A MEGAWATT SOLID-STATE INVERTER TO POWER THE CORNELL 10 GeV ELECTRON SYNCHROTRON*

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The Cornell Electron Synchrotron has a radius of curvature of 100 meters. It is a fast cycling machine which will operate initially at 60 Hz. The magnets are capable of operation to 20 GeV. It is connected in a White[1] series resonant circuit except that it does not have a central power distributing transformer. There are 192 magnet and 4 quadrupole modules each with a transformer and resonating capacitors; these components are mounted on the individual magnet support beams. The module transformers are fed through a ring busbar system also housed in the support beam structure.

Because of the extended feed system sinusoidal rather than pulse excitation is preferred to reduce the distribution losses. Also, reduction of the harmonic content of the drive waveform will tend to minimize the excitation of delay-line modes of the magnet circuit, which may become a serious problem in such a large system. The inverter circuit described below operates with about 15% harmonic content when the machine is in the sinusoidal mode. (Flat-topping is envisaged later and will, of course, dramatically increase the harmonic content.)

We have taken advantage of recent technological advances to construct an inverter using only solid-state components, rather than ignitrons. Such a supply is efficient, flexible, quiet, economical, and takes the minimum of space.

For the projected excitation to 15 GeV the power requirement is one megawatt of single phase power at 600 Vac and 60 Hz. This is derived from the three phase line in the following steps:

(i) SCR controlled rectification; (ii) LC Filters for filtering and energy storage; (iii) inversion by solid state DPDT switches [2]; (iv) filtering by series resonant circuits. The switches are commutated by the reactive power in the series filters which are tuned somewhat above 60 Hz for this purpose.

Inverter Operation

A schematic of one of the inverters (DPDT switches) is shown in Fig. 2. The SCRs [3,4] and their protective softening networks are lumped into a symbol for a switch. The 5μH and 20μH inductors limit the rate of current rise but are not important for the discussion that follows.

When a diagonal pair of SCRs is triggered, current rises and falls as befits a series resonant load. When the current reverses, the reverse diodes which parallel the SCRs begin to conduct. The other SCR pair may then be triggered and a reverse cycle of current begins.

The load conditions under which the current will reverse within the required time under transient and steady state conditions are of interest. For a simple series resonant circuit, in order that the current can pass through zero in less than 180°, the equivalent load must be capacitive at 60 Hz.

The load cannot be adequately represented as a simple series resonant circuit. Figure 3 shows an equivalent circuit sufficient for steady state analysis. Because the current I_{in} from the inverter is reasonably free from harmonic content, it is convenient to consider only the fundamental component V_{in} of the square-wave voltage applied to the equivalent load.

Figure 3 shows the parallel resonant magnet load as a conductance G in parallel with an admittance Ψ. The admittance represents the amount of mistuning of the magnet load and is normally inductive. The phasor diagram relates V_{in} to the magnet load voltage V_0. In practice Ψ varies with temperature and line frequency while L_1, C_1 and G do not vary significantly. We desire to regulate V_0.

The load V_{in}/I_{in} seen by the inverter will be capacitive if

$$\gamma \equiv \left(\frac{1}{\omega C_1} - \omega L_1\right) 2G > 1 \qquad (1)$$

It will commutate only if

$$Q^* \equiv (G^2 L_1/C_1)^{1/2} \gtrsim 1 \qquad (2)$$

If Q* is large, the stored energy in L_1C_1 is expensive. We find $1.2 < Q^* < 1.6$ attractive.

Normal operation($\gamma \simeq 1$) is made by starting the inverter with the magnets nearly in tune ($\Psi = 0$) . As the resonating capacitors warm up the tuning becomes inductive and operation stabilizes near the minimum shown in Figure 4.

Analysis of behavior upon turn-on is difficult, therefore our "analog computer" (a prototype powering 8 magnets to 10 GeV) was used. The system is stable for $\gamma \gtrsim 0.7$ and for Q*'s between 1.2 and 2.0. At the start of operation the conduction angle of the SCRs oscillates about the steady state value with a period of a few tenths of a second. The oscillations damp to the steady state value in about one second. Operation, where possible, below $\gamma = 0.5$ shows a much less damped and occasionally anti-damped behavior. If the magnet load is suddenly shorted (crowbarred), the inverter current changes largely in phase and not in magnitude. We will use this accident to drain energy from the magnet ring upon detection of a fault.

Softening Networks

Figure 7 shows the network used to minimize di/dt during the first few microseconds of conduction and dV/dt when the SCR is off. The observed maximum values of dV/dt < 60 V/μs and di/dt<30A/μs are in agreement with calculated values. Experiments have been performed only for voltages up to 350 Vdc and the values given above are extrapolated for 700 Vdc operation.

The bus bar to the anode of the SCR passes straight through ferrite cores forming an inexpensive and quiet saturable inductance with a frequency response useful to about 500 kHz.

Delay Line Modes

The many magnet modules, all in series, have stray capacitances to ground forming a delay line. The period of the delay line around the machine is about 5 ms. Standing voltage waves may be excited by harmonic components in the magnet supply current. The capacitive currents to ground caused by delay line modes may upset the equality of current around the ring. This effect is particularly critical at injection time, when the magnet excitation current is instantaneously low; very small quadruature unbalance currents excited by the full drive amplitude then assume important proportions. Moreover, the radial aperture of the synchrotron is only about $\pm 3 \times 10^{-4}$of the radius of curvature; hence unbalanced magnet currents must be kept very small.

The possible excitation of delay line modes and the desire to keep bus bar losses small are important reasons for having chosen a near-sinusoidal excitation system.

We have made provision to damp delay line modes. This has been done by insulating the cases of the resonating capacitors and then connecting them to ground through a resistor. In this way, part of the stray capacitance has a low effective Q. The effective Q of each of the 196 sections of the delay line can be less than ten over a wide range of frequencies.

Tests with about one half the magnet ring have not shown difficulties with delay line modes or with phase variations of the AC magnetic field from magnet to magnet.

* Work supported by National Science Foundation

1) M. G. White, F. C. Shoemaker, G. K. O'Neill, A High Intensity Proton Synchrotron, CERN Symposium Bd1, H150, S525 (1956)

2) R. R. Ott, L. A. Schlabach, A Unique Silicon Controlled High-Power Inverter with Sine-Wave Output Voltage. Digest of Technical Papers, 1962 International Solid State Circuits Conference (IRE, AIEE), p. 100. We became aware of this paper after development of our 20kW prototype. They suggest more complicated commutation filters which are desirable when load voltages must be maintained constant while the load impedance varies in phase and magnitude.

3) The SCRs used in the inverter are General Electric C500X1's. They consist of two 840A, 1800 V units mounted back to back for use in AC switching. The integral water-cooled heat sink is very attractive. For sinusoidal output from the inverter we are using these SCRs for conduction in one direction only.

4) The fuses are Chase-Shawmut A50A300 series which are available in sizes up to 400 A. They are rated at 500 V and will interrupt DC voltages of at least 440 V. Fuses for full protection of large SCRs operating at high voltages do not seem to be available; the I^2t ratings are generally too high. Also, the ability to interrupt large DC voltages is not claimed.

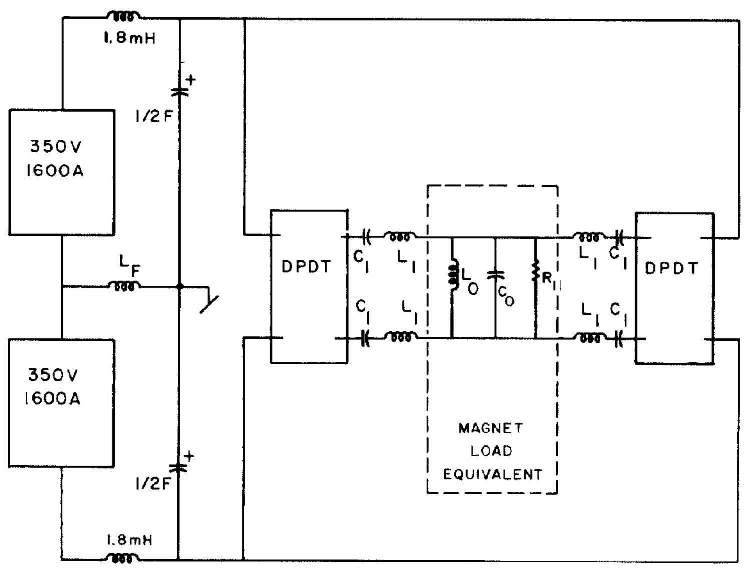

Fig. 1. Block diagram of inverter.

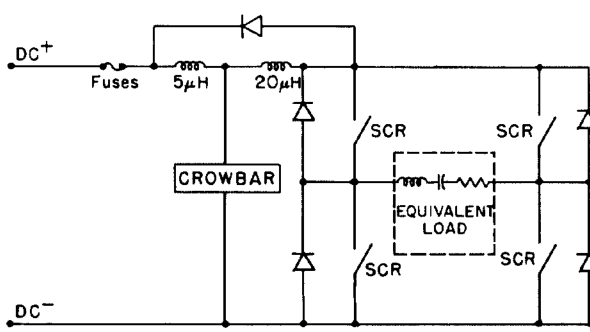

Fig. 2. Schematic of an inverter.

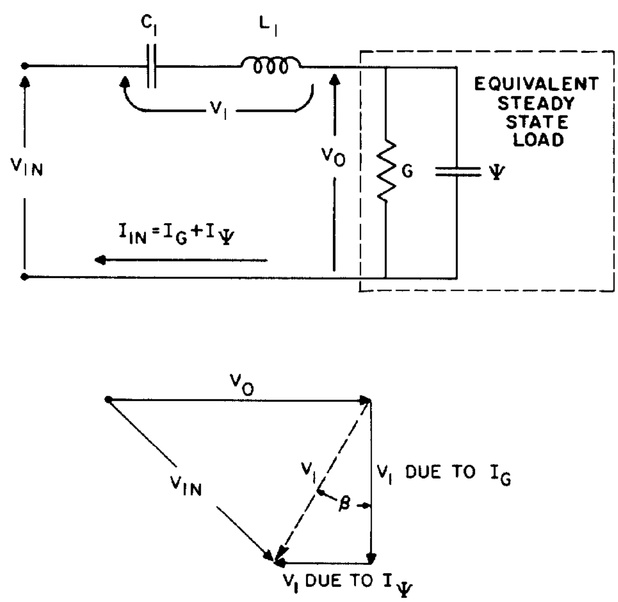

Fig. 3. Steady-state equivalent load as seen by inverter. The magnet load is shown in the box. The conductance G remains quite constant while the reactive admittance Ψ may vary widely.

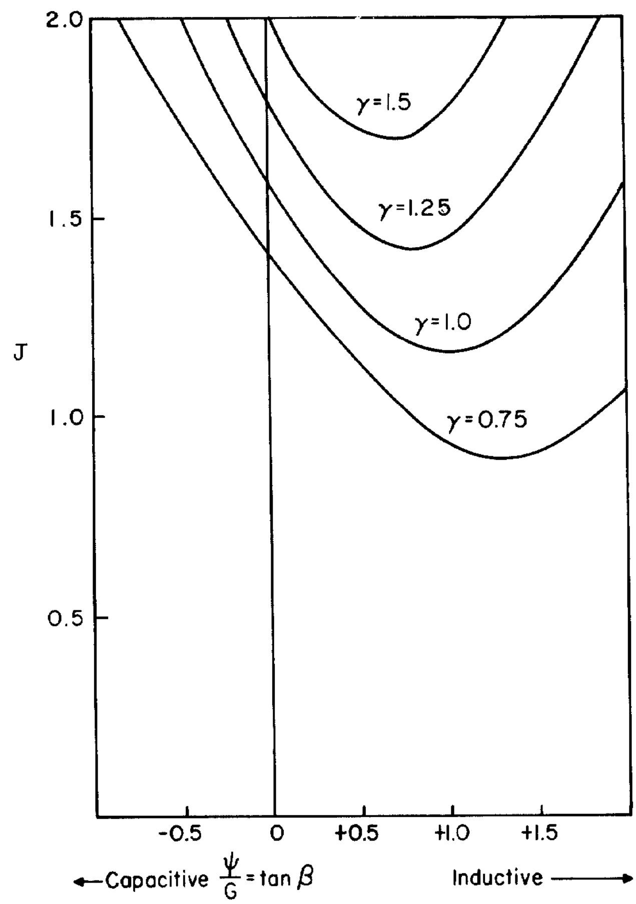

Fig. 4. Ratio, J, of dc input voltage to ac load voltage, vs tangent of phase angle of magnet load.

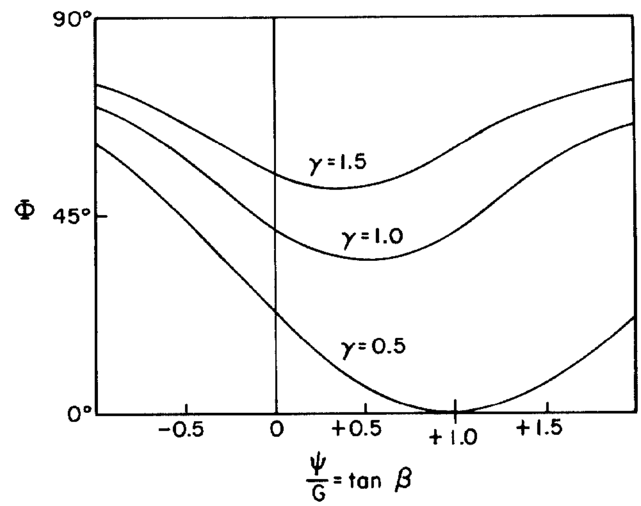

Fig. 5. Conduction angle of reverse diodes vs tangent of phase angle of magnet load.

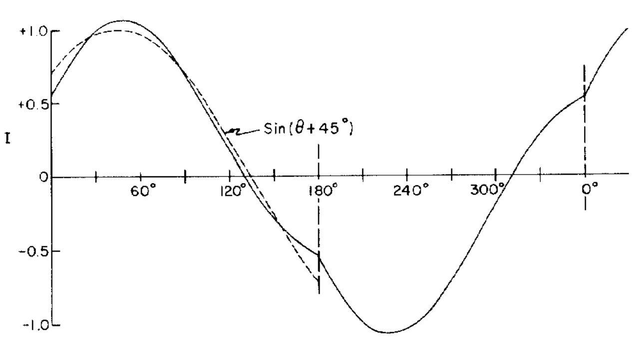

Fig. 6. Normalized current vs time for a typical operating condition. The discontinuity of the derivative when an SCR is fired is rounded over a period of about 100 μ s.

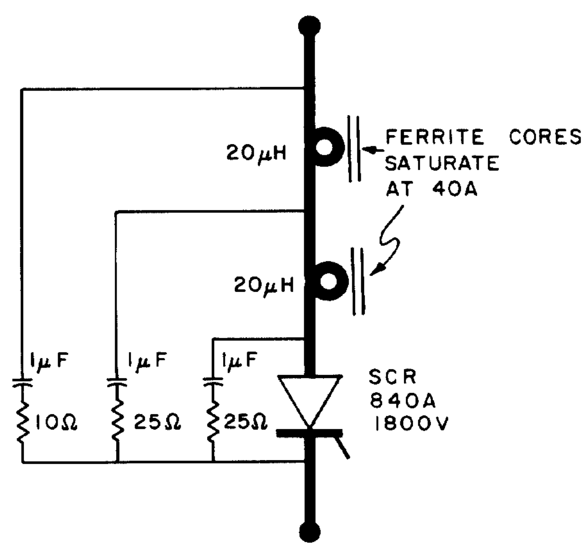

Fig. 7. SCR softening network.