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A Novel Current and Voltage Regulated Energy Discharge Power Supply 200 A, 600 V

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A NOVEL CURRENT AND VOLTAGE REGULATED ENERGY DISCHARGE POWER SUPPLY 200 A, 600 V

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Abstract. The fast spill beam extracted from the 1000 GeV particle accelerator at Fermi National Accelerator Laboratory requires two pulsed magnet and power supply systems to steer the beam to the designated experimental area. This beam steering requires a magnetic field integral of 4kGm per magnet for a duration of 4 msec at a rate of one shot per 5 seconds, and limited to 6 shots per 63 seconds. Each shot cannot last any longer than about 100 msec from start to finish. The magnetic field must be constant to within 1% during each 4 msec spill period. This paper describes an energy discharge type power supply and magnet that meet these requirements. This unique power supply has two regulators. One regulator preregulates the storage voltage and the other regulates the required peak current. The magnet and power supply design are interwoven to allow the use of easily available commercial parts for the power supply. Power supply and magnet design should always go hand in hand.

Keywords. Pulsed power supply, energy discharge power supply, energy discharge.

AS BUILT EQUIPMENT PARAMETERS

The final equipment parameters are listed below:

Magnet	
Gap	- 2"H x $2\frac{1}{16}$"W x 25.5"L
Peak current	- 200 A
RMS current, tested	~ 18 A at 100°C hot spot, 40°C amb.
Peak voltage	~ 600 V
Coil insulation class	- 155°C
Field	- 6.7 kG at 200 A
Field integral	- 4.4 kGm at 200 A
Number of coil turns	- 140, AWG #9, ESSEX HGP, Cu
Coil resistance	- 0.503 Ohm at 20°C
Magnet inductance	- 16.5×10^{-3} H
Magnet weight	- 400 LBS
Coil hipot test	- 2000 VDC
Power supply	
Type	- Pulsed, flattop current regulated energy discharge
Stored energy	- 800 Joules at 600 V
Input	- 120 V, 20 A, 1 Phase
Output pulse	- 200 A at 600 V
Operating discharge frequency	- 16 Hz with above magnet
Pulse rate	- 1 Pulse per 5 sec. continuous at 40°C ambient
Pulse rate limit set	- 1 pulse per 4 sec.
Current regulation envelope peak to peak	- 0.6% of set value including peak to peak ripple, from 20 A to 200 A during 6 millisecond
Control loc/remote	- 20 A/V, range 20 A to 200 A
Readback	- 1 V/20 A, updates every pulse
Firing pulse, remote	- +5 V, TTL, 1 μsec wide
Delay from firing pulse to flattop start	- 10.2 msec
Recovered energy	- 40%
Size	- R. Rack, 24"W x 30"D x 72"H

A method showing how to arrive at these values is described in this note.

INTRODUCTION

There are several ways to produce a pulsed magnetic field integral BL = 4 kGm for a beam spill duration of 4 msec. This could be accomplished by discharging a capacitor into a magnet. The difficulties increase, however, when the total current pulse duration cannot exceed 100 msec, the field has to be flat to within 1% at the top for 4 msec duration and there is a need for one pulse at 5 second intervals. The peak value of the pulse must furthermore be adjustable from 20% to 100% of rated value.

Some allowance should be made for timing misalignment. This can be done by requiring each flattop current to last 6 msec. A simple sinusoidal discharge current from a voltage regulated storage capacitor remains flat within 1% around the top from 82° to 98° and requires a pulse duration of at least 180/16 x 6 = 67.5 msec. This approach could be made to work, but it still requires matching the magnet inductance and the energy storage capacitor so that they yield the correct discharge frequency of 7.4 Hz maximum to 5 Hz minimum. The value of the resulting discharge current is also affected by temperature drift.

Other ways to produce the correct pulse would be to connect a programmable current regulated ac power supply to the magnet, or switch the required current stored in a large inductor to the magnet, or sequentially discharge capacitors to the magnet. All these approaches are rather complex. Another interesting approach is to take any sinussoidal discharge current within the required time boundaries and regulate the top flat at the required current value. This approach allows a lot more room to design the magnet inductance value and the energy storage capacitor. Series regulation could be done with power transistors connected in series with the magnet. These series transistors would start regulating at the required current and keep it constant for 6 msec. A drawback of this approach is the high instantaneous power dissipation in the transistors. Another serious draw back is that the transistors will fail, if they are accidentally programmed open during a discharge. This type of circuit is prone to failure, and therefore not very practical. However, the series regulation idea should not be abandoned. Series regulation could be made to work reliably by replacing the transistor with an on/off switch in parallel with a resistor as shown in Fig. 1. In the case of Fig. 1 the current would build up to the desired value through the closed regulating switch 3, after switches 1 and 2 close. When the magnet current reaches the desired value, the regulating switch switch opens and inserts the resistor in series with the magnet, which makes the current drop. The switch closes again when the current drops too low. A quick estimate reveals that the switching rate needs to be in the order of 2 kHz for 1% regulation. This approach has substantial advantages as follows:

1. The high instantaneous power is now dissipated in a rugged series resistor instead of the series transistor.
2. The magnet current is never fully interrupted, even when there is a control failure during a discharge. Limiting the resistor value such that the maximum possible voltage $I_{max}R$ is less than about half the switch voltage rating would yield a very reliable system.
3. The frequency requirement for the sinussoidal discharge current is not so stringent anymore, because of current regulation at flattop.
4. Strictly voltage regulated energy discharge power supplies are prone to load current drift during warm up. These types of power supplies regulate the voltage at the storage capacitor to yield the desired discharge current value. They need more charge when the load temperature increases. Current regulated power supplies automatically compensate for load changes caused by different temperatures.

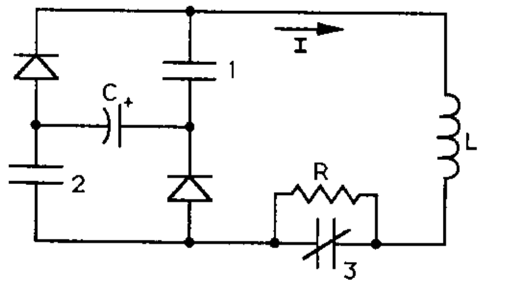


Fig. 1: Basic current regulated energy discharge power supply.

The problem is now, what switch to use and how to measure the discharge current fast enough for current regulation. An Insulated Gate Bipolar Transistor, IGBT, is a good choice for the switch. High power IGBT's with maximum available ratings of 200 A at 1000 V can easily switch at a rate of about 10 kHz. A dc transductor can be used to measure the discharge current changes fast enough. It appears that a switching type regulator can be made to work as long as we stay within the IGBT ratings. A voltage rating safety factor of about two should be used for the IGBT. It is now possible to summarize the preferred circuit parameters as follows:

1. Use the circuit shown in Fig. 1.
2. Recover the stored energy in the magnet after each pulse. This will reduce heat built up and power dissipation.
3. Circuit voltage and current should be limited to about 500 V and 200 A. Multiples of 200 A might be used.
4. The magnet gap is specified at 2" x 2".
5. It is specified that the magnet cannot be longer than 36".
6. The flattop time has to be 6 msec, which yields 2 msec. safety for timing misalignment.
7. The frequency of the LC discharge circuit has to be higher than 5 Hz, because each pulse may not last any longer than 100 msec.
8. The frequency of the sinussodial discharge current must be lower than 23 Hz. This can be concluded from some choices that need to be made in order to build a reasonable series regulated system. A look at Fig. 4 may be helpful at this point. A practical choice is to set the regulated 6 msec long flattop at 90% of the unregulated peak discharge current value. The 6 msec regulation period would therefore start at 65° into discharge sinewave of the current and finish at 115°. This corresponds to a discharge frequency of 23.1 Hz. Higher frequencies need more overcharge at the storage capacitor in order to achieve 6 msec flattop duration. At some point this becomes unreasonable. The conclusion is that the current discharge frequency f has to be 5 Hz < f < 23 Hz. This large range of usable frequencies gives us quite a lot of flexibility to choose L and C.

The above 8 points set the desired equipment limits for a preliminary design.

COMPONENT CHOICES FOR A PRELIMINARY DESIGN

The biggest difficulties with the design of a system like this is, how to start. A general plan of attack is described hereafter. It can be used as a guideline for other systems. The magnet is the best known part of the whole system. It is logical to start there and work backwards to design the power supply. In this case it is possible to meet the required parameters as can be seen from the equipment parameter listing.

<u>Magnet, preliminary design</u>
The magnet requires a 2" x 2" gap, is less than 36" long and needs to produce a field integral BL = 4 kGm. A 10% safety factor requires 4.4 kGm from the magnet. Some interesting observations can be made about the magnet.

The stored energy in the magnet can also be expressed using the magnet gap volume and field strength as shown in Eq. 1.

$$\frac{1}{2}LI^2 = \frac{1}{2}\frac{B^2V}{\mu_o} \tag{1}$$

Another interesting thing to note is that field integral BL needs to be constant. A short magnet needs, therefore, a higher field than a longer magnet and requires more stored energy than a longer magnet for the same BL value. Let the short magnet have length L and the long magnet a length xL. The stored energy is now:

$$\frac{1}{2}\frac{B^2 L A}{\mu_o} \quad \text{for the short magnet} \tag{2}$$

and

$$\frac{1}{2}\frac{\left(\frac{B}{x}\right)^2 x L A}{\mu_o} \quad \text{for the long magnet} \tag{3}$$

A = cross sectional area of the magnet gap.

The ratio of the stored energy in the short magnet and the long magnet for the same BL is:

$$\frac{\text{short magnet energy}}{\text{long magnet energy}} = \frac{B^2 L A}{\left(\frac{B}{x}\right)^2 x L A} \tag{4}$$

Equation 4 reveals that the stored energy needed by a short magnet is x times larger than the energy needed by a long magnet for the same product BL. x represents the ratio of the magnet lengths. This interesting observation suggests that it is better to choose a longer magnet and a lower field, because it requires less stored energy in the capacitor and also less ampereturns at the magnet.

The magnet steel can be made from grain oriented tape wound steel transformer cores, which are commercially available parts. The core manufacturer can easily cut a 2" section, for the magnet gap, out of these high grade electrical steel parts. The cut is then etched to eliminate shorts between the 12 mil thick steel core laminations. Cores with a steel cross section of 2-1/16" thick x 6-3/8" long can be chosen from catalogs. Four cores in a row yield a magnet gap of 2-1/16"W x 2"H x 25.5"L. This method of magnet construction is very economical and yields excellent pulse response. A field integral of 4.4 kGm requires 6.8 kG field in a 25.5" long magnet gap. The stored energy at 6.8 kG can be calculated from Eq. 1.

$$\frac{1}{2}\,\frac{0.68^2 \times 0.6477 \times 0.0524 \times 0.0508}{4\,\pi \times 10^{-7}} = 317 \text{ Joules} \qquad (5)$$

The ampereturns required for 6.8 kG in the 2" magnet gap can be calculated as follows:

$$B = \mu_0 H \qquad (6)$$

$$H = \frac{0.68}{4\pi \times 10^{-7}} \times 0.508 \quad \text{AT/2"} \qquad (7)$$

$H = 27{,}489$ Ampereturns

This requires N = 137 turns at 200 A. The required ampereturns for the magnet steel are negligible. Choosing N = 140 turns requires 196 A of magnet current to produce 6.8 kG in a 2" magnet gap. The magnet inductance is:

$$L = \frac{N\phi}{I} \qquad (8)$$

$$L = 16.5 \times 10^{-3} \text{ H.} \qquad (9)$$

This magnet has a 10% field integral safety factor. The coil copper cross section will be selected later.

Energy storage capacitor

The required energy in the capacitor has to be stored at about 500 V and must be larger than the 317 Joules stored in the magnet at 4.4 kGm. Several estimated correction factors have to be applied to the calculated storaged energy in the magnet in order to arrive at the required stored energy in the capacitor. Allowances should be made for:

1. Flattop current regulation Current regulation starts at 90% of the unregulated peak discharge current value through the magnet. The stored energy in the capacitor must be able to deliver the unregulated peak current value of:

   $$I_{peak} = 1.11\, I_{flattop} \qquad (10)$$

   It is a known fact that the stored energy in a magnet increases with the square of the current. A multiplication factor of $1.11^2 = 1.23$ must therefore be applied to the amount of stored energy in the magnet during flattop, in order to calculate the required energy at the storage capacitor.

2. Damping The oscillatory discharge current into the magnet is damped due to circuit and magnet losses, Fig 2. The instantaneous value I of the discharge current of Fig. 2 is:

   $$I = \frac{V}{2\pi f L}\, e^{-Rt/2L}\, \sin 2\pi f t \qquad (11)$$

   and has a ringing frequency $f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$ (12)

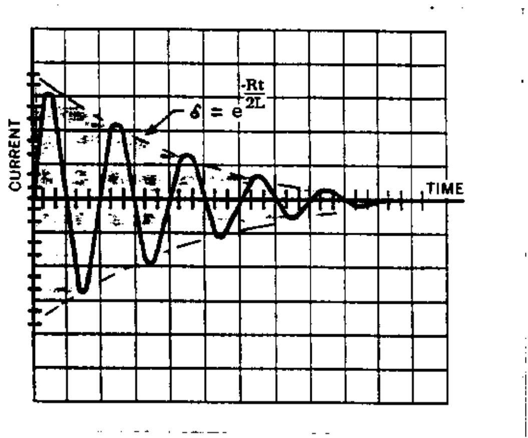


Fig. 2. Oscillatory discharge current of a damped RLC circuit.

The oscillatory component $\sin 2\pi f t$ is unity at 1/4 period and yields a first peak current value of:

$$I_{peak} = \frac{V}{2\pi f L}\, e^{-R/8Lf} \qquad (13)$$

$\frac{V}{2\pi f L}$ represents the undamped peak current value and $\delta = e^{-Rt/2L}$ is the damping factor. The damping at 1/4 period is:

$$\delta_{1/4} = e^{-R/8Lf} \qquad (14)$$

A reasonable estimate for the damping at 1/4 period is 0.75. This means that the actual peak value of the current arriving at the magnet is 25% lower than may be expected from a circuit without losses. The stored energy at the capacitor has to be able to deliver:

$$I_{peak\ undamped} = 1.25\, I_{peak\ needed} \qquad (15)$$

Thus the needed stored energy in the magnet must be multiplied with a factor $1.25^2 = 1.56$ to yield the required energy at the capacitor.

3. Magnet stray field The energy in the magnet was calculated without any allowance for magnetic stray fields. A saddle coil around the magnet gap, is used, and is the best coil to keep stray fields low. However, there will be stored energy in the stray fields. The stray field energy is estimated to be 20% of the gap energy.
4. Magnet iron losses The magnet steel weighs 320 lbs and has listed losses of about 0.05 Watt/lbs at 25 Hz and 7 kG. These steel losses can be scaled down to about 0.03 Watt/lbs at 18 Hz, or estimated to be about 0.01 Watt/lbs for unidirectional pulses, because in that case only half the frequency applies and there are no hysteresis losses. The estimated total steel losses are 0.01 x 320 ~ 3 Watt/pulse. The steel losses are negligable in this case.

It is now possible to estimate the required stored energy at the capacitor by adjusting the stored energy in the magnet at flattop as follows:

$$\frac{1}{2} C V^2 = 1.23 \times 1.56 \times 1.2 \times 317 = 730 \text{ Joules} \qquad (16)$$

These 730 Joules are a reasonable preliminary estimate for the required stored energy at the capacitor. It is now possible to calculate C because the charge voltage should be about 500 V to permit the use of a 1000 V rated IGBT with a voltage rating safety factor of 2.

$$\frac{1}{2}CV^2 = 730 \text{ Joules} \tag{17}$$

$$C = 5840\ \mu F \text{ for } V = 500 \text{ V.} \tag{18}$$

Choosing $C = 4500\ \mu F$ requires about 570 V charge at 730 Joules. The approximate frequency of the discharge circuit can be determined from:

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{19}$$

and yields f = 18.6 Hz. This is within the previously determined allowable frequency range of 5 Hz < f< 23 Hz. The final frequency may be somewhat lower because the stray inductance is not included and the effects of damping have been omitted.

Series regulating resistor

The series regulating resistor must be small enough so that the IR drop at 200 A does not exceed 500 V which is half the voltage rating of the IGBT. Thus R has to be smaller than 2.5 Ω. Another requirement is that the resistor needs to be large enough to make the current drop during current regulation. This means that the IR drop during regulation must exceed the remaining charge voltage at the storage capacitor. If this were not the case, the current in the magnet would still increase, although at a slower rate. The capacitor started out with about 730 Joules stored energy for 200 A operation. About 1.2 x 317 = 380 Joules is at the magnet when it reaches 200 A and about another 160 Joules are spent on damping losses at that point. There are thus about 190 Joules at 290 V left in the capacitor at the start of current regulation. This requires the regulating resistor including the circuit resistance to be larger than 290/200 = 1.45 Ω. Estimate the circuit resistance to be 0.45 Ω. Thus the regulating resistor needs to be 1 Ω < R < 2.5 Ω. A value of 1.67 Ω was chosen.

Magnet coil

The estimated frequency of the sinussoidal discharge current pulses through the coil is about 18 Hz and yields 28 msec, total pulse duration for each pulse. There are 6 pulses per 63 seconds. Each pulse could be conservatively replaced with a 28 msec, 200 A peak square wave pulse for coil temperature rise calculations. The equivalent RMS value of such a pulse train is:

$$I_{RMS} = 200\sqrt{\frac{6 \times 28 \times 10^{-3}}{63}} \tag{20}$$

$$I_{RMS} = 10.3 \text{ A} \tag{21}$$

The RMS value of the ampereturns around the magnet pole is:

$$140 \times 10.3 = 1442\ AT_{RMS} \tag{22}$$

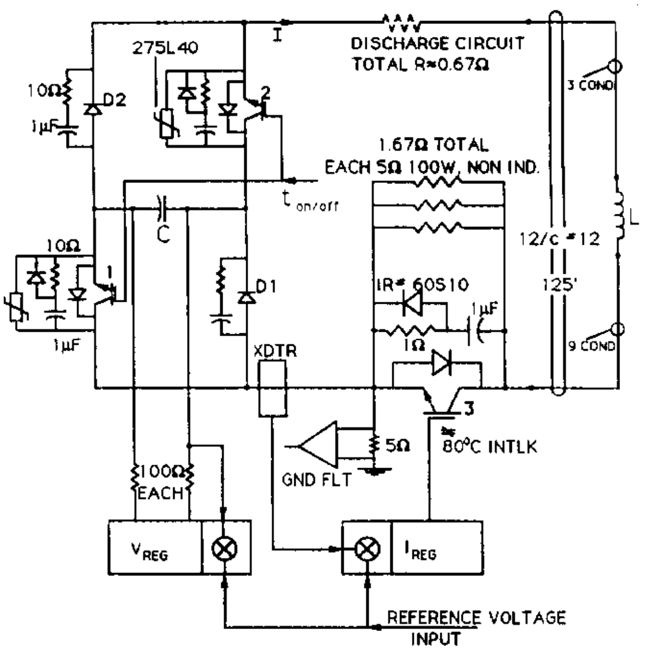
The current density in the coil determines the coil temperature rise. A temperature rise estimate for the air cooled coil may be made from tabulated temperature rises at rectangular copper bus bars at various currents. These tables show that a 1/2" x 3" bus bar at 2050 A rises 65°C in temperature. The coil cross section of the windings must therefore be in the order of 1/2" x 3". Larger cross sections are preferred to keep the coil resistance and thus the circuit damping low. The final coil is made from 140 turns AWG #9 square wire and has a finished cross section of 3/4" x 3-1/2". It can handle 18 A_{RMS} at 100°C hot spot and has a resistance of 0.503 Ω at 20°C. This is a larger coil than needed for temper-ture rise but the large cross section was chosen to keep the circuit damping low. Pulsing requires the coil to be securely supported by the magnet steel and to be potted with epoxy.

Pulse transmission

Coaxial cables are often used to transmit the current pulses from an energy discharge type power supply to a magnet. The power supply and magnet are 125 ft. apart. Coaxial cables have relatively low inductance and do not produce external stray fields. Most coaxial cables have undesirably high resistances, except for the larger ones, such as RG220, which are expensive, require a large bending radius and have a low temperature rating. An economical coaxial transmission line can be constructed from 600 V multiconductor power-control cables. These cables are economical, are very flexible, have a high 90°C temperature rating and can be used up to several thousand volts in these applications. They are available in a large variety of sizes and number of conductors. A 12/c AWG #12, is chosen for transmission of the current pulse train. This choice is much better than a coaxial cable for this application. The individual conductors are connected such that the current flows to the magnet via the 3 wires in the center of the bundle and returns via the 9 outer wires. Different or parallel multiconductor cables can be used to construct transmission lines with less resistance.

Summary conclusion

It is practical to make a reliable current regulated power supply within the required restraints. The final magnet and power supply circuit is shown in Fig. 3.



1,2,3 - IGBT Toshiba #MG200NIUSI 1000 V, 200 A
D1,2 - IR #IRKE71-12, 1200 V, 71 A
C - 4460 µF, 1000 V_{peak} 2xGE#17L611NJ
XDTR - Current transductor LEM #LA200S-SP24, 200 A
L - Magnet, 16.5×10^{-3} H, 0.5 Ω at 20°C

Fig. 3: Energy discharge power supply circuit.

CONTROL

Power supply control is rather simple. Figure 3 shows a dc voltage reference that controls both the charge voltage and the regulated flattop current. The reference gains are set such that the charge voltage automatically tracks the required flattop current. The charge voltage is regulated to always yield an unregulated peak discharge current which is 11% larger than the required flattop current. This is shown in Fig.

4. Charge regulation does not have to be very precise. The charging power supply is always left connected to the storage capacitor, via current limiting resistors.

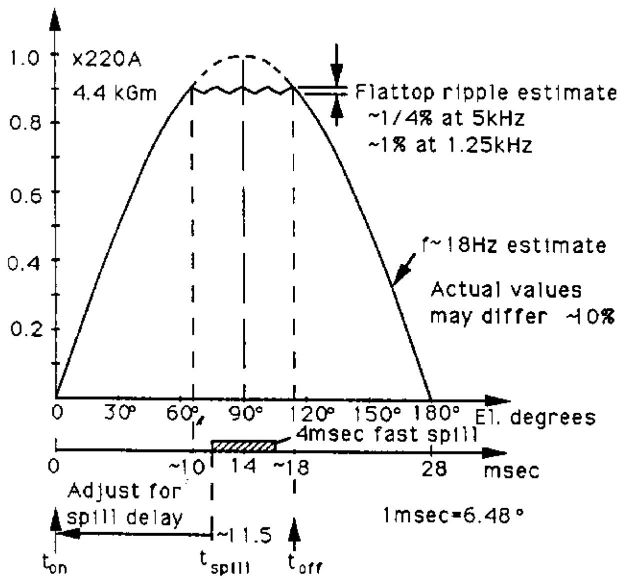


Fig. 4: Discharge current pulse from the power supply in Fig. 3.

The storage capacitor is floating and is connected at the center of a bridge consisting of diodes 1, 2 and IGBT's 1,2. The series regulating IGBT3 and resistor are operated close to ground potential. Extreme care must be taken to keep the stray inductance in the loop consisting of the IGBT switching transistor 3 and it's parallel resistor as low as possible. An effective spike snubber is installed around these components. The power supply pulse period is internally limited to 4 seconds. The only remote control needed is a reference and a firing pulse. A remote firing pulse closes IGBT's 1 and 2 at the storage capacitor bridge about 11 msec. before the beampulse arrives as shown in Fig. 4. This command causes

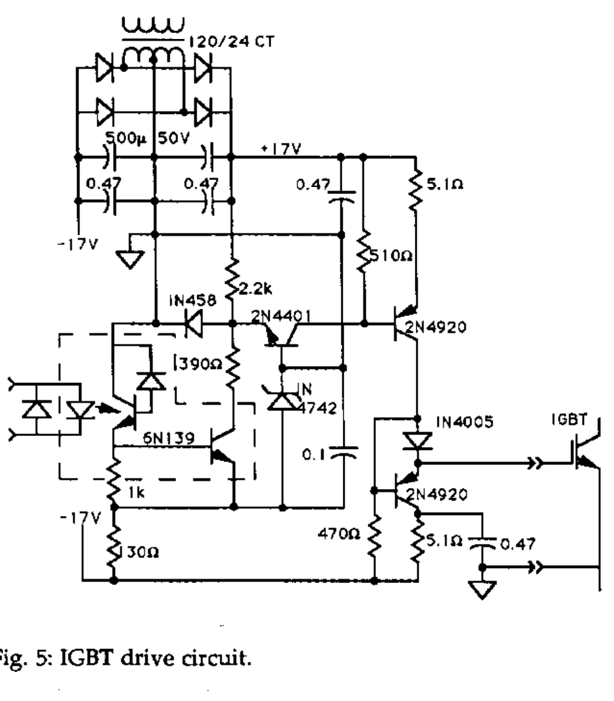


Fig. 5: IGBT drive circuit.

the current in the magnet to rise until it reaches the set flattop current value about 10 msec later. The discharge current is measured with a dc current transductor, connected to a regulator. This regulator switches the series regulating IGBT3 on and off in order to keep the magnet current constant during flattop. A timing pulse, generated by internal supply controls, opens IBGT's 1 and 2 in the bridge around the storage capacitors after flattop is over. The stored energy in the magnet will at that instant start to flow back to the storage capacitor. All losses are replenished by the charging power supply so that there is again enough stored energy for the next shot 4 seconds later. The measured peak current value of every discharge pulse is available for remote and local readout. This value is stored in a sample and hold and updated at every pulse. The control for the IGBT's requires a + and - 17 V control voltage to switch them on and off. Switching needs to be fast in order to keep switching losses to a minimum. The drive circuit for the IGBT's is shown in Fig. 5.

CONCLUSION

Operation of both power supplies has been very reliable and without any major failures. This proves that a series regulated power supply can be made reliably. The performance of the equipment was checked and is tabulated below. The required charge voltage for 200 A is slightly higher than expected.

Tabulation of measured equipment performance.

Magnet Field	Magnet Current Set	Capacitor Charge	Capacitor Recovered Charge	Flattop Total ΔI of Set Value
kGauss	20 A/V Amp	Volt	Volt	%
6.70	200	658	400	0.4
5.35	160	527	330	0.4
4.00	120	396	250	0.4
2.74	80	264	170	0.6
1.40	40	133	84	0.6
0.70	20	67	45	0.4

ΔI includes ripple, overshoot, droop.

Regulator switching frequency changes from:	- 5 kHz at 200 A
to:	- 2.6 kHz at 20 A
Flattop length:	~ 6 msec.
Discharge frequency:	~16.1 Hz
Pulse to pulse variation & regulation:	< ±50 mA per day
Set to repeatability:	< ±50 mA
Temperature regulation:	< 50 ppm/°C, est.

Note: All tests with 145 ft 12/C #12 load cable, 5 sec. rep. rate, 116 Vac. T_{off} set at 18 msec. Magnet current set to and readback 20A/V.

COMMENTS

Commercially available IGBT's are presently limited to voltage ratings in the range of 1000 V and several hundred amperes. Higher current ratings are available at lower voltage ratings. The energy discharge power supply shown in Fig. 3 is therefore limited to about 600 V and 200 A, until higher rated IGBT's become available. Looking at Fig. 3, it becomes apparent, that IGBT's 1 and 2 are operated in series, and that one of these IGBT's will momentarily block the full charge voltage at C if they are not switching on simultaneously. The photo transistors for the IGBT 1 and 2 drive circuits, shown in Fig. 5, are driven in series from one trigger source. This gives the best assurance that they both trigger simultaneously. Triggering IGBT's 1 and 2 via a fiber optic cable at higher than 600 V is recommended. Snubbers should be installed.

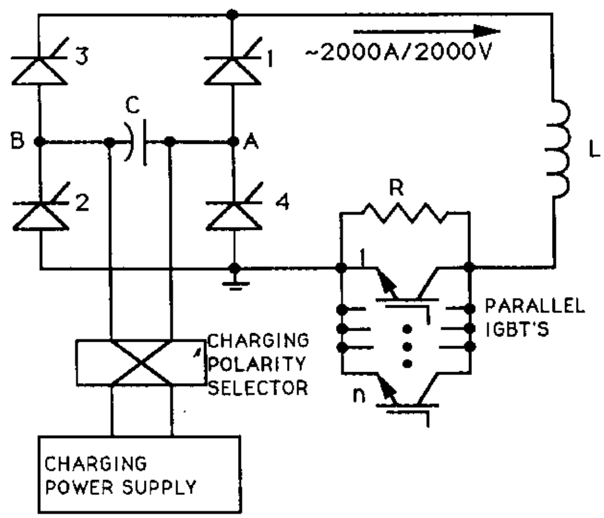


Fig. 6: A high power current regulated energy discharge power supply.

Designs requiring operating voltages of several thousand volts and several thousand amperes are not practical for the power supply in Fig. 3. Especially IGBT's 1 and 2 around the capacitor will experience unreasonably high voltages. The regulating IGBT 3 ratings can possibly be taken care of by running several in parallel and reducing the regulating resistor R. The circuit shown in Fig. 6 is a slight modification of Fig. 3 and offers interesting possibilities for much higher rated energy discharge systems. Figure 6 shows that the IGBT's and diodes around storage capacitor C are replaced with 4 SCR's. SCR's are economically available at ratings of several thousand amperes and several thousand volts. Several regulating IGBT's could be operated in parallel to handle the current. Another interesting idea is to install some auxiliary turns at magnet L which get shorted out by the regulating IGBT's at the desired current. The answer current in this auxiliary winding keeps the magnet field constant. Control of the circuit in Fig. 6 would be rather simple. There is a "charging polarity selector" between the charging power supply and C. Suppose C gets initially charged positive at A. All SCR's 1, 2, 3, 4 receive a firing pulse to start the discharge current. Only 1 and 2 stay on, 3 and 4 are reverse biased. The current now discharges through L and the stored energy in the magnet will be recovered in C with polarity B being positive. The charging polarity selector determines that B is positive and adds charge to C, at B positive, to replenish the losses. Again, all 4 SCR's get fired and C will now recover charge at A is positive. The polarity at C reverses from pulse to pulse.

A quick preliminary estimate for the circuit parameters of Fig. 6 can be made, following the same procedure as before. This procedure is summarized below.

1. Magnet. Choose the magnet length from the required field integral. It makes sense to choose a long magnet because it reduces the required amount of stored energy, Eq. 4, the ampereturns and the iron losses.
2. Circuit current. Determine the maximum current from the selected components.
3. Circuit voltage. Determine the maximum voltage using a voltage safety factor of 2 for the selected components.
4. Circuit frequency. Determine the lowest permissible frequency from the allowed pulse duration. Determine the highest practical frequency from the required flattop duration, lasting from 65° to 115° in the discharge sinewave current.
5. Magnet. Calculate the stored energy in the magnet from the gap volume and the required magnetic field strength.See Eq. 1.
6. Magnet. Calculate the magnet inductance using the magnet stored energy and the maximum selected current value. See Eq. 1.
7. Magnet. Estimate the magnet iron losses from published loss curves and select thinner laminations, when the iron losses are too high.
8. Capacitor. Multiply the stored energy in the magnet with 2.5 to find the required stored energy in the capacitor Similar to Eq. 16.
9. Capacitor. Find the amount of capacitance needed for the selected charge voltage limit.
10. Frequency. Calculate the approximate ringing frequency of the LC circuit. See Eq. 19.
11. Check. Select a higher operating current if the frequency is too high and a lower operating current if the frequency is too low. This will change the magnet inductance L. The stored energy remains the same.
12. Regulating resistor. Determine the maximum value of the regulating resistor by limiting the maximum voltage drop to half the switching regulator voltage rating. Find the minimum value for the regulating resistor by requiring the IR drop at maximum load current to be larger than half the operating charge voltage.
13. Magnet coil. Calculate the RMS value of the current pulse trains, Eq. 20, and design the coil. Determine the required ampereturns from Eq. 6. Choose a low resistance for the coil to keep the damping low.
13. Conclusion. It may not be reasonable to use current regulation for very large systems. The above is a reasonable way to quickly find out whether a system is practical or whether other building blocks, such as a longer magnet need to be chosen. After this it is possible to make a final design choice.

ACKNOWLEDGEMENT

Walt Jaskierny made substantial contributions to the improvement of various control circuits and assembled and tested the power supply.

CONVERSION FACTORS

Some conversion factors are given below for readers who are more familiar with the mks system.

Dimension	1 mil	= 2.54×10^{-3} cm
Dimension	1 inch (1")	= 2.54 cm
Dimension	1 foot (1')	= 30.48 cm
Force	1 lb(s)	= 0.4536 kg(s)
Wire size, crossection	AWG #9	= 6.63 square mm