HIGH REPETITION RATE PULSERS FOR BEAM SWITCHING MAGNETS*

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Summary

This paper describes a type of pulsed power supply which has been developed to energize deflection magnets with a field of either direction, for a right or left beam deflection, on a pulse-to-pulse basis, at repetition rates up to 360 pulses per second, and to recover most of the energy at the end of the pulse.

The scheme consists basically of using ignitron tubes to switch energy stored in a capacitor bank to the pulsed magnet and back to the capacitor bank with relatively small losses, and using a dc supply to recharge the capacitor bank between pulses.

Two capacitor banks, one charged to a positive polarity and the other to a negative polarity, with their associated ignitron tubes, are connected to one magnet to permit energizing the magnet with a field in either direction as desired on a pulse-to-pulse basis. The two capacitor banks can be charged to different voltages, thus permitting the deflection of two different energy beam pulses.

The current pulse through the magnet is a one-cycle sine wave of the resonant frequency of the capacitance of the energy storage bank and the inductance of the magnet, with the timing of the pulse arranged such that the beam passes through the magnet at the peak of the sine wave. Regulation of the peak current in the magnets to the order of 0.1% has been achieved.

General

The electron beam from the Stanford two-mile linear accelerator is analyzed by a high quality magnetic deflection system in the beam switchyard and transported to the experimental areas. The first magnetic element in this system is a group of pulsed magnets which are used to deflect the accelerator electron beam to either transport system on a pulse-to-pulse basis and with different energy pulses at a repetition rate of 360 pulses per second. These pulsed magnets have to be energized in one polarity for a deflection to the left, and the other polarity for a deflection to the right, and have a continuously adjustable field strength to cover energy ranges from 2.5 to 25 BeV at a deflection of 0.5 degrees.

There are five pulsed magnets in series, each capable of a 0.1-degree deflection. Each of the five pulsed magnets has two pulsed power supplies, one of each polarity, which are capable of energizing the magnets to a peak current of 316 amps (120 joules) as required by the operational pattern signal from the accelerator. The operational pattern signal may require the pulsed power supplies to operate at any arbitrary pulse rate from single pulse operation to a maximum of 360 pulses per second.

The circuit used for the pulsed power supply is an energy recovery scheme essentially the same as that suggested previously by Cole, Hedin, and Muray.[1]

Power Supply Circuit

The pulsed power supply can be divided into three functional blocks: (1) the switch tubes used to connect the energy storage capacitor bank to the pulsed magnet, (2) the energy storage capacitor bank with the associated means of regulating the amount of stored energy, and (3) the dc charging supply to recharge the energy storage capacitor bank at the end of the cycle. The basic circuit of the pulsed power supply is shown in Fig. 1, and the sequence of operation is as follows.

(1) A signal is applied to the grid of the series regulator tube (V1), allowing the dc charging supply to charge the energy storage capacitor bank to the desired voltage level; then the grid is biased negatively so that the tube is cut off.

(2) The switching ignitron (V2) is then fired, allowing the energy storage capacitor bank to discharge into the pulsed magnet (L1). The current in the magnet builds up with the wave shape of a sine wave of the resonant frequency of the capacitance of the energy storage capacitor bank (C1) and inductance of the pulsed magnet (L1). During this time V1 is kept cut off by a negative grid bias so that the energy storage bank is isolated from the dc charging supply, and the voltage across the energy storage capacitor bank decreases with a cosine wave shape as the energy is transferred from the capacitor bank into the pulsed magnet. When the magnet current reaches its peak value, the voltage across the capacitor bank is zero and the energy is stored in the pulsed magnet. Due to the relatively high Q resonant circuit, the magnet now becomes a source of energy and discharges back into the capacitor bank, charging it to a negative polarity. The current continues to flow through the switching ignitron (V2) until the energy stored in the magnet has been transferred back to the capacitor bank, at which time the ignitron de-ionizes and opens the circuit as the current tries to

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reverse. This leaves the capacitor bank charged to a negative polarity.

(3) The second switching ignitron (V3) is then fired, allowing the energy storage capacitor bank to discharge again into the pulsed magnet in order to reverse the polarity of the voltage across the capacitor bank to its original polarity. The ignitron (V3) conducts until the current goes to zero, when the energy has been transferred from the capacitor bank to the pulsed magnet and back to the capacitor bank. Ignitron (V3) de-ionizes at the end of the current pulse, leaving the capacitor bank charged to its original polarity.

(4) A signal is again applied to the grid of the series regulator tube (V1), which recharges the energy storage capacitor bank to make up for the losses during the previous cycle. When the capacitor bank has been recharged to the desired voltage, tube V1 is biased off and the pulsed power supply is ready for the next pulse.

A resonant frequency of about 600 cycles per second between the capacitance of the energy storage capacitor bank and the inductance of the pulsed magnet is chosen. At this frequency, the above sequence of operation can be accomplished in less than 2.7 milliseconds, thus allowing the pulsed magnet to be pulsed at 360 pulses per second, the maximum repetition rate of the linear accelerator.

Operation

Two pulsed power supplies are connected to each of the pulsed magnets in the beam switchyard of the linear accelerator. One power supply is connected so that its energy storage capacitor bank is charged to a positive polarity, and the other is connected so that its energy storage capacitor bank is charged to a negative polarity, thus allowing a deflection of the beam from the accelerator to either the right or left, as desired, on a pulse-to-pulse basis. The pulsed power supplies are independent so that the capacitor banks can be charged to different voltages, if desired, thus allowing different energy beam pulses from the accelerator to be deflected to the two experimental areas. Three experimental areas can be served; one by energizing the pulsed magnets to give a left deflection, one by energizing the pulsed magnets to give a right deflection, and one straight ahead by not energizing the pulsed magnets for that beam pulse.

The firing signal to the switching ignitron V2 is applied only when it is desired to energize the pulsed magnet as determined by the operational pattern signal of the accelerator. In order to assure that the energy storage capacitor bank is kept at the desired voltage level, the signal to the grid of the series regulator tube (V1) is applied at a constant 360-pulse-per-second repetition rate so that both of the pulsed power supplies are ready in the event the next pattern signal calls for them to be used.

Description of the Major Components

Pulsed Magnets

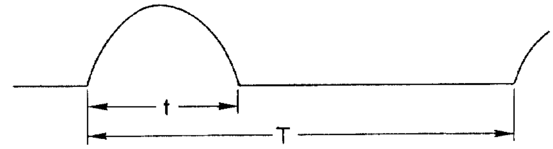
The pulsed magnets that the pulsed power supplies have to energize require a peak current of about 316 amperes and have an inductance of 2.4 millihenries. At the operating resonant frequency of 600 cycles per second, a peak voltage of 2844 volts is required. The Q of the magnet alone is about 200, but the losses of the long leads connecting the magnet to the power supply and the losses in the vacuum chamber in the gap of the pulsed magnet reduce the Q of the power supply load to about half this value.

The Switching Ignitrons

The switching ignitrons (V2,V3) must be capable of withstanding twice the operating voltage, 5688 volts in this case, during the periods of time when they are not conducting, because there are two power supplies with opposite polarities connected to the same magnet. They must also be rated to carry the peak and average current at the 360-pulse-per-second repetition rate, and must be capable of de-ionizing sufficiently to withstand the fast voltage reversal to which they are subjected at the end of the current pulse. Measurements indicate that the reverse voltage goes from zero to maximum in about 15 microseconds as soon as the tube stops conducting.

Tests conducted with rectifier type ignitrons without grids, such as the 5552, 5555, and 4681 ignitrons, indicated that while these tubes work satisfactorily at low repetition rates, they were not capable of recovering sufficiently to operate at full voltage and 360 pulses per second. Two types of ignitrons with one or more grids, the GL-5630 and GL-7736, were then tried and both found to be satisfactory in this operation.

The current through each switching ignitron has the wave shape of a half sine wave.



The average current for this waveform has the relationship:

$$I_{average} = (2/\pi)(t/T)\, I_{pk}$$

For a peak current of 316 amps, a resonant frequency of 600 cycles per second, and a repetition rate of 360 pulses per second, the maximum average current through each ignitron is 61 amps.

The ignitron type GL-5630 has a peak current rating of 500 amps and an average current rating of 50 amps; therefore, for use in this application it would be operating beyond ratings on an average current basis even though the peak current is well within ratings.

The ignitron type GL-7736 is designed for 2400-volt ac control service or 2100-volt rectifier service and has a peak current rating of 2400 amps and an average current rating of 300 amps. This ignitron has been chosen for the switching tubes even though the operation is over the published manufacturer's ratings, because extensive testing at an operating voltage of 3 kV has been achieved without malfunction and short periods of operation at voltages as high as 5 kV have been done without ignitron breakdown. It has been determined that the temperature of the ignitron jacket cooling water needs to be maintained at approximately $30 \pm 5\ ^{\circ}C$ for best operation.

The use of series-connected silicon controlled rectifiers has been proposed as a substitute for the switching ignitron tubes but has not yet been tried.

Energy Storage Capacitor Bank

The energy storage capacitor bank is made up of several pulse type capacitors in parallel to give a total capacitance of 33 microfarads in order to obtain the 600-cycle resonant frequency. The capacitors are of the type using a polyethylene dielectric and silicone fluid impregnant in order to achieve the lowest possible temperature coefficient of capacitance. Changes in the capacitance of the bank with temperature will result in a change in the resonant frequency and hence would require a change in the peak voltage required to give the desired peak current in the pulsed magnet.

The chosen resonant frequency of the circuit is a compromise between the allowable peak voltage across the magnet terminals, the time allowed between pulses, the peak recharge current, and the amount of heating that can be allowed in the magnet and its internal vacuum chamber. The resistive heating of the magnet conductor and the connecting leads increases as the frequency is lowered because the r.m.s. value of the current wave shape increases for constant peak current and repetition rate; however, the peak voltage required across the magnet terminals and the heating due to eddy currents in the internal vacuum chamber is reduced as the resonant frequency is lowered. In this case it was desired to keep the resonant frequency as low as possible consistent with a repetition rate of 360 pulses per second in order to keep the voltage across the magnet to a minimum. The 600-cycle frequency seems to be the best compromise as to heating, required voltage, and peak charging current.

Series Regulator Tube

The series regulator tube (V1) is a large transmitting type vacuum tube (such as a 3W5000) which is rated as being able to supply the required peak charging current during the relatively short period, about 1 millisecond, available for recharging the energy storage capacitor bank between pulses. It must also be rated to hold off twice the operating voltage during the pulsing cycle, because the voltage on the energy storage capacitor bank swings to essentially the same voltage in the opposite polarity during the cycle and the dc charging supply remains at a fixed output voltage.

A voltage divider across the energy storage capacitor furnishes a signal that can be compared to a reference voltage, which is used for feedback control of the voltage to which the capacitor bank is charged. During the period available for recharging the energy storage capacitor bank, the grid of the tube is driven into the positive grid region to achieve the lowest feasible tube drop and acts essentially as a constant current type charging impedance until the desired voltage level on the capacitor bank has been reached. At the time the switching ignitron (V2) is fired, the series regulator tube (V1) is gated off and held in a nonconducting state to provide isolation between the energy storage capacitor bank and the dc charging supply.

DC Charging Supply

The dc charging supply is a solid-state, three-phase, rectifier type power supply operating from three-phase ac line voltage. It can be of the fixed output voltage type because the series regulator tube can absorb the difference in voltage between the desired operating voltage on the energy storage capacitor bank and the output of the dc charging supply. The range of operating voltage required on the capacitor bank is only two to one for any one magnet, as there are a total of five magnets to give the desired beam deflection at 25 BeV. At lower energy beam operation all five magnets need not be energized; therefore, the total range of beam operation from 2.5 to 25 BeV can be accomplished with only a two-to-one range of current in the pulsed magnets.

Test Results

The desired goal of operation for the pulsed power supply is that it be able to supply pulses of current to the pulsed magnets which are reproducible from pulse to pulse to within 1 part in 1000. There is no problem in being able to charge the energy storage capacitor bank to the same voltage within 1 part in 1000 on a pulse-to-pulse basis. However, the peak current in the pulsed magnet is a function of the voltage across its terminals; therefore, variations in the drop across the switching tubes during the pulse will cause a variation in the voltage on the magnet terminals. Oscilloscope pictures taken of the arc-drop in the ignitrons over a period of many pulses indicate that the arc-drop is reproducible from pulse to pulse to within about 1 volt most of the time; however, occasionally an arc-drop picture is obtained which shows variations in arc-drop as high as 4 or 5 volts during the pulse with oscillations as low as 100 kilocycles. At the minimum required operating voltage of approximately 1400 volts, these variations would amount to about 1 part in 300 in the voltage applied to the magnet terminals. Whether or not this results in variations in peak current, or peak flux, of greater than 1 part in 1000 has not yet been determined.

The operation of the prototype pulsed magnet power supply built to test the feasibility of using ignitrons in this application has been very successful and has shown that ignitrons can be used in this switching application at repetition rates as high as 360 pulses per second, with no de-rating required.

Another pulsed power supply for a magnet requiring 600 joules peak energy is now under design. It is planned to use type 6228 ignitrons at an operating voltage of 8500 volts, a peak current of 625 amperes, and a resonant frequency of about 600 cycles per second at a repetition rate of 360 pulses per second.

References

1. J. Cole, B. Hedin, and J. Muray, "Model Pulsed Magnet," Internal Report, Stanford Linear Accelerator Center, Stanford University, Stanford, California (1963).

Acknowledgments

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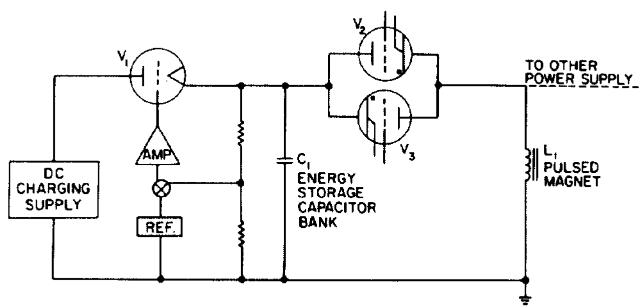

Fig. 1. Basic Circuit of Pulsed Power Supply.