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AN INEXPENSIVE PULSED POWER SUPPLY FOR A SEPTUM MAGNET*

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Summary

A 16 μH, 6 mΩ septum magnet load must be pulsed while extracting beam from the 200 MeV booster of the Zero Gradient Synchrotron (ZGS). A power supply was designed for this purpose that can deliver ~ 2 ms wide, half sine wave pulses with a PRF of 30 pulses per second. The peak current is adjustable from 3 kA to 10 kA and repeatable within ± 0.05% by means of a novel charging circuit. By providing a transformer between the magnet and the capacitor bank, the overall cost of the system was reduced to less than one half of that of a conventional capacitor discharge system. A high-Q choke shunts the negative half wave of the current around the transformer, thereby extending the life expectancy of the magnet and increasing the circuit efficiency.

Introduction

During the extraction of the proton beam from the 200 MeV booster of the ZGS, a septum magnet must be pulsed. The pulse must have a rise time of ≤ 1 ms, a flattop of ≥ 100 μs during which the current is maintained within ≤ ± 0.5%, and a peak current adjustable between 3 kA and 10 kA. These requirements can be met with a half sine wave pulse. In its simplest form, this is done by discharging the energy stored in a capacitor bank into the magnet as illustrated by Fig. 1.

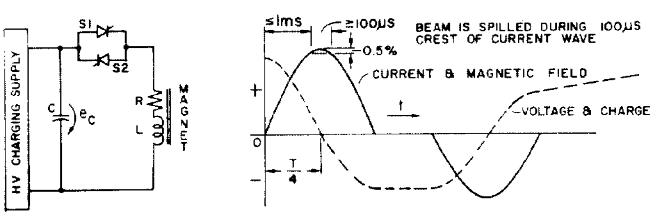

FIG. I CONVENTIONAL CAPACITOR DISCHARGE CIRCUIT AND ASSOCIATED WAVEFORMS

On triggering the forward thyristor S1, the energy stored in capacitor C is discharged into the magnet circuit. S1 turns off at the end of the first half cycle of the damped oscillation. The capacitor is then left with a smaller charge of opposite polarity until the reverse thyristor S2 is triggered and the second half cycle takes place in the opposite direction. The difference between the original and the final charge is supplied from the charging supply between pulses. In cases where the heat load on the magnet must be reduced or where the energy return is low, an improvement is possible by shunting the second half cycle around the magnet through a high-Q choke.

In our application, a cost reduction of more than 50% over the conventional discharge system was achieved by providing a transformer between the capacitor bank and the magnet. This greatly reduced the cost of capacitors for energy storage. A novel charging circuit and a switched high-Q charge recovery choke give improved circuit efficiency, the latter also reduces the heat load of the transformer and of the septum magnet.

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Comparison of Switching Circuits

Circuit Equations

When the capacitor of Fig. 1 is discharged into the load, an oscillatory current will result provided the total resistance in the circuit is sufficiently low.

The resonant frequency of the circuit is

$$f_r = \frac{\beta}{2\pi} \qquad \left[s^{-1}\right], \qquad (1)$$

where

$$\beta = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \qquad \left[s^{-1}\right]$$

C = circuit capacitance [F]

L = circuit inductance [H]

R = circuit resistance [Ω].

The current at any time is

$$i = \frac{E}{\beta L} e^{-\alpha t} \sin \beta t \qquad [A], \qquad (2)$$

where

t = time after discharge starts [s]

$\alpha = R/2L$ $\left[s^{-1}\right]$.

The time at which the current reaches its first peak is:

$$t_p = \frac{1}{\beta} \tan^{-1} \frac{\beta}{\alpha} \qquad [s]. \qquad (3)$$

The first current peak does not occur at precisely the first quarter period of the discharge cycle, but at a point in time before. The term $\tan^{-1} \beta/\alpha$ describes the phase angle at which peak current occurs.

In high current discharge applications, every effort is made to make R appreciably less than the value for critical damping. With $1/LC \gg R^2/4L^2$ we can write $\beta \approx 1/\sqrt{LC}$ and the above equations can be simplified to:

$$f_r \approx \frac{1}{2\pi\sqrt{LC}} \qquad \left[s^{-1}\right], \qquad (1')$$

$$i \approx E\sqrt{\frac{C}{L}}\, e^{-\alpha t} \sin \frac{t}{\sqrt{LC}} \qquad [A]. \qquad (2')$$

The peak current is then

$$I_p \approx E\sqrt{\frac{C}{L}}\, e^{-\frac{\pi R}{4}\sqrt{\frac{C}{L}}} \quad [A], \qquad (2'')$$

and the voltage on the first reversal becomes

$$E_r \approx -E\, e^{-\frac{\pi R}{2}\sqrt{\frac{C}{L}}} \quad [V]. \qquad (4)$$

Critical damping occurs at a resistance

$$R = 2\sqrt{\frac{L}{C}} \quad [\Omega]. \qquad (5)$$

Circuit Parameters

Resonant Frequency

With reference to Fig. 1 and the pulse specifications mentioned in the introduction, the sine wave that has crest values within 0.995 of its peak for ≥ 100 µs can be calculated from

$$\frac{T}{4} \geq \left(\frac{90^\circ}{90^\circ - \sin^{-1} 0.995}\right) \frac{100\ \mu s}{2} = 785\ \mu s \qquad (6)$$

as

$$f_r \leq \frac{1}{T} \leq \frac{1}{4 \times 785\ \mu s} \leq 318\ \text{Hz}. \qquad (6')$$

A frequency of 255 Hz ($T/4 = 943\ \mu s$) was chosen to have a safety margin of 20%. For our application, the circuit inductance is approximately 16 µH and the circuit resistance is approximately 6 mΩ.

Capacitor Bank

For a resonant frequency of ~ 255 Hz we require a capacitance value of $C \approx 1/\omega^2 L = 24.35$ mF ≈ 24 mF. The circuit would be critically damped with a resistance of R = 51.6 mΩ. From Eq. (3) the current peak occurs after $t_p = 0.624$ ms at an angle of 83.3°. From Eq. (2) the capacitor bank must be charged to a voltage

$$E \geq I_p L\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}\; e^{\frac{R t_p}{2L}} \geq 288.3\ \text{V} \sim 300\ \text{V}.$$

In this case, the simplified equation (2'') would give a capacitor voltage that is 7.5% too high.

Current Ratings

With a PRF of 30 and a peak current of 10 kA, the rms and average currents are:

a) for a full sine wave (magnet of Fig. 1 and capacitor bank of all circuits).

$$I = I_{rms} \leq \frac{I_p}{\sqrt{2}}\sqrt{30\ T} \leq I_p\sqrt{15\ T} \leq 2.43\ \text{kA},$$

$$I_{ave} \leq \frac{2}{\pi} I_p\ 30\ T \leq \frac{60}{\pi}\ I_p\ T \leq 749\ \text{A}.$$

b) for a half sine wave (rectifiers of all circuits, magnets, chokes and transformers of Figs. 2 and 3)

$$I \leq I_p\sqrt{7.5\ T} \leq 1.71\ \text{kA},$$

$$I_{ave} \leq 749\text{A}/2 \leq 374\ \text{A}.$$

Pulsing Directly Into Load

Heat losses in the magnet can be cut by nearly 50% and the circuit efficiency can be increased by adding a high-Q charge recovery choke to the circuit of Fig. 1. This results in the circuit of Fig. 2.[1] In this circuit the operation has been simplified by replacing the reverse thyristor S2 shown in Fig. 1 with the diodes shown in Fig. 2. The circuit operation is explained by the waveforms shown.

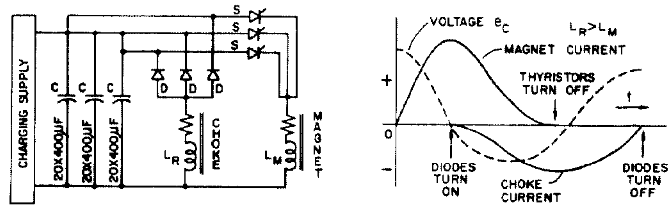

FIG. 2 CIRCUIT WITH CHARGE RECOVERY CHOKE AND ASSOCIATED WAVEFORMS. IF DIODES D ARE REPLACED WITH THYRISTORS THE WAVEFORMS OF FIG. 1 APPLY.

Capacitor bank C prevents transient voltages from the charging supply to reach thyristors S and diodes D. Therefore, their voltage rating need not be much higher than the operating voltage. For their current rating the repetitive surge current rating is important; this automatically gives a large safety factor for the rms current rating.

In this application 500 V thyristors with surge ratings of 6 kA and 500 V diodes with surge ratings of 5 kA would be chosen. Individual cables between the capacitors and the rectifiers and between the rectifiers and the magnet and the choke would be provided to force current sharing. The choke would be wound with three conductors in parallel, each conductor connecting to one rectifier. The inductance of the choke in Fig. 2 must be ~ 1.25 times the inductance of the magnet. This will give the thyristors time to turn off before forward voltage is reapplied.

The life of a capacitor is inversely proportional to the fifth power of the applied voltage.[2] The life is reduced by one-half for each 10°C rise in temperature above the rated temperature.[3] The greater the voltage reversal, the shorter the life. Therefore, for continuous operation over many years (approximately 9×10^8 charge-discharge cycles per year) conventional capacitors must be greatly derated. To achieve practically infinite life for this application, 400 µF units rated 3 kV would have been selected. A total of 60 units would be required at a cost of ~ $21,000.

Pulsing Through A Step Down Transformer

For energy storage capacitors the cost per joule versus voltage goes down as the voltage increases and reaches a minimum around ~ 10 kV. Above 10 kV the cost goes up in proportion to the voltage. In our case, the cost of storing a given amount of energy ($W = 0.5CV^2$) can be reduced by using higher voltage capacitors and a transformer to match the capacitors to the magnet load. With thyrsitors of 1600 V rating available, a transformer turns ratio of 4:1 was chosen. This reduces the capacitor bank to 24,000 μF/16 = 1500 μF, and increases the peak voltage to E ~ 4 x 300 V = 1200 V. For practically infinite life time 8 capacitors each rated 190 μF, 8 kV and costing a total of ~ $4,000 were chosen.

Figure 3 shows the improved circuit. With the recovery choke before the transformer, the transformer and the magnet carry only the positive half sine wave of current, the choke carries the negative half sine wave. Thyrister S1 carries a peak current of 2500 A (I = 1710/4 = 428A), thyristor S3 and diode D1 carry 69% of this current. Diode D2 carries the magnetizing current which resets the transformer core. Thyristors rated 1600 V, 1600 A rms and 6 kA repetitive surge current were selected for S1 and S3 and a 1600 V diode with a 1350 A rms and a 4.8 kA surge current rating was selected for D1. A 1400 V, 100 A diode is used for D2. Thyristors S2 carry the same current as the three thyristors S1 shown in Fig. 2. However, since the transformer secondary was wound with eight cables in parallel, four thyristors, each rated 500 V and 4.8 kA repetitive surge current, were used in the circuit of Fig. 3.

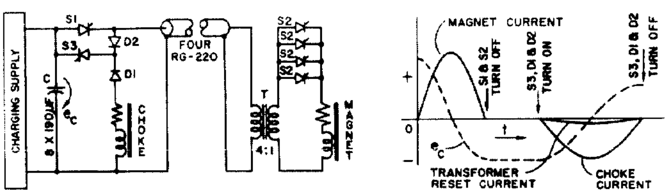

FIG 3 DISCHARGE CIRCUIT WITH MATCHING TRANSFORMER AND ASSOCIATED WAVEFORMS

The discharge is initiated by triggering thyristors S1 and S2, diode D1 blocks C from discharging into the choke. Diode D2 blocks current from flowing through the choke when the magnet current has passed its peak. At the end of the first half cycle the thyristors block and the capacitors are charged to ≈ -830 V. Triggering S3 initiates the recovery half cycle via D1 through the high-Q choke. S3 also connects the transformer in parallel with the capacitor via D2, permitting a magnetizing current to flow which resets the transformer core. Thyristors S2 in the transformer secondary block current flow during the last quarter of the recovery cycle. It is worth mentioning that one thyristor in the place of D2 could replace both D1 and D2. This thyristor would be turned on with S3 to reset the transformer.

The transformer is located as close as practicable to the magnet on top of the shielding blocks which cover the ring magnets. Four RG-220 coaxial cables in parallel connect the transformer primary to the thyristors and diodes which are mounted ~ 40 ft away in an enclosure which also houses the capacitor bank, the choke, and the charging supply. The transformer primary has 8 turns of two 4/0 cables in parallel, the secondary has 2 turns of eight 4/0 cables in parallel. The tape wound transformer core has a 6 in x 12 in cross section of grain oriented silicon steel made from 0.012 in thick laminations. The secondary turns connect through thyristors S2 to the magnet via 7 ft of a flat-strip transmission line.

Cost Comparison of Discharge Circuits

Circuit	Fig. 2	Fig. 3
Capacitor bank	$21,000	$4,000
Thyristors and diodes	600	1,100
Charge recovery choke	2,000	2,000
Transformer	----	3,000
Control and monitoring circuits	600	700
Cables and bus bars	400	300
Cooling water circuits	500	500
Total	$25,100	$11,600

Charging Supply Circuits

Rectifier Phase Control

Large capacitor banks are usually charged from a three phase HV power supply. A constant charging current is achieved by thyristor phase control on the low voltage rectifier transformer primary. The transformer secondary is usually wye connected and feeds a 3-phase full wave HV rectifier bridge. When the capacitor bank has reached the desired voltage, the control loop initiates blocking of the thyristors thereby terminating the charging cycle.

Charging Through a Resistor and Thyristor Turn-off Circuit

Capacitor banks of ≤ 5 kJ are often charged from an unregulated 3-phase rectifier and the voltage is controlled by a thyristor turn-off circuit. Figure 4 shows a typical example. The 3-phase rectifier output voltage is larger than the desired capacitor peak voltage $\hat{e}_{C1}$. When S1 is turned on, the charging current i_{C1} is limited by resistor R1. When the capacitor bank C1 is within 0.05% of the desired voltage, S2 is turned on. This causes a reverse current to flow out from the capacitor bank C1 through S1, and S2 into the turn-off capacitor C2. This reverse current will turn off S1. Capacitor C2 will be charged to

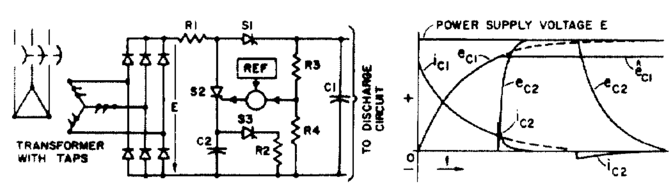

FIG.4 CHARGING CIRCUIT WITH THYRISTOR TURN-OFF AND ASSOCIATED WAVEFORMS

the power supply peak voltage at which time S2 turns off. The circuit is ready for the next charging cycle after C2 has been discharged via S3 and R2. The drawbacks of this charging circuit are the high losses in resistors R1 and R2.

A Controlled Charging-Choke Circuit

A much more efficient charging circuit than the one described in the above paragraph has been developed for this application which uses a choke with a crowbar thyristor.

A conventional charging-choke circuit is shown in Fig. 5. When the capacitor discharges, rectifier D conducts current i in the direction shown but does not let the current reverse. The current flowing through the choke charges capacitor C. The capacitor voltage e_C from time t_0 up to a value of time t_2 when current i tries to reverse follows the equation

$$e_C = E \left[1 - \epsilon^{-\alpha t} \left(\frac{\alpha}{\beta} \sin \beta t + \cos \beta t \right) \right] . \qquad (7)$$

After time t_2, e_C remains constant until the discharge circuit operates at time t_3 and removes the energy from C in a short length of time. The circuit then repeats this cycle, as shown.

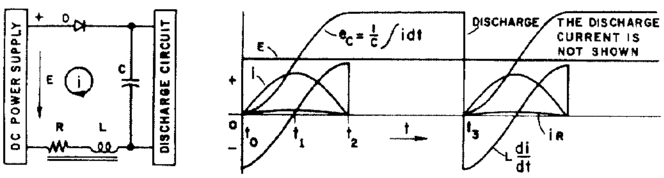

FIG. 5 CONVENTIONAL CHARGING CHOKE CIRCUIT AND ASSOCIATED WAVEFORMS

The waveforms in Fig. 5 show the charging current and the voltages on the components of the circuit. At time t_0 the supply voltage E begins to drive an essentially sinusoidal current through the charging circuit

$$E = iR + L\frac{di}{dt} + \frac{1}{C} \int_0^t i \, dt . \qquad (8)$$

At time t_1 the current is at its peak and with L di/dt = 0 we have

$$E = iR + \frac{1}{C} \int_0^{t_1} i \, dt.$$

Between t_1 and t_2 the decaying charging current generates a voltage L di/dt which aids the supply voltage to charge the capacitor C to a voltage larger than E. In the case where $R \to 0$, this voltage will be, at time t_2,

$$e_C = E + L\frac{di}{dt} = 2E.$$

By providing a thyristor (or other suitable switch) across the charging choke as shown in Fig. 6 the charging cycle can be terminated at any instant between times t_1 and t_2.

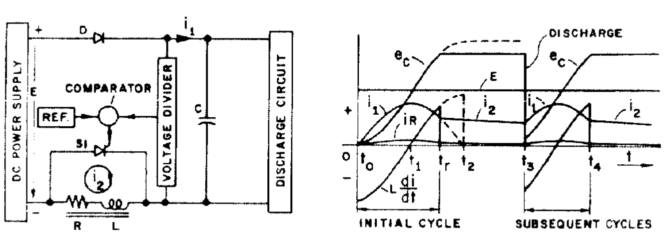

FIG 6 CHARGING-CHOKE CIRCUIT WITH TURN-OFF THYRISTOR AND ASSOCIATED WAVEFORMS

In the circuit of Fig. 6 a fraction of the capacitor voltage e_C is compared with a reference voltage. At time t_r, when these voltages are equal, a pulse is generated which turns on S1. With S1 conducting, the driving voltage L di/dt is removed from the circuit and with the capacitor voltage e_C larger than the power supply voltage E, diode D is back-biased and the charging current i_1 stops. The current i_2 flowing in choke L at time t_r will decay with a time constant L/R, where R is the resistance of the choke and thyristor circuit. Thyristor S1 remains turned on until at time t_3 the capacitor discharges into the load. With the capacitor discharged, the supply voltage E is back-biasing S1 and thereby turning it off. This returns the choke back to the charging circuit and the above cycle repeats. The current i_2 flowing in the choke when S1 is turned off will aid in charging capacitor C (the energy 0.5 L i_2^2 is returned to the circuit). This makes the circuit not only a very precise voltage regulator but also very efficient.

Fig. 7 shows an HV charging circuit in which part of the discharged energy is recovered from the magnet load together with the current and voltage waveforms of the charging circuit. Between times t_0 and t_1 the magnet current has gone through one cycle as described earlier for the circuit of Fig. 1. The capacitor is being recharged at time t_2 when thyristor S1 applies the unregulated HV dc power supply voltage E. When capacitor voltage e_C has reached a level corresponding to the reference voltage, a trigger pulse is generated turning on S2. S2 removes, by transformer action, the driving voltage L di/dt and terminates the charging cycle. In this case, a reactor-transformer is used in order that a low voltage thyristor S2 can be used in the HV charging circuit. Between charging cycles the current i_2 of the reactor-transformer decays exponentially; this current transformed to the primary is shown as i_2' in Fig. 7.

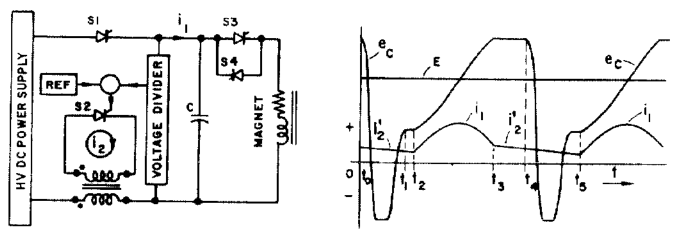

FIG.7 REACTOR-TRANSFORMER CHARGING CIRCUIT WITH TURN-OFF THYRISTOR AND ASSOCIATED WAVEFORMS

At time t_5 thyristor S1 is triggered on, which reapplies the power supply voltage E to the charging circuit. The voltage difference E - e_C, applied across the reactor-transformer, turns off S2. With the reactor-transformer inductance back in the circuit, capacitor C is being charged again to a voltage determined by the reference voltage. The capacitor voltage (magnet current) can be controlled over a wide range by varying the power supply voltage E. This is done by selecting different taps on the rectifier transformer (see Fig. 4).

References

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