not involve transfer of pneumatic valves, response is fast and consistent. Transfer time for the switch is 10 ms from control impulse to closure of the circuit. After the experiment the switch is pneumatically reset. The key specifications of the switch are:

1) making duty only, no breaking ability
2) test voltage: 2,000 V
3) maximum current: 300 kA for 3 s
4) maximum rate of rise of current: 50 kA/ms.

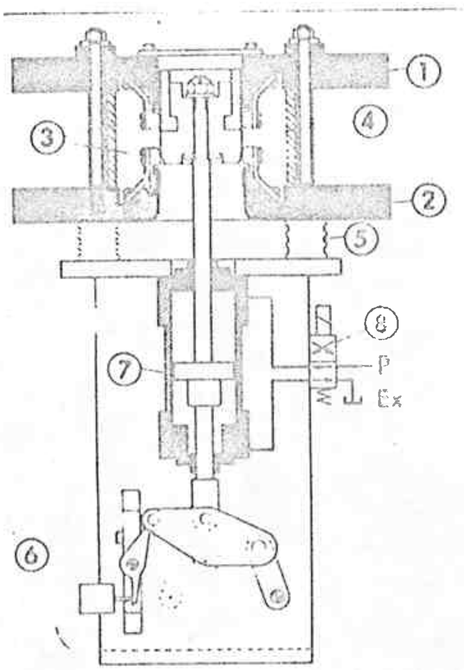

Figure 2. Making switch (schematic cross section)

1, 2	Terminals
3	Contact fingers
4	Moving contact
5	Insulator
6	Latch system
7	Operating cylinder
8	Control valve

Resistor/Switch. The application requires a resistor having a high thermal capacity, low inductance for low resistance values and high currents, and capable of stepless regulation. An electrolytic resistor satisfies all these requirements. Prior applications have been reported (Ref. 2).

S_2 is an on/off device, whereas S_3 has two functions. It is a controlled regulating resistance between the times t_2 and t_3 and a fast opening switch immediately after the end of the experiment. The electrolyte chosen is NaOH in aqueous solution with resistivities of 5Ωcm and 50Ωcm for S_2 and S_3 respectively. Electrodes will be fabricated from low carbon steel. Tests are presently being conducted at the Fusion Research Center to establish basic design data such as permissible current densities on the electrodes, voltage gradients, etc.

A tentative design of this resistor is shown in Figure 3. The electrodes consist of two interleaved arrays of flat plates. One set of plates is part of the electrolyte container, the other is the moving electrode. The two electrolyte containers are insulated from ground and represent the two terminals of the resistor assembly. The two moving electrodes are connected by a bridge operated by a hydraulic mechanism. By varying the depth of insertion of the movable electrode, the effective cross-sectional area can be varied. In order to open the circuit, the movable electrodes are completely drawn out of the electrolyte tank and the final interruption takes place when the electrolyte stream running off the movable plates breaks off. Velocities of the movable plates in the order of 2 m/s seem feasible which will result in interrupting times in the order of .25 s.

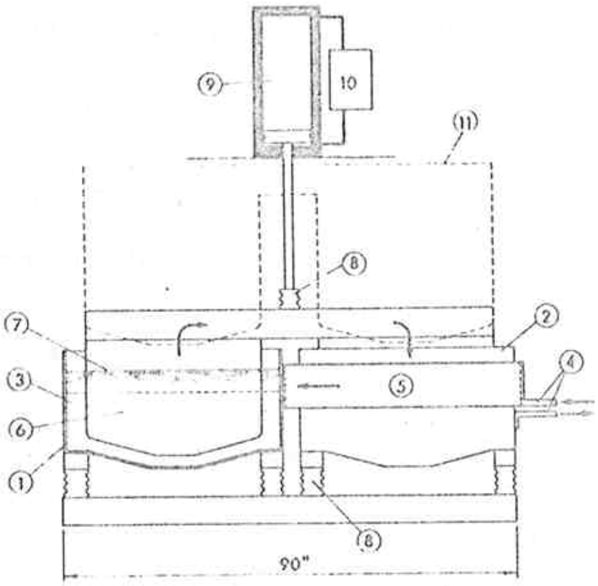

Figure 3. Switching resistor (schematic, shown in fully inserted position; arrows indicate current path)

1, 2	Electrolyte container with stationary electrodes (3)
4	Current terminals
5	Return conductor
6	Moving electrodes
7	Electrolyte level
8	Insulators
9	Operating cylinder
10	Control valve
11	Electrodes in retracted position.

In the tests presently being conducted, we are also investigating the possibility of making metallic contact in the electrolyte in the closed position and breaking this contact at the beginning of the opening motion. Since the resistance parallel to the contacts would be in the order of .2 mΩ, there is reason to believe that this approach will be successful.

OHMIC HEATING POWER SUPPLY

Power Supply Requirements

The TEXT conceptual design has an iron core and an ohmic heating (OH) coil of 44 turns. The plasma minor radius is 28 cm, major radius 100 cm, and current will be 400 kA. The tight coupling provided by the iron core results in OH coil current of approximately 9.1 kA.

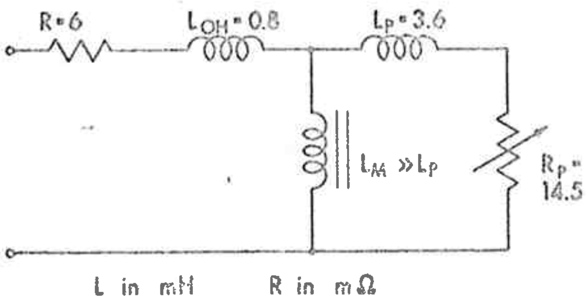

Figure 4. OH equivalent circuit

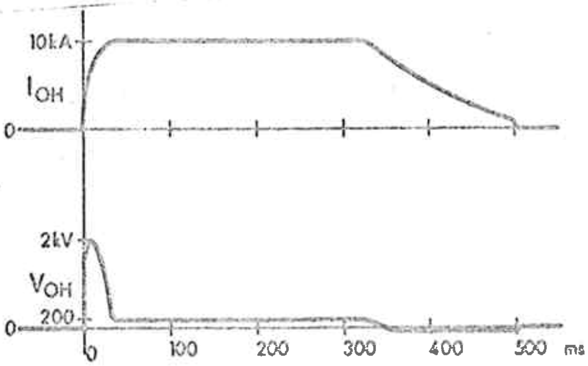

Figure 5. OH current & voltage waveforms

An equivalent circuit of the OH - plasma system referred to the 44 turn OH Coil terminals may be drawn as in Figure 4. R includes coil and busbar resistance, approximately 6 mΩ. L_{OH} is the leakage inductance of the

OH circuit. Lp is leakage inductance of the plasma, about 3.6 mH. L_m is the iron core shunt inductance, very much greater than L_p. R_p is the plasma resistance which is a strong function of plasma electron temperature, density, impurities, and current distribution. After ionization, R_p drops to about 15 mΩ for typical conditions at a current of 9.1 kA.

The desired OH current waveform and required driving voltage are shown in Figure 5. To get maximum pulse length from the iron core, it is first premagnetized to 1.6 T in the reverse direction by establishing a bias current of 250 A in the OH coil from a premagnetizing power supply.

The current pulse has a rise time of approximately 30 ms, a flat-top at roughly 10 kA for 300 ms, then a faster-than-exponential decay, due to increasing plasma resistance as the current falls. At a low value of current the plasma goes unstable and current ceases abruptly. The current is driven by an initial voltage pulse, supplied by capacitor discharge to ramp current up in the leakage inductances. The 10 kA peak current and 30 ms rise time require a 220 kJ capacitor bank at 2 kV.

During the current flat-top, the OH power supply must deliver a controlled current of 10 kA at a nominal 200 V to drive the combined resistance of the OH coil and the plasma. The power level is approximately 2 MW, and the total energy delivered to resistance and plasma is about 600 kJ. At the end of the pulse, the driving voltage is reduced to zero or slightly negative and the current allowed to decay in an approximate time of $L/R \simeq .22$ seconds. A particular requirement is fast response time for the supply output voltage. The output voltage must rise quickly to 200 V to take over the supply of power from the capacitor bank as the initial discharge reaches peak current. The ideal supply would incorporate feedback control from the plasma current to program it according to a preset waveform. Certain plasma experiments may require sharp changes in OH voltage. With these considerations the required response time is 10 ms for a zero to full scale voltage swing.

Because of electrical power limitations at the site, the ohmic heating pulse requires some form of energy storage which provides a relatively stiff voltage source for the full length of the pulse. The most practical alternatives are the following:

1) Motor - flywheel - alternator system with direct SCR phase control at the output; and

2) Homopolar generators with suitable DC power modulator.

   a) Linear power modulator
   b) Chopper or switching modulator.

The proposed OH supply system for TEXT uses the homopolar generators as a power source, modulating the OH voltage by means of an SCR controlled DC chopper. This approach offers the following advantages over an AC phase controlled power supply or a linear DC modulator:

1) Use of homopolars for energy store avoids pulsing laboratory supply buses with the 2 MW OH pulse.

2) The DC chopper deals naturally with the negative di/dt at the end of the pulse. The SCR conduction pulses are terminated, and inductive load current decays through the crowbar diode that is an integral part of the chopper circuit.

3) The chopper avoids heat transfer problems and complexity of linear modulators for high peak power pulses.

4) It is cost competitive with transformer plus full wave phase control SCR bridge systems, especially when power line filters and output voltage smoothing are included.

5) The response time requirement may be met by using a high effective chopping frequency.

The voltages and currents are within the range of available thyristor switching devices, and numerous invertors and DC choppers have been built to operate at power levels of a few MW. The concept for this application employs several switching modules, each containing a power switching SCR, a commutating circuit, free-wheeling diode and smoothing inductor. The modules are connected in parallel and the combination placed in series between the generators and a voltage smoothing filter. The SCR's are fired at constant frequency and output voltage controlled by modulating the conduction pulse width. The overall effective chopping frequency is raised to a few kHz by phasing the conduction pulses of the modules with respect to one another.

The variable electrolytic resistor-switches and the SCR controlled DC chopper appear to present the most practical and economic solutions for control of DC current from the homopolar generators to the TF and OH systems of the proposed TEXT machine. Use of the resistors to terminate TF current before the end of the free-discharge cycle minimizes coil heating and reduces energy consumption significantly. The DC chopper provides the required performance for the OH pulse system without using additional rotating storage or machines.

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