FLAT TOPPING THE PPA SYNCHROTRON MAGNET

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Introduction

A project is currently under way at the Princeton-Pennsylvania Accelerator to modify the Synchrotron Magnet Circuit in such a way as to make flat topped operation available for up to 50% duty. Whereas, the magnet circuit is now resonant at approximately 19Hz and the magnetic field is a sinusoidal function of time, flat topping will permit latching the field at its peak value (corresponding to 3 GeV) for up to 50 milliseconds. Flat topping is to be achieved by short circuiting the capacitors of the circuit at the appropriate time and regulating the magnet current with series power supplies. The resulting pseudo acyclic operation requires that the rotating machinery presently used to excite the circuit be replaced by all electronic sources. All electronics will be solid state. The modified magnet circuit is shown in Figure 1.

Details of the Planned Approach

Switches

Figure 1. depicts the entire magnet system equipped for flat-topping. In this scheme the switches S1 are closed at peak magnet current ($\dot{B} = 0$ and the voltage on C1 - C2 is zero, going positive). These switches consist of a series-parallel array of water cooled silicon controlled rectifiers. They are solid state, regenerative electronic switches requiring very little power in the control electrode circuit. The manufacturers contacted, indicated that an array of 40 to 50 units of a type currently in production would handle the job satisfactorily. The switch would be required to pass a 1400 A. pulse of current during the flat-top phase. For 50% flat-top (50 ms duration) the rms current per switch is 1000 A. These switches are similar to ignitrons in the requirements for turning them off. It is necessary to externally interrupt the forward current for some period of time so that the switch may fully recover and be capable of blocking voltage in the forward direction. There are several techniques for doing this. The method that appears most practical consists of placing the switch in series with a low inductance transformer winding and coupling a reverse bias pulse into the circuit through this transformer at turn-off. The switch branch of the circuit must be low inductance. The reason for this is that the volt-seconds required to produce the required current in such inductance would cause intolerable ripple in the main magnet current. For this reason, the turn-off transformer will be located in the capacitor branch of the circuit. The design of this transformer calls for a secondary output of 480 V Peak at 625 Hz. The output will be 1 cycle of a cosine wave, the first 1/4 cycle acting as the turn-off pulse. The required 17 transformers will be driven in parallel from a charged capacitor in series with a switch. The switch will be an SCR array, similar to the one used for flat-topping. A 30 microhenry inductor will be included in series with each transformer in order to limit peak, accidental capacitor discharge currents to 50,000 A. The output of the turn-off transformer is designed to produce the appropriate current flow in this inductance and thereafter, hold the switch reverse biased for an additional 100 microseconds.

Power Supply #2

The IR drop per magnet at peak current is very nearly 90 volts. It is anticipated that the forward voltage drop of each S1 will be about 20 volts. Therefore, the total dc voltage required to maintain constant current during flat-topping is approximately 1800 volts. To achieve this, another 600 volts or so is required in addition to the 1180 volts supplied by P.S. #1. The simplest, most economical approach to this is to have one or more electronically switched power supplies in series with the magnet circuit which are turned on during flat-top and are by-passed otherwise. Practical considerations such as transistor voltage ratings have indicated that four such power supplies, each producing approximately 150 volts, is a suitable number (see Figure #2). Since the magnet current is unidirectional, these power supplies can be properly by-passed by a diode. The supply is turned on and off by the transistor regulator bank. When it is turned on the diode becomes reverse biased and the current shunts over to the power supply. Therefore, the power supply current is a 1400 ampere pulse which occurs during flat-topping. During flat-topping the transistors operate linearly serving as a regulator on the power supply output. The regulation requirements are that the magnet current can be maintained constant during a 50 ms flat-top to one part in 10^5 if the voltage of all power supplies is regulated to 0.02% which is not at all difficult in this type power supply.

Power Supply #1

Power Supply #1 supplies the dc bias current to the magnet circuit and directly replaces the dc generators presently used. It is required that this power supply produce 1180 V dc at 726 amperes during sinusoidal operations while C2 carries the 700 ampere peak sinusoidal current component. But during flat-topping C2 carries no current and the power supply current jumps to the full 1426 amperes. This can easily be seen by noting that when the switches S1 close, the voltage across C2 (the one around P.S. #1) must remain constant at 1180 V dc and therefore its current is zero. These current requirements are very similar to those of P.S. #2 and hence a very similar design was made. In the case of P.S. #1 the output current discontinuity is only half of that in P.S. #2. For this reason a smaller value filter capacitor may be used.

AC Drive

An all electronic source of ac excitation is desirable if flat-topping is to be performed. An electronic source has the inherent flexibility to provide the pseudo acyclic excitation required during flat-topping operation. In addition, an electronic source should be more reliable, easier to repair than rotating machinery and provide certain operating advantages. Among the latter is faster regulation response in that an electronic system does not incorporate the long inertial time constants of rotating machinery and, in fact, allows cycle to cycle control of excitation. The scheme devised for providing A.C. excitation is similar to that used at CEA[5] (see Figure 3). Basically, the existing air core transformer - choke is used to couple single ended, class C drive into the circuit. When the magnet circuit capacitors are nearly fully charged and the magnet current has approached the D.C. bias value and is decreasing (no beam is in the Synchrotron) a charged resonant circuit is switched onto the primary of the transformer-choke. One half cycle conduction results and energy is transferred from the driving circuit capacitor to the magnet circuit capacitors, raising their voltage by approximately 270 volts and adding approximately 50 kJ to the stored energy. The driving capacitor then recharges through a second resonant circuit which includes a series diode. Thereafter, the driving capacitor remains charged until the next drive pulse. During this time, the capacitor voltage may be changed over a small range in accordance with the cycle to cycle drive requirements of the magnet circuit. The switch used is to be identical with the flat-topping switches.

Regulation and Timing

Much of the present regulation schemes can be retained. The ac drive would be controlled by means of the existing system which utilizes a measurement of B at the time of Bmin. The regulation loop response would have to be re-designed in view of the new drive source transfer function. The regulation of the dc supplies would be somewhat complicated by flat-topping. During sinusoidal operation P.S. #1 must be current regulated. However, since the current in P.S. #1 jumps up during flat-topping, the average value of the current is a function of the flat-topping duty factor. One alternative is to superimpose an appropriate command waveform on the reference for P.S. #1 during flat-topping which would force P.S. #1 to attempt to regulate the flat-top current. However, the supplies functioning as P.S. #2 have more range and flexibility available to do this job and P.S. #1 has a large capacitive load. Therefore, it is planned that during flat-top operation P.S. #1 would be switched to a voltage regulate mode which would be designed to maintain its output voltage constant during flat-top at its current value. Therefore, during flat-top P.S. #1 would serve as a regulated voltage and power source and the job of short term regulation to maintain constant flat-top current would fall to P.S. #2. The P.S. #2 supplies then would be switched "ON" during flat-top to produce very nearly the correct voltage for constant current. However, a vernier range in their output voltage would be utilized to servo the $\dot{B}$ signal to zero during flat-top. Forcing $\dot{B}$ to zero is a better "handle" on maintaining constant current than simply regulating voltage to a pre-set value. Regulating voltage would not correct for variations in the forward voltage drop of the switches S1 or for variations in magnet resistance or peak magnet current at the beginning of flat-top. Forcing $\dot{B}$ to zero guarantees constant current (within the capability of the servo) independent of these other parameters.

It appears quite desirable to have the capability to lock the magnet system in frequency and phase to an integral sub multiple of the 60 Hz power frequency. That means that the desirable operation frequencies would be 20, 15, 12 and 10 Hz. These correspond to flat-top durations of approximately 0, 16 2/3, 33 1/3 and 50 milliseconds respectively. This may be achieved quite simply. A synchronous clock would be derived from the power line and counted down to provide pulses at the desired machine frequency (i.e. 20, 15, 12 or 10 Hz). These pulses would be used to end flat-top. They would be used, for instance, to trigger the switch turn-off system. The start of flat-top would be determined by the magnet circuit itself and the characteristics of the switches S1. The magnet circuit natural resonant frequency would be adjusted to be slightly higher than 20 Hz (e.g. 20.4 Hz). Thus, the natural period of oscillation would be on the order of 49 milliseconds and then, were the "Stop Flat-Top" pulse to be at a 20 Hz rate, a nominal 1 millisecond flat-top would persist. This short flat-top would automatically vary to compensate for short term drift in the natural resonant frequency. Occasional re-tuning may be required but probably no more frequently than once a week. With the magnet system thus locked in frequency and phase to the 60 Hz power source the effect of power frequency perturbations in synchrotron components will be minimized.

Model Study

Many of the circuits and features described here have been incorporated into a 200 Hz scale model of the magnet circuit and tested. However, several areas warrant additional tests. These are primarily related to transients. In particular, the turn-on of the P.S. #2 supplies will tend to excite the "transmission line" modes of the magnet circuit. Preliminary investigations indicate that this is not a serious problem (the measured modes are quite high in frequency) but the exact treatment needs to be defined. Another consideration is transient voltages (with associated high dv/dt) impressed on the switches (S1) by random faults to ground in the magnet circuit. The solution to this problem may well be difficult and time consuming.

Careful consideration must also be given to monitoring of voltage and current waveforms and the proper interlocking of these signals to minimize the possibility of circuit malfunction, particularly with respect to the triggering of the flat-topping switches.

Acknowledgments

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References

1. Flat-Topping the Princeton-Pennsylvania Magnet, J. Riedel, PPAD 539C, February 2, 1965.

2. Supplement No. 1 to Flat-Topping the Princeton-Pennsylvania Magnet, J. Riedel, Class A-223, December 1, 1965.

3. Flat-Topping Modd Program, E. Ambjor, Class A-240, January 31, 1966.

4. Magnet Flat-Topping Symposium Summary, J. Riedel, PPAD 581D, February 9, 1966.

5. Ignitron Switches for the PPA Flat-Topping Scheme, R. D. Bedford and R. N. Bushman (General Electric Research and Development Center), Class A-222, August 9, 1965.

6. Further Engineering Details for Flat-Topping the Princeton-Pennsylvania Accelerator, D. Huttar, PPAD 597D, August 17, 1966.

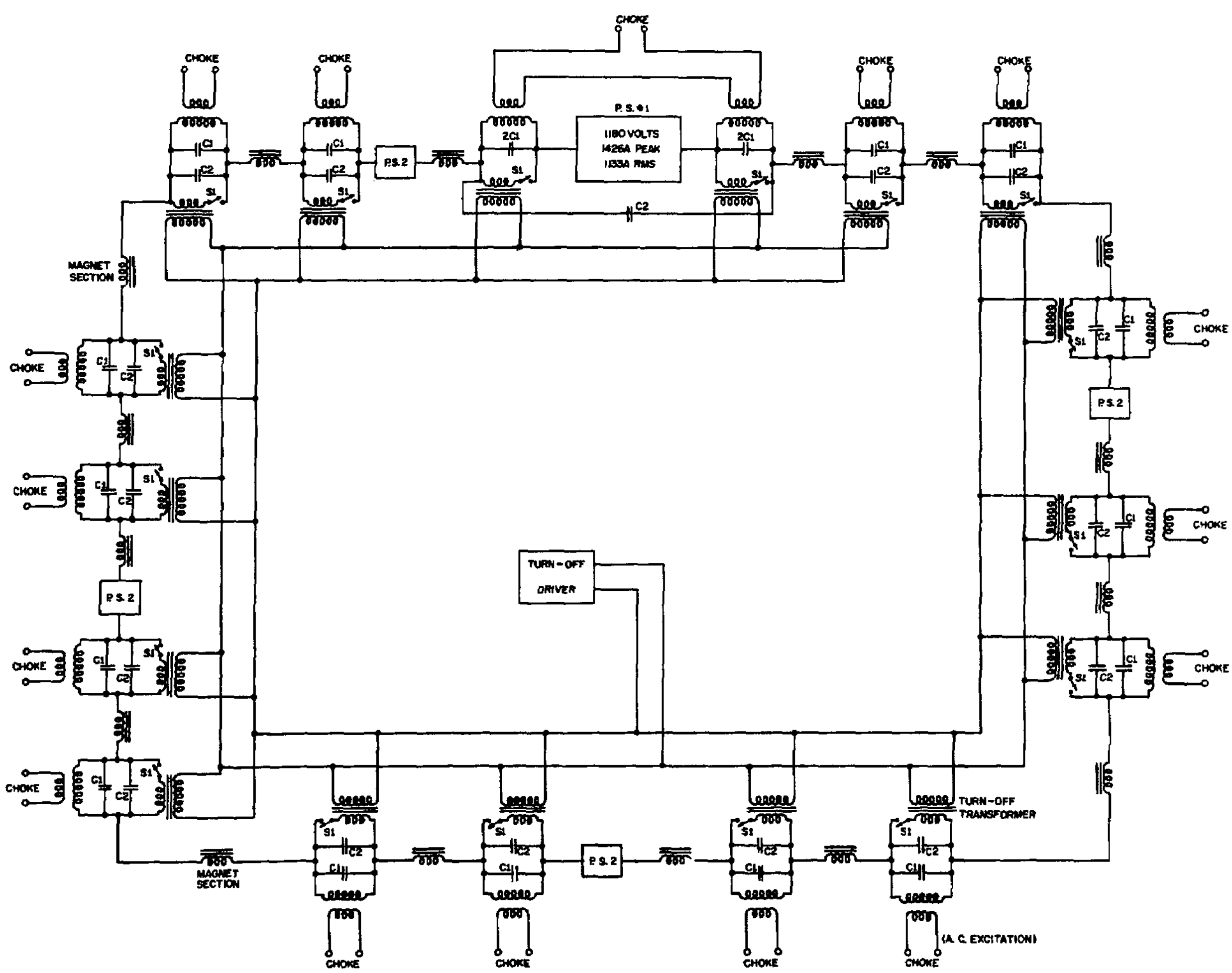
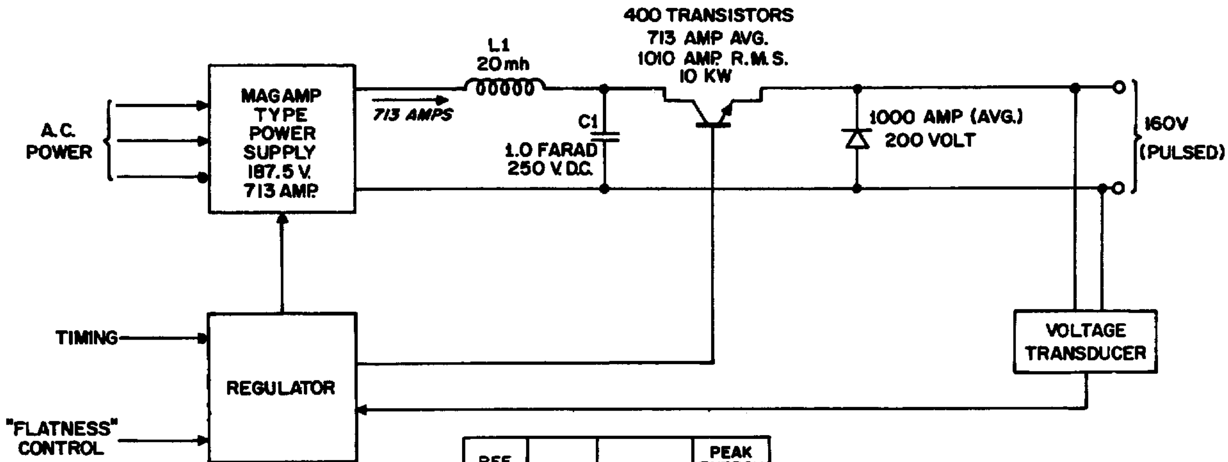
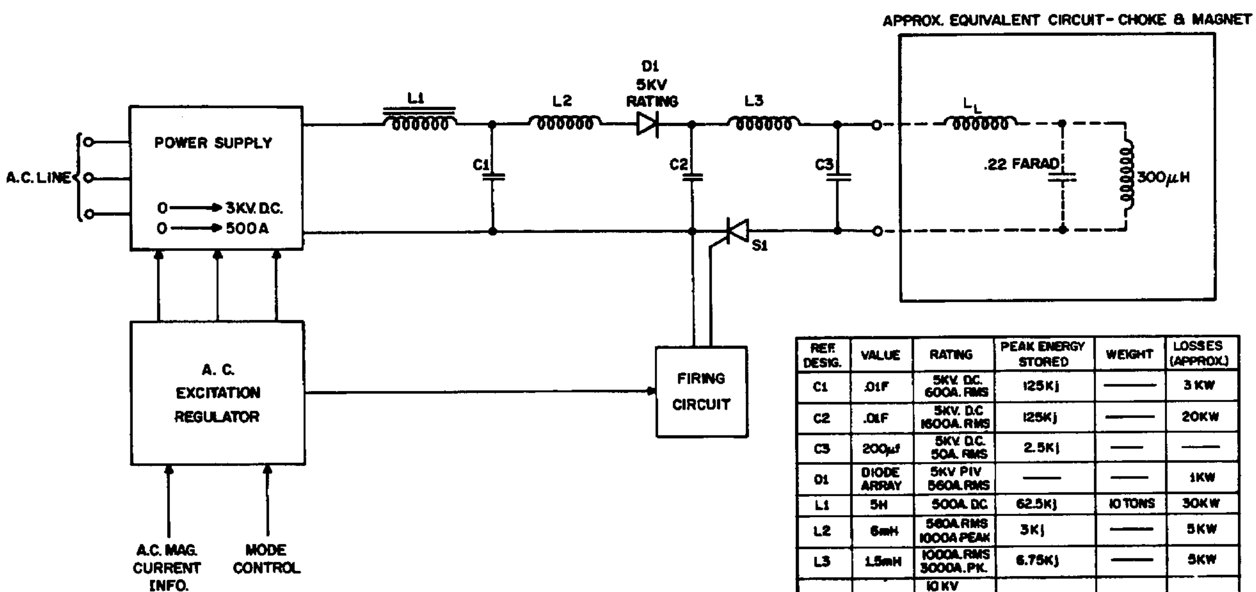


Fig. 1. Magnet Circuit Diagram.



REF. DESIG.	VALUE	RATING	PEAK ENERGY STORED
C1	1.0F.	250V.D.C. 713A. RMS	21Kj
L1	20mh	713 AMP.	5Kj

Fig. 2. Flat-Topping Booster Supply.



REF. DESIG.	VALUE	RATING	PEAK ENERGY STORED	WEIGHT	LOSSES (APPROX.)
C1	.01F	5KV. D.C. 600A. RMS	125Kj	——	3 KW
C2	.01F	5KV. D.C 1600A. RMS	125Kj	——	20KW
C3	200μf	5KV. D.C. 50A. RMS	2.5Kj	——	——
D1	DIODE ARRAY	5KV PIV 560A. RMS	——	——	1KW
L1	5H	500A. DC	62.5Kj	10 TONS	30KW
L2	6mH	560A. RMS 1000A PEAK	3Kj	——	5KW
L3	1.5mH	1000A. RMS 3000A. PK.	6.75Kj	——	5KW
S1	SCR ARRAY	10 KV 1100A. RMS 500A. AVG. 3000A PEAK	——	——	15KW

Fig. 3. A.C. Excitation Source.