A REGULATED, PULSED CURRENT SYSTEM FOR FOCUSSING MAGNETS*

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Introduction

As a part of the continuous program to increase the beam intensity of the Brookhaven National Laboratory linear accelerator, used as the injector for the Alternating Gradient Synchrotron, improvements were made on the beam transport system between the preinjector and linac. For this it was necessary to construct new 3-in. aperture quadrupole focussing magnets and associated power supplies. The design parameters of the magnets suggested that a pulsed power supply system would be necessary.

The requirements for the final system were:

Output current of 50 to 500 amperes for 50 microseconds with regulation of 0.5% during the pulse, and a repetition rate of 5 pulses per second. The magnets each had an inductance of 1 mH and a dc resistance of .080 ohms. The actual magnets were composed of two types; a "full-length" quadrupole with the parameters mentioned above, and a "half-length" quadrupole with half the resistance and inductance of the large one. Since most of the magnets are used in triplets, the power supply is capable of pulsing either a full-length quadrupole or two of the half-length quadrupoles in series.

The power supply uses a well known method of charging a capacitor from a dc source and then resonating it with the magnet coil in series with an undirectional element, limiting the current to a half sine wave. The frequency is chosen low enough so that the flat portion of the peak of the sine wave is within the current change tolerance during beam acceleration time, which is of the order of 50 microseconds.

Principles of Operation

The output of a dc power supply (Fig. 1) feeds into a large filter capacitor bank, which stores the energy used in recharging the resonating capacitor. The capacitor is replenished after each cycle via the charging regulator section of the system. The charging regulator feeds the capacitor storage, allowing a certain amount of charge to be deposited on the capacitor, depending upon the amount of current required in the magnet coils. The output of this capacitor storage is connected to a current switch which is in turn connected to the magnet. The current switch is pulsed when it is desired to turn on the current and allow it to flow from the storage element into the magnet.

In order to obtain the specified current through the magnet it is necessary to have a specific voltage appear on the capacitor for each pulse. A charge pulse coming from the magnet timing system enters the charging regulator and allows charge to start to flow from the filter bank into the capacitor storage. During this time the output of the capacitor is sensed by the comparator where it is continuously compared to some reference voltage. This voltage has a specific value relative to the amount of magnet current required. When these two voltages reach a comparison, a gate is generated which is used in terminating the charging process, indicating that sufficient charge has been deposited on the capacitor. This is done by opening the switch between the RC filter and the capacitor storage. In order to pulse the magnet, the timing system sends out a magnet pulse to trigger the current switch, allowing current to flow between the capacitor storage bank and the magnet.

During this time a sinusoidal pulse of magnet current causes the capacitor bank to become recharged but in the negative direction. At the end of this time, after the magnet has been pulsed, it is desired to recharge the capacitor to the same value for the next magnet pulse. In order to regain some of the charge which is on the capacitor, but with the wrong polarity, a flyback system is used. A flyback pulse from the magnet timing system enters the charging regulator and allows the capacitor to resonate with a flyback coil, bringing the voltage on the capacitor up towards the correct value and with the correct polarity. Because of the losses in the magnet and the flyback coil, additional charge is required on the capacitor for the next magnet pulse. This is supplied when the next charge pulse enters the regulator and the cycle repeats itself.

During the initial turn-on of the equipment or during a possible transient malfunction, the capacitor storage bank may charge to a value higher than required by the setting of the reference voltage. In this case it is necessary to inhibit any further charge pulses from entering the charging regulator. This is done by sending the output of the comparator back to the timing system, preventing any further charge pulses from being generated until the capacitor bank voltage prior to pulsing is below the required value.

Circuit Description

A circuit diagram of the pulsing system is shown in Fig. 2, and the corresponding waveforms

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in Fig. 3. The circuit operation is as follows: Assume that the circuit is in the time interval between t_4 and t_1 such that the correct voltage is present on the resonating capacitor, C_r. At this time all the SCR's are in their non-conducting state. At time t_1, a magnet pulse arrives from the timing system and triggers S_1 into conduction. This allows a half sine wave of current to flow through C_r and the magnet coils. The current is limited to a half sine wave since the attempt of the current to reverse direction only serves to shut off S_1. This leaves C_r charged to a voltage near its voltage at t_4, but of the opposite polarity.

The magnet pulse also triggers S_4, located in the regulator portion of the circuit, but its action is independent of S_1, since the two are separated by non-conducting S_3. S_4 is triggered at this time to prepare C_t for the turnoff action of the regulator. During the t_4 to t_1 interval, C_t is charged to the full supply voltage with a polarity plus, minus, as indicated. When the trigger at t_1 occurs C_t and L_t are allowed to resonate, causing the polarity of voltage to reverse, and leaving C_t charged, minus, plus as indicated in the parentheses.

At time t_2, some 10 ms after t_1, the timing system sends out a flyback pulse to trigger S_2. S_2 is connected in the correct polarity to resonate L_f with the reverse-charged C_r. Thus a half sine wave of current is allowed to pass through C_r, leaving it charged in the correct polarity, but with a voltage which is insufficient for the next magnet cycle.

Approximately 10 ms after S_2 has fired, and the flyback action is completed, the timing system initiates the regulation portion of the cycle by firing S_3. This connects the output of filter bank C_f to C_r through charging resistor R_c. C_r begins charging exponentially with a time constant $\approx R_c C_r$. When the comparator circuit (discussed below) senses that the correct voltage on C_r has been reached, a pulse is sent to fire S_5, driving the bottom of C_t to ground. This abrupt change in voltage is applied to the anode of S_3, shutting it off. At this time, t_4, the charging of C_r is complete and the regulation cycle is ended. Since S_5 was turned on to force off S_3, it will remain on while C_t charges to the supply potential. S_5 is allowed to turn off by starvation, i.e. the reduction of the current through the SCR to below the holding current value. The timing of the turnoff pulse, t_4, is dependent upon the amount of charge that must be added to C_r and will vary with different settings of the magnet current and also from pulse to pulse, depending upon the value of the unregulated input voltage.

A meter shunt of .001 ohms resistance is used in series with the magnet coils to produce a voltage which is proportional to the magnet current. This signal is used for monitoring.

Basic Parameter Calculations

The expression for the current in a series RLC circuit with an applied step of voltage is:

$$i(t) = \frac{V_o}{\beta L}\left[\varepsilon^{-\alpha t}\sin\beta t\right]$$

Where: V_o = resonating capacitor voltage

L = magnet self-inductance

R = magnet series resistance

I_{pk} = peak magnet current

f_o = frequency of the LC resonant circuit

$\omega_o = 2\pi f_o$

$\alpha = \frac{R}{2L}$

$\beta = \sqrt{\omega_o^2 - \alpha^2}$

For the 3-in. quadrupole magnets:

L = 1.0 mh

R = .080 ohms

α = 40

Assuming that $\beta \approx \omega_o$, then I_{pk} =

$$\frac{V_o}{\omega_o L} = V_o\sqrt{\frac{C}{L}} \quad\text{or}\quad V_o = I_{pk}\sqrt{\frac{L}{C}}$$

Trial solutions with commercially available capacitance values showed 800µf to be a good choice.

$$V_o = 550\sqrt{\frac{1 \times 10^{-3}}{.8 \times 10^{-3}}} = 616 \text{ volts}$$

$$\omega_o = \frac{1}{\sqrt{1 \times 10^{-3} \times .8 \times 10^{-3}}} = 1120 \text{ Radians/sec}$$

since now $\omega_o^2 \gg \alpha^2$ we see that $\beta \approx \omega_o$ is a valid assumption.

f_o = 178 c/s

a 1/2 sine wave is $\frac{1}{2f_o}$ = 2.81 ms

At this frequency, a change of 1/2% over the peak of the sine wave allows a time of 180 µs. This is reasonable for the acceleration of a 50 µs beam, allowing for timing jitter and component tolerances.

Calculating $\varepsilon^{-\alpha t}$ at $t = \frac{2.81}{2}$ ms = 1.40 ms

$$\varepsilon^{-\alpha t} = .945$$

Thus, the peak obtainable current is less than calculated by about 5%. Since $I_{pk} \propto V_{o(max)}$ increasing the supply voltage by 5% from 616 volts to 650 volts should allow a peak current of 550 amperes.

Components and Construction

1. Timing System

The timing system which supplies pulses at times t_1, t_2 and t_3 is constructed from printed circuit board building blocks which are used in other portions of the linac timing system. It consists of rather conventional monostable multivibrators, pulse shaping circuits and line drivers. The timing circuits also contain an inhibit feature which prevents a charge pulse from being sent to S_3 if the voltage on C_r is higher than required, due to a transient malfunction. This is constructed from simple NOR circuits.

2. SCR Drivers

The pulse outputs from the timing system which is located in the linac control room, drive 93 ohm coaxial cables, terminated in the magnet pulsing equipment. Since the pulses used to fire SCR's must inject current between the gate and the cathode terminals, the actual SCR drivers must be isolated from ground. To accomplish this, and to provide the current drive required, the circuit shown in Fig. 4 is used. The pulses arriving from the timing system are a minimum of 10 volts in amplitude and a minimum of 25 microseconds wide. These pulses are used to saturate the transistor amplifier which has a transformer coupled output, insulated for the maximum possible potential difference appearing between primary and secondary. The transformer has a current step-up ratio of 4:1 and will drive 1 ampere into a 3 ohm load. This supplies adequate current for the SCR's. A coarsely regulated 12 volt supply provides the collector current for the transistor. Each driver has an individual RC filter to prevent transient coupling from one driver to the other through the supply line.

3. Comparator

A diagram of the comparator is shown in Fig. 5. The variable reference voltage which controls the magnet current level, is derived from a ten turn potentiometer, which is driven from a well regulated -10 volt dc power supply. The voltage from the arm of the potentiometer is fed to an emitter follower on the comparator printed circuit board. If this output is called V_R and the input to R_1, coming from the top of C_r is called V_C, then the input to the buffer stage:

$$V_i = \frac{R_2}{R_1+R_2}(V_C + V_R) - V_R$$

If we now require that at the time when C_r has reached its correct value $V_i = 0$,

then $\frac{V_C}{V_R} = \frac{R_1}{R_2}$

Since $R_1 = 300k$ and $R_2 = 5k$, the ratio is 60:1, and thus -10 volts from the reference corresponds to +600 volts on C_r.

A buffer stage, used to avoid loading R_1 and R_2, follows the resistor network and feeds into a conventional Schmitt trigger circuit. The output is fed through an emitter follower and then to a two diode OR gate. This gate allows a safety pulse from the timing system to pulse the driver for S_5, in the event that no trigger is available from the comparator.

4. Power Supply

The basic power supply for the system is fed from the 440 volt, 3 phase line. It is capable of supplying 5 amperes at 650 volts, and each unit is used to drive two pulsing systems, via 10 ohm isolating resistors. The circuit is a standard three-phase, full-wave type, utilizing controlled avalanche rectifiers for maximum reliability. The rectifiers are replaceable from the front panel of the supply in case of failure. A total of three supplies are used for the five pulsing systems and all are controlled from a motor driven variable transformer on the input side. This allows lower power dissipation when the maximum currents are not needed.

5. Filter Bank

The capacitative filter bank is composed of two 25,000 µf banks in series. Each bank is constructed by using 25, 1000 µf, 400 vdc capacitors in parallel. The mechanical construction of the banks permits easy replacement of damaged units. The capacitors are arranged on a tray, and are connected to the circuit by means of Supercon plug and socket connectors, allowing rapid replacement in the event of failure. There are no potential dividing resistors for the two banks in series, since it was felt that the random values of leakage currents would balance out. This proved to be the case, the maximum unbalance being about 10%.

6. Flyback Coil

The flyback coil has a mean diameter of 15 in., composed of 56 turns of #4 wire. The coil is solidly mounted to a tray which slides into the cabinet in the manner of the filter capacitors. It has an inductance of 1.4 mH and a dc resistance of .055 ohms.

7. Resonating Capacitor

The resonating capacitor, C_r, consists of two 400 µf units in parallel. These are General Electric Energy Storage Capacitors, type 14F1057, and are rated at 1000 volts. This rating allows for long life even at 100% voltage reversals.

8. SCR Chassis

The remaining small components are mounted on a standard aluminum chassis, which slides into the rack. All wires carrying heavy currents are #4 welding cable, including the connections to the magnets on the injection line-up. All signals are carried on shielded wire. It was found necessary to use a small RC low pass filter directly at the input to each SCR, to prevent low energy spikes from prematurely triggering the circuit. All the SCR's used are G.E. type C46T. These are rated at 55 amperes RMS and are easily able to carry the 550 amperes on a low duty cycle basis, t/T being about 1-1/2%. The minimum forward breakover voltage, $V_{(BR)FO}$, is 900 volts, for 2 ma of current at + 125°C. This is adequate for all but S_3 and S_5, which require about 1100 volts. When the actual units were tested, the $V_{(BR)FO}$ was found to be at least 1200 volts at 4 ma, at room temperature. Since this was the maximum voltage rating of any available SCR's at the time of construction the C46T's were used, and have given no trouble. At this time higher voltage units are available and the spare components for S_3 and S_5 are IRC type 36RE130, with a rating of 1300 volts. S_1 and S_2 which carry the heavy currents, are mounted on Wakefield type NC-421 heat sinks, while the remaining SCR's are bolted to 3 x 3 x 1/8 in. copper plates. While the heating of the SCR's is not a problem, it was felt that keeping the junction temperature to a minimum would increase the life of the devices, and also help to raise the $V_{(BR)FO}$, since this parameter decreases with increasing temperature.

50 MeV Pulsed Bending Magnet

A system similar to the one described above is used to pulse a 5° bending magnet[2] located at the end of the linac tank. This magnet bends all of the linac pulses into a beam line which is 5° out of line with the AGS injection line-up. Located further along this 5° line is an analyzer magnet and a Faraday cup used for energy and energy spread analysis.

This system is identical to the above with the exception of the values of components. For the 5° bending magnet system:

L = 2.2 mH

$V_{o(max)}$ = 450 volts

R = .015 ohms

I_{pk} = 500 amperes

f_o = 50 c/sec

T/2 - 10 ms

C_r = 5000 µf

C_f = 50,000 µf

L_f = 3.1 mH

S_1, S_2 - G.E. C80M

S_3,S_4,S_5 - G.E. C46T

Results and Conclusions

The 3-in. quadrupole magnets and their associated pulsing systems were installed in October of 1964 and have been in service since that time. The system is able to deliver 50 to 500 amperes to within the original design accuracy. During the test and debugging phase some problems were encountered with the location of grounds. The only component failures to date have been a bad transistor in one of the SCR driver modules, and a shorted shield to the center conductor at one of the SCR gate connections.

This type of system would seem to be advantageous for the pulsing of small magnets where the accuracy requirement is rather high and the duty ratio is on the order of 1%.

Acknowledgment

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References

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2. R.A. Larson and R.J. Orgass, "Linac Pulsed Bending Magnet and Power Supply", BNL Accel. Dept. - AGS Internal Report RAL/RJO-1, Mar. 2, 1965.

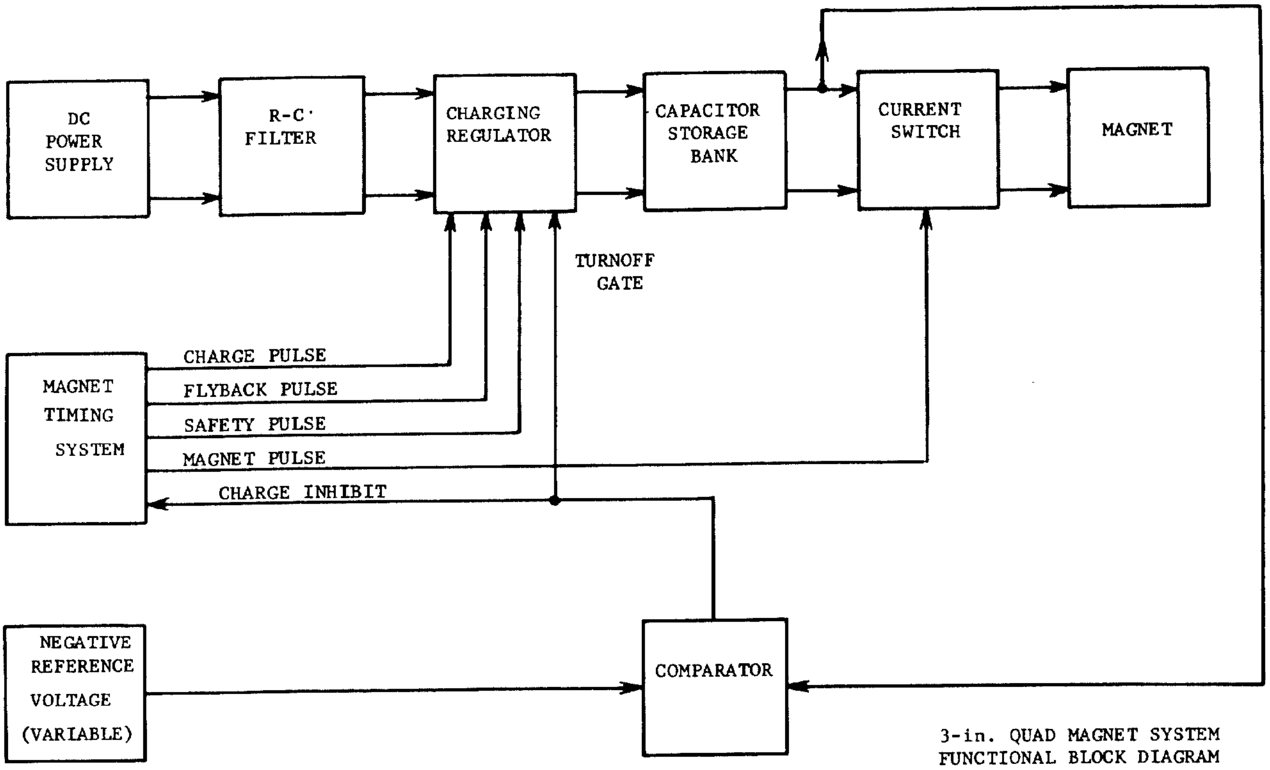


Fig. 1. 3-inch Quad Magnet System Functional Block Diagram.

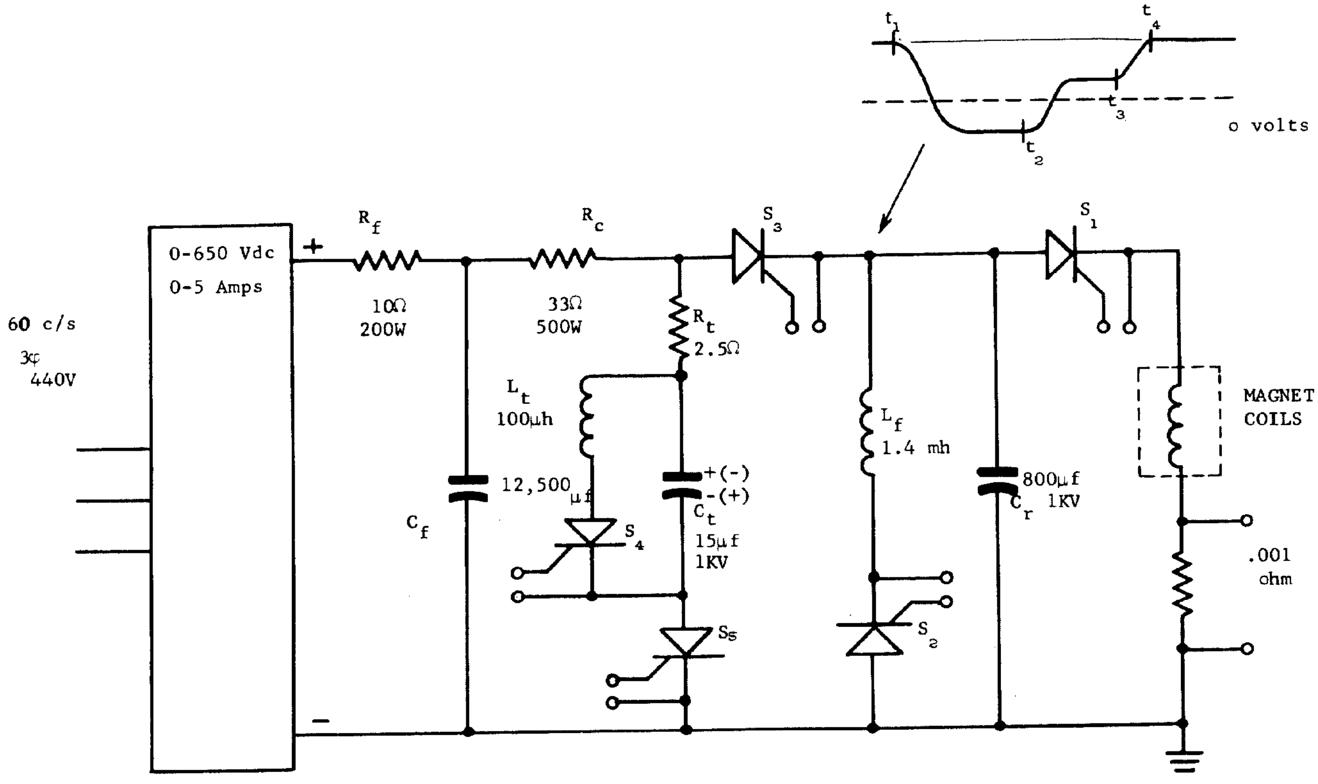


Fig. 2. Schematic Diagram Magnet Pulser.

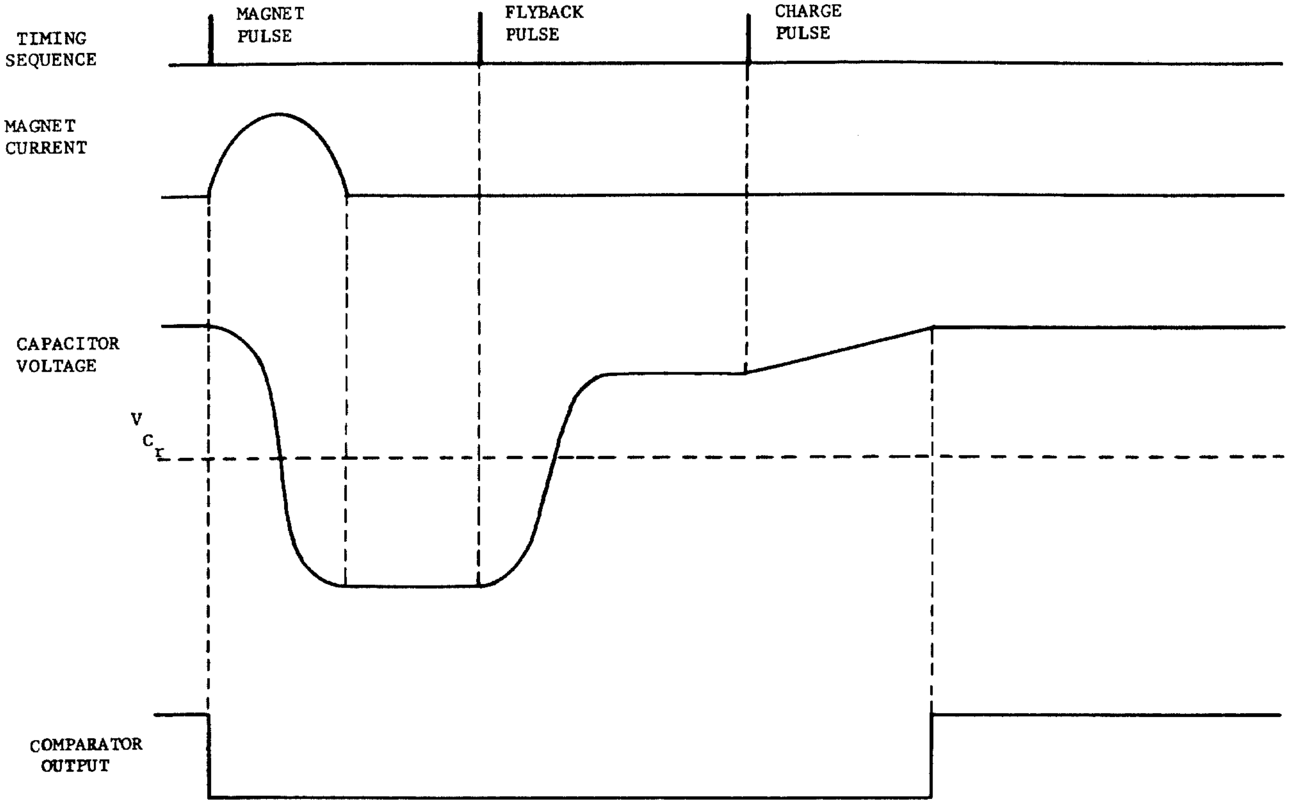
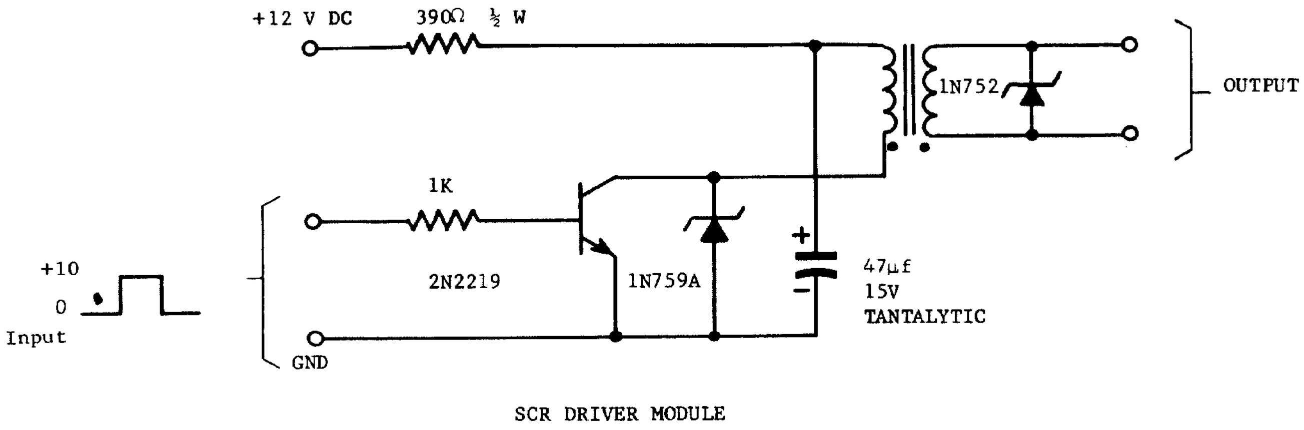


Fig. 3. Magnet Pulser Waveforms.



TRANSFORMER:

PRIMARY: 48 TURNS #30 ENAMELED

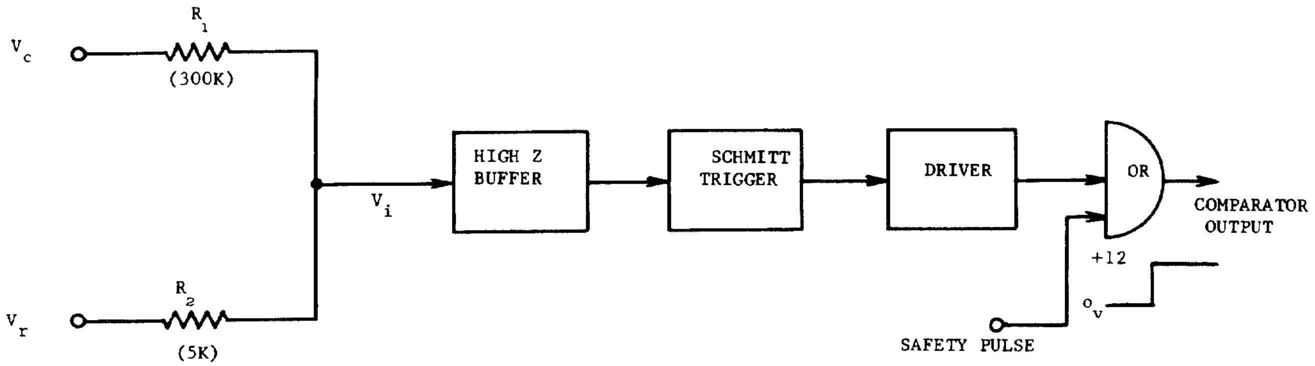
SECONDARY: 12 TURNS #24 TEFLON

FERRITE CUP & CAP

STACKPOLE CARBON CO.

CUP 57-7421 } CERAMAG 27
CAP 57-7751 }

Fig. 4. Schematic Diagram SCR Driver Module.



$$V_i = \frac{R_2}{R_1+R_2}\left(V_c + V_R\right) - V_R$$

FOR $V_i = 0$, THE COMPARATOR OUTPUT STATE WILL CHANGE

THUS: $V_c = V_R \frac{R_1}{R_2}$

Fig. 5. Voltage Comparator.