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Praeg

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[54] **ACTIVE CROWBAR FOR A SWITCHING MAGNET**

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[52] **U.S. Cl.** **307/108**

[51] **Int. Cl.** **H03k 3/00**

[58] **Field of Search**..... 307/106, 107, 108, 307/109, 110

[56] **References Cited**

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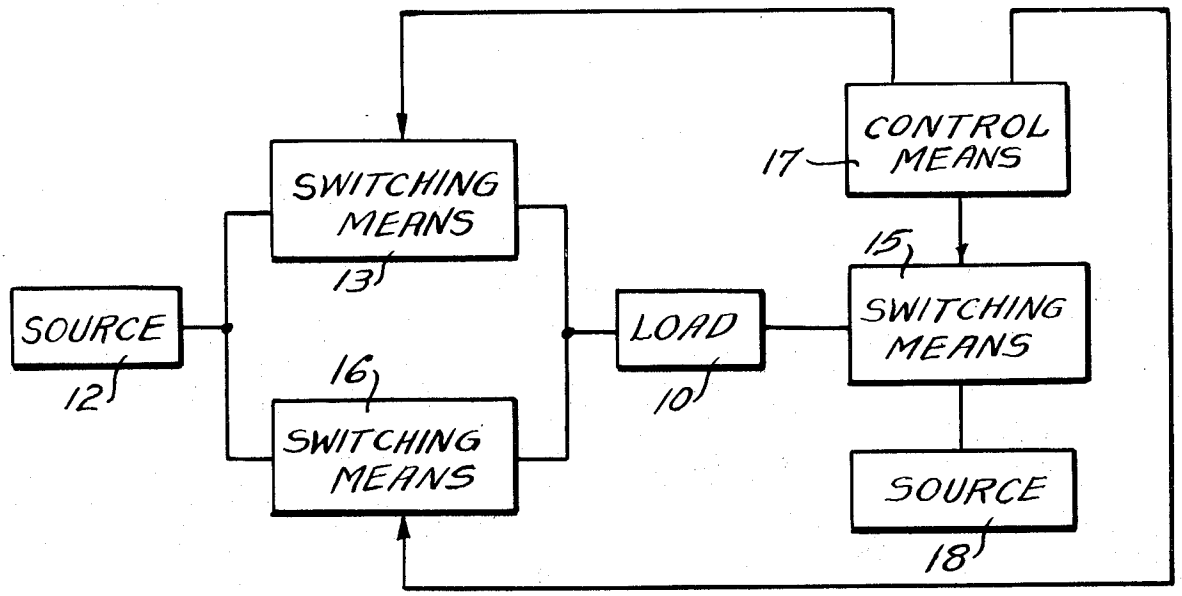
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Primary Examiner—Robert K. Schaefer
Assistant Examiner—M. Ginsburg
Attorney—John A. Horan

[57] **ABSTRACT**

A first electrical source is connected to an electromagnet by silicon-controlled rectifiers (SCR's) to produce a rapid rise in current in the load. A second electrical source is then connected by SCR's to the load and the first is disconnected to produce a constant current in the load. A connection is then established to discharge the stored energy from the electromagnet, producing a rapid drop in current, and the second source is disconnected. The stored energy may be returned to the first electrical source.

8 Claims, 5 Drawing Figures



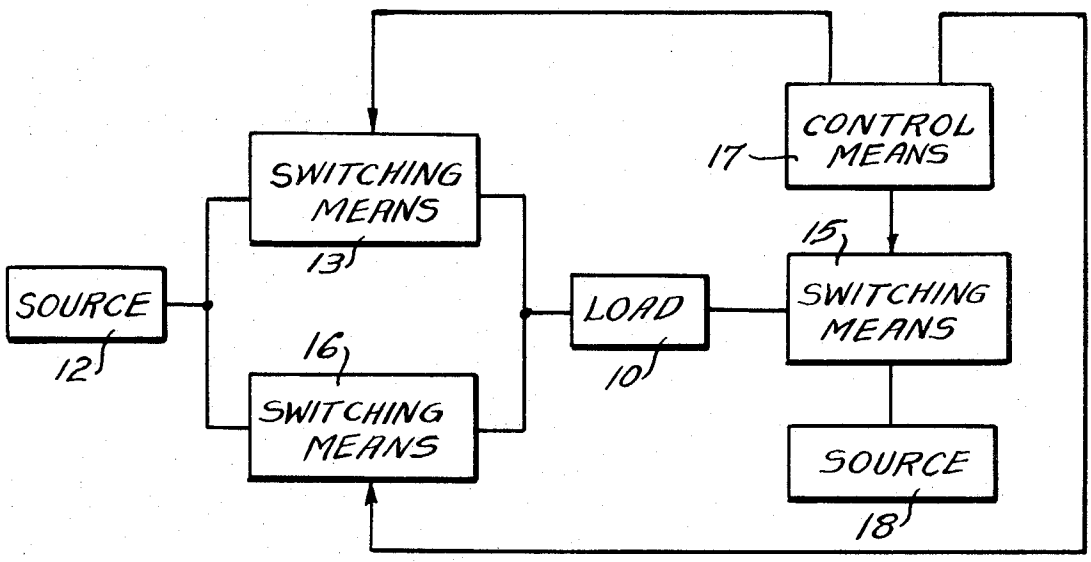

CONTROL MEANS
17
SWITCHING MEANS
13
15
SOURCE
12
LOAD
10
SWITCHING MEANS
16
SWITCHING MEANS
SOURCE
18

Fig — 1

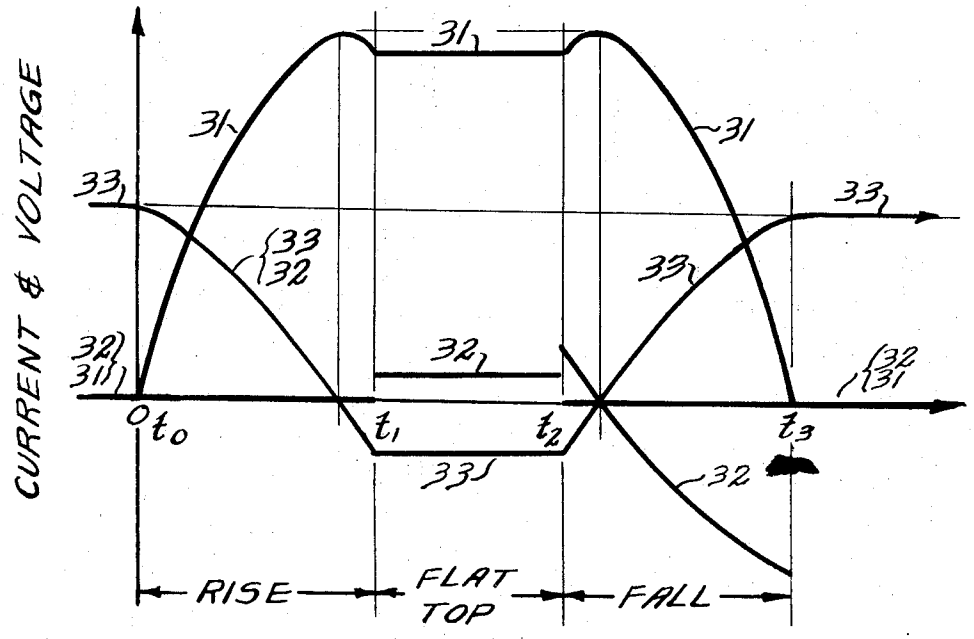
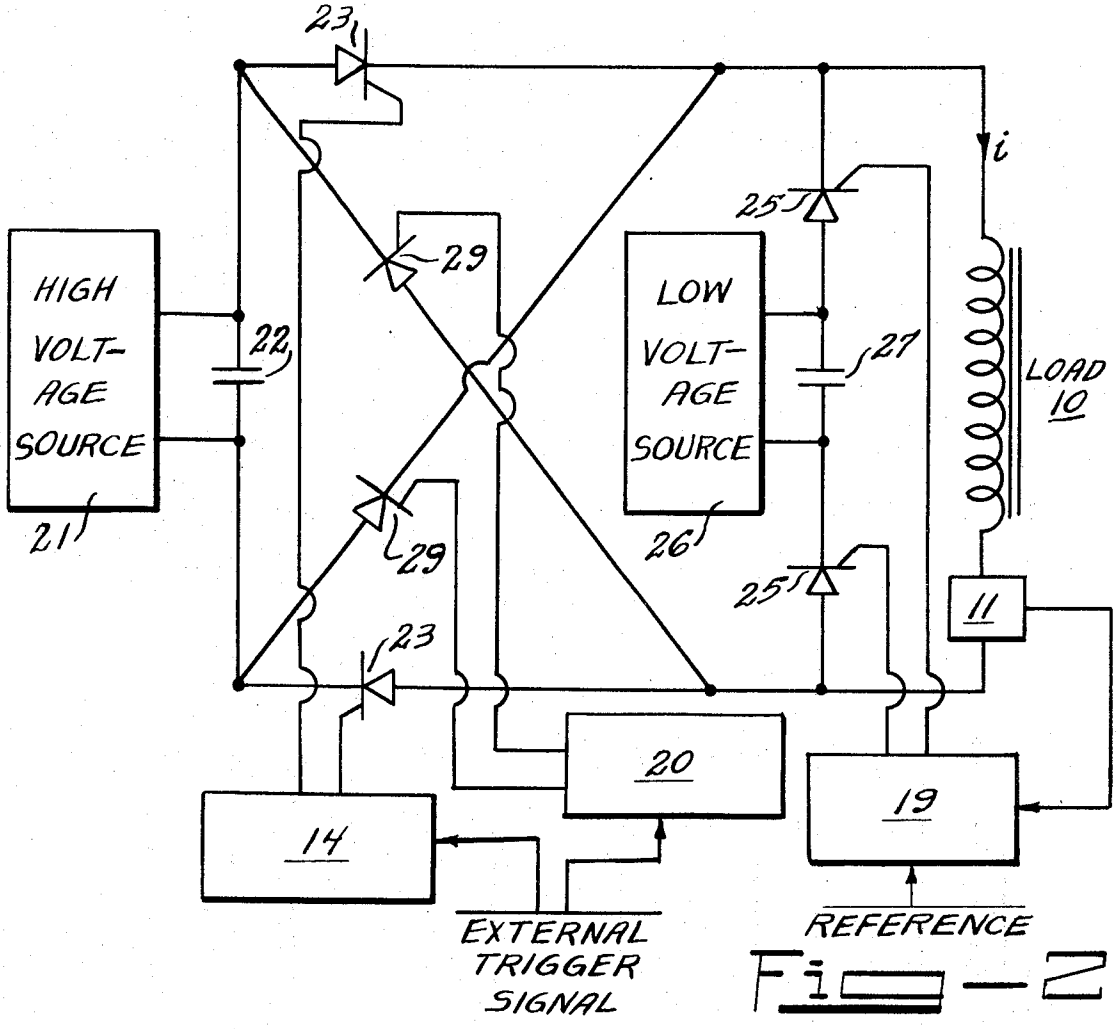
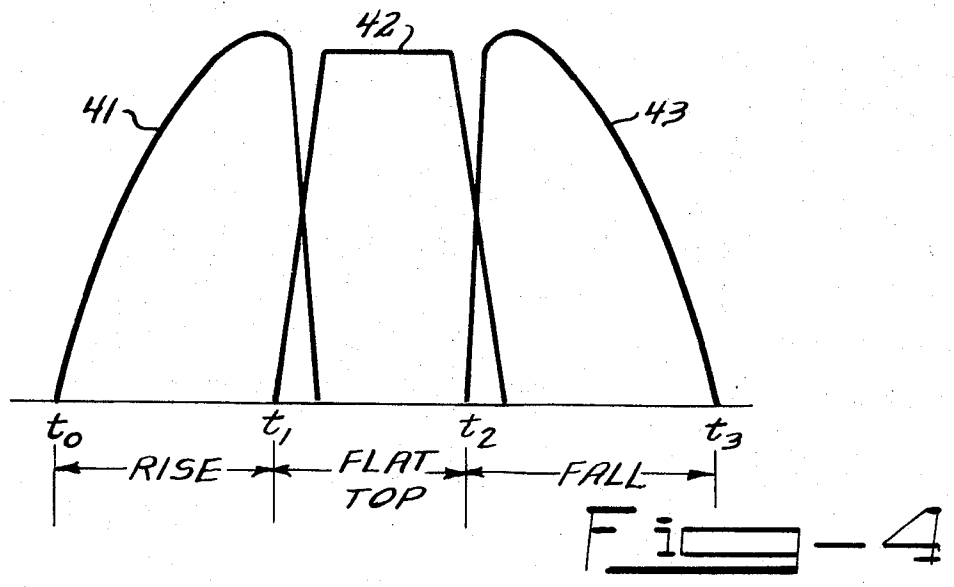

CURRENT & VOLTAGE
31
31
31
33
33
33
33
32
33
32
32
31
32
31
0
t_0
t_1
t_2
t_3
33
32
RISE
FLAT TOP
FALL

Fig — 3

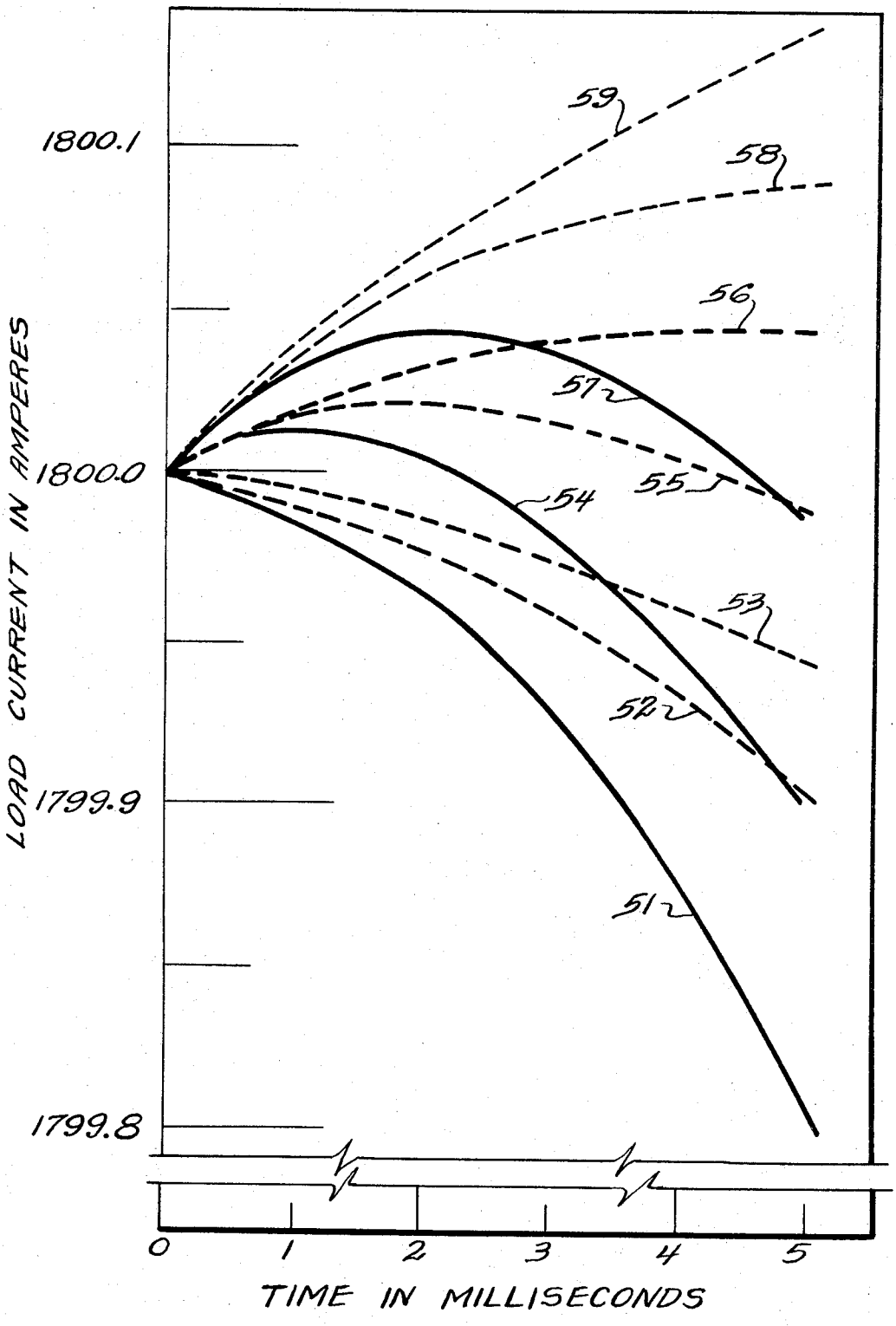

23
25
i
HIGH VOLT-AGE SOURCE
21
22
29
29
LOW VOLT-AGE SOURCE
26
27
25
LOAD 10
11
23
20
19
14
EXTERNAL TRIGGER SIGNAL
REFERENCE

Fig—2


42
41
43
t_0
t_1
t_2
t_3
RISE
FLAT TOP
FALL

Fig—4

Fig-5


1800.1
1800.0
1799.9
1799.8
LOAD CURRENT IN AMPERES
59
58
56
57
55
54
53
52
51
0
1
2
3
4
5
TIME IN MILLISECONDS

ACTIVE CROWBAR FOR A SWITCHING MAGNET

CONTRACTUAL ORIGIN OF THE INVENTION

The invention described herein was made in the course of, or under, a contract with the UNITED STATES ATOMIC ENERGY COMMISSION.

BACKGROUND OF THE INVENTION

This invention relates to a method and means for control of pulses of electric current in an inductive load. In particular, it relates to a method and means of generating in an electromagnet pulses of current having a rapid rise, a constant-value flat top within a high degree of precision for a predetermined period of time, then dropping rapidly to zero.

Control of pulsed magnetic fields by the generation of current pulses is required for proper operation of switching magnets in particle accelerators. The basic requirement for generating current pulses is an energy source that can store the necessary energy and can transform and deliver it to a load in a relatively short time. This is also a requirement in delivering energy to radar transmitters, and a picturesque term that was applied to radar pulse modulators during World War II is still used to describe a process for such rapid delivery. The term is "crowbar" and is used to describe an apparatus that suddenly applies a short circuit in a network, in analogy to the dropping of a crowbar across a pair of electrical terminals. This effect has been achieved in the past by the use of gas tubes such as thyratrons and ignitrons and also of solid-state devices such as silicon-controlled rectifiers. Typical operation comprises connecting a charged capacitor or bank of capacitors through a switch in series with a low-resistance inductive load such as a magnet. The design parameters are chosen to approximate an oscillatory RLC network, and the time necessary to achieve the first peak of current, the quarter period, is one parameter in the design. When current is near the first peak, the capacitor bank is "crowbarred" by the application of a short circuit, the crowbar, across both the capacitor bank and the inductive load. This fixes the voltage across the inductive load at the value of the *iR* drop in the crowbar. Since the voltage across the inductive load is also measured by L *di/dt*, where L is the series inductance and *di/dt* is the time rate of change of the current through the load, it is evident that for a fixed inductance L, a short circuit results in a low *di/dt* and thus a relatively constant current. The state of the art is summarized in the attached table which is abstracted from Table 6.II of "Pulsed High Magnetic Fields" by Heinz Knoepfel, North-Holland Publishing Company, Amsterdam-London, and American Elsevier Publishing Company, Inc., New York (1970).

TABLE 6.II

Large, fast capacitor banks (1968)

Laboratory	Energy (MJ)	Voltage (KV)	Inductance (nH)	Max. Current (MA)	Quarter Period (microsec.)
Garching, Ger.	2.65	40	11.6	21.3	9.5
Culham, Eng.	1.1	40	10.7	12.1	6
NRL, Washington	2	20	10	17	16
Livermore, Cal.	1.64	70	5	25	2.9
Los Alamos, N.M. (projected)	10	60		150	4

N.B. All banks can be crowbarred at current maximum with L/R decay times of the order of **100** microsec. (with the exception of the Livermore bank).

The meaning of the footnote to the table is that application of a crowbar at the current peak initiates an exponential decay with the specified time constant, resulting in a current variation that is slow in comparison with the rate obtained as the current rose to its peak. The slope of the current waveform immediately after crowbarring is inversely proportional to the L/R decay time, which thus sets a limit upon the constancy with which current can be maintained by crowbarring.

For an application such as beam switching in a particle accelerator, conventional crowbar circuits have disadvantages associated with the exponential decay of current. Ideal operation of a switching magnet would comprise an instantaneous rise to a constant value and an instantaneous drop to zero. The finite rise and fall time of current pulses in actual magnets either results in loss of beam during the buildup and decay of the pulse or else requires scheduling the buildup and decay while the beam is off. Variations about the desired constant value of current, and thus of magnetic field, cause dispersion of the beam into a spread deflection angle. To minimize this dispersion and beam loss, it is desirable to maximize the approach to the ideal pulse. Thus, the prior-art crowbar circuits cannot produce through an electromagnetic load a current pulse having a rapid rise time, an extremely flat top portion (within 0.005 percent), and a rapid drop-off to zero.

It is therefore an object of the present invention to provide a method and means of generating a current pulse having an extremely flat top in an inductive load.

It is a further object of the present invention to provide a current in an inductive load having a rapid rise, a flat top, and a rapid return to zero.

It is a further object of the present invention to provide a method and means of generating a current pulse in a switching magnet for a particle accelerator, said current pulse having a portion that remains within ±0.005 percent for a period of 5 milliseconds.

It is a further object of the present invention to provide a method and means of returning electrical energy stored in an electromagnet to a source to terminate a current pulse.

SUMMARY OF THE INVENTION

The present invention is a method and means of generating in an inductive load a current pulse having a rapid rise, a flat top, and a rapid drop. A first electrical source is connected to the inductive load to produce a rapid rise in current. At a predetermined value of current, a second electrical source is connected to the inductive load and the first source is disconnected from the load. After a predetermined time, a loaddischarging electrical connection is established and the second electrical source is disconnected from the load.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of an apparatus for the practice of the present invention.

FIG. **2** is a circuit diagram showing a preferred apparatus for the practice of the present invention.

FIG. **3** is a plot of current and voltage waveforms in the circuit of FIG. **2**.

FIG. 4 is a plot of current waveforms in certain elements of the circuit of FIG. 2.

FIG. 5 is a plot of current waveforms in a switching magnet.

DESCRIPTION OF A GENERAL EMBODIMENT

FIG. 1 is a block diagram illustrating a general apparatus for the practice of the present invention. Load **10** is an inductive device having low resistance, such as an electromagnet. A source **12** is connected electrically by switching means **13** to load **10** to begin the rise of electric current in load **10.** At this time and during the buildup of current in load **10,** switching means **15** and **16** are in an open-circuit condition. All of the switching means **13, 15** and **16** are controlled by control means **17.**

When the electric current in load **10** reaches a desired value, usually just past a peak value, control means **17** operates switching means **15** to connect a second source **18** to load **10.** Switching means **15** in combination with source **18** comprises an active crowbar which maintains the electric current in load **10** at a highly constant value. At the time of application of source **18** to load **10,** control means **17** operates to open-circuit switching means **13** between source **12** and load **10,** thereby electrically disconnecting load **10** from source **12.**

When it is desired to end the current flow in load **10,** control means **17** operates to close switching means **16** and to open switching means **15.** Source **12** is thereby connected to load **10** in an electrical polarity opposite to that originally applied. This causes much of the stored energy in load **10** to be returned to source **12.** The time sequence of operations is concluded when load **10** is discharged and switching means **16** opens. All connections are thus returned to their original condition with no current flow through any of the switching means or through load **10.** The cycle of operation is thus as follows: (1) buildup of load current through switching means **13;** (2) crowbarring of load current through switching means **15;** and (3) decrease of load current through switching means **16.**

DESCRIPTION OF PREFERRED EMBODIMENT

A circuit diagram of a preferred apparatus using silicon-controlled rectifiers to accomplish switching is shown in FIG. **2.** Load **10** is here indicated as an iron-core inductor, which is a typical circuit representation of an electromagnet. Load **10** is in series with current sensor **11,** a precision shunt. High-voltage source **21** and paralleled capacitor **22** are connected by silicon-controlled-rectifier (SCR) pair **23** to load **10,** in response to a pulse from pulse generator **14,** to produce a fast-rising electric current in load **10.** Pulse generator **14** is actuated by an external trigger signal. Crowbar pulse generator **19** actuates SCR pair **25** at a desired condition of current through load **10** as sensed by current sensor **11,** which is a precision shunt. A preferred method of operation is to compare in crowbar pulse generator **19** the condition of the current as sensed by current sensor **11** with a reference signal, and to operate SCR pair **25** after the current in load **10** has passed a peak value, so that SCR pair **23** will disconnect automatically from source **21** because of the unidirectional nature of conductivity of the SCR's. This process can be described as automatic commutation of the current.

The result of operating SCR pair **25** is to connect low-voltage source **26** and, in parallel with it, capacitor **27** to load **10.** In normal operation, the buildup of current in load **10** during the previous time interval through SCR pair **23** has reduced the voltage across capacitor **22** to a low value that is opposite in polarity to the polarity of its original charge. Connection of source **26** to load **10** thus applies a back bias to SCR pair **23,** reducing their electric current to zero. Source **26** and capacitor **27** now supply all the current flowing through load **10,** and the variation of that current can be determined by the parameters of source **26** and capacitor **27** independently of the parameters of source **21** and capacitor **22,** which are disconnected from load **10.**

After a desired time has elapsed, pulse generator **20** is caused to trigger SCR pair **29,** in response to an external timing signal. Load **10** is thus connected to source **21** and capacitor **22** in a polarity that is opposite in sense to that first applied through SCR pair **23.** SCR pair **25** will now be back-biased and will become open-circuited. Electromagnetic energy stored in the form of magnetic fields in load **10** is now returned to source **21** and capacitor **22,** restoring much of the charge on capacitor **22.** When the current in load **10** reaches zero, SCR pair **29** becomes an open circuit and the system is quiescent, with all SCR pairs not conducting and with no current flow in load **10.** The results of energy dissipation during the pulse cycle are now apparent only in reductions in the stored energy in and thus the voltages across capacitors **22** and **27.** High-voltage source **21** will recharge capacitor **22** and low-voltage source **26** will recharge capacitor **27** to restore the original conditions to the circuit.

It should be appreciated that circuit arrangements other than those of FIG. **2** could be used to practice the present invention according to the structure of FIG. **1.** For example, any switching means **13, 15,** and **16** could be used to make and break the desired connections, including, but not limited to, relays, thyratron tubes, and knife switches. Sources **12** and **18** could be any sources of electrical energy, including, but not limited to, batteries, capacitor banks, and generators.

Further understanding of this invention may be gained from noting FIG. **3,** which is a plot of various current and voltage waveforms in the circuit of FIG. **2** as a function of time. Load current curve **31** is a plot of current i, the current in load **10,** as a function of time. Current i is seen to be zero before time t_o. At time t_o, SCR pair **23** in FIG. **2** has been triggered by an external signal, and current i rises to a peak value and starts to decrease. Time t_1 marks the end of the rise interval and the beginning of the flat top. At time t_1 SCR pair **25** is triggered responsive to the sensed current direction and amplitude, and current i is seen to stay essentially constant due to the crowbarring action heretofore described. At time t_2 SCR pair **29** is triggered responsive to an external signal, and current i enters its fall interval. Current i continues to fall until it reaches zero at time t_3, after which time it remains at zero.

Load voltage curve **32** is plotted on the same time axis as current i, and is taken with a reference at the top of load **10.** Load voltage curve **32** is seen to be at a high value associated with the voltage across high-voltage source **21,** at time t_o. After time t_o, during the rise interval of the load current i, load voltage drops through zero to a negative value at time t_1. At time t_1 load voltage curve **32** jumps discontinuously. Between times t_1

and t_2, load voltage curve **32** remains at an essentially constant value equal to the voltage across low-voltage source **26.** At time t_2 the load voltage begins a return to the magnitude of its original value. Because of the reversal in directions associated with the connection of third SCR pair **29,** load voltage curve **32** approaches a negative voltage as load **10** discharges its energy back into source **21** and capacitor **22.** This can be seen by referring to curve **33,** which is the voltage across capacitor **22** with voltage reference at the top. During the rise, curve **33** coincides with load voltage curve **32.** During flat top, which is the interval $t_1 - t_2$, capacitor **22** is disconnected from the load and its voltage remains constant. During fall, capacitor **22** is connected across load **10** in the opposite sense, and curve **33** is thus the reflection of load voltage curve **32** about the time axis.

Further illustration of the function of circuit elements is provided by FIG. **4,** which shows currents in various elements during a current pulse. Current waveform **41** is the current through SCR pair **23.** Current waveform **42** is the current through SCR pair **25.** Current waveform **43** is the current through SCR pair **29.** The sum of these three currents comprises load current curve **31** as shown in FIG. **3.** The commutation of currents as the load is switched from one source to another is exaggerated at times t_1 and t_2 to show that the fast changes of current flow in opposite directions add to produce the smooth waveform of load current curve **31.**

The principles of the present invention were used in an actual switching magnet used to deflect a beam of protons at 12.5 GeV at the Zero Gradient Synchrotron at Argonne National Laboratory. This particular switching magnet was designed to produce its rated magnetic field at a current of 1800 Amperes. The magnet has a coil resistance of 0.020 Ohms and a d-c inductance of 0.053 H. It was desired to maintain a flat top of current within 0.005 percent, a tolerance of ±0.090 A, for a period of 5 milliseconds. The capacitor **22** of FIG. **2** was a bank totalling 1200 microfarads, charged to 12.9 kilovolts. The switching magnet comprising load **10** and first capacitor **22** in this embodiment thus had a resonant frequency of approximately 20 Hz, providing a quarter-cycle time of 12.5 ms. This is approximately the length of the rise time from t_o to t_1 for the particular embodiment. At time t_1 the desired voltage across second capacitor **27** was calculated to be 1800 A × 0.053 Ohms = 95.4 volts, the amount needed to hold load current i constant at 1800 A. Several values of the capacitance of capacitor **27** and of the initial voltage across capacitor **27** were used, and the results are shown in FIG. **5,** which is a plot of load current versus time for several conditions. Parameters in FIG. **5** are the initial voltage on second capacitor **27** and the capacitance of second capacitor **27.** The curves have the parameters listed in the following table.

Capacitance	2.25 F	4.50 F	9.00 F
Initial voltage			
95.400 V (100%)	51	52	53
96.354 V (100%)	54	55	56
97.308 V (102%)	57	58	59

The values actually chosen for use were those providing curve **57,** namely, 97.308 V and a capacitance of 2.25 F. This curve is seen to stay well within the allowed tolerance of ±0.090 A over the desired time interval of 5 milliseconds.

In the practice of this invention, various modifications may be made to the circuit of FIG. **2.** For example, economical use of silicon-controlled rectifiers may dictate the use of a plurality of such devices in series or in parallel or both in place of each indicated one of an SCR pair, according to requirements of voltage rating or current capacity. It may be desirable to insert current-limiting inductances in series with some or all SCR's, and it may be advantageous to use capacitors or RC networks across SCR's to facilitate switching.

It will be understood that the invention is not to be limited by the details given herein but that it may be modified within the scope of the appended claims.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. An apparatus for supplying an inductive load with a pulse of current comprising:

1. a first electrical-energy source means operably connectable to said inductive load;
2. first switching means to effect an electrical connection of said first electrical-energy source means to said inductive load to produce a rapidly rising electric current to a predetermined value in said inductive load;
3. a second electrical-energy source means operably connectable to said inductive load;
4. second switching means to effect an electrical connection of said second electrical-energy source means to said inductive load and disconnect said first electrical-energy source means from said inductive load to provide a constant current at said predetermined value in said load; and
5. means for reducing electric current in said inductive load to zero and disconnecting said second electrical-energy source means from said inductive load, a pulse of current being thereby produced in said inductive load having a rapid rise, a flat top, and a rapid drop.

2. The apparatus of claim **1** wherein said first electrical-energy source means comprise a capacitor in parallel connection with an electrical voltage source.

3. The apparatus of claim **2** wherein said second electrical-energy source means comprise a capacitor in parallel connection with an electrical voltage source.

4. The apparatus of claim **1** wherein said first and second switching means comprise silicon-controlled rectifiers.

5. The apparatus of claim **1** wherein said means for reducing electric current in said inductive load to zero comprise a silicon-controlled rectifier connected to discharge said inductive load into said first electrical-energy source means.

6. An apparatus for controlling electric current in an electromagnet comprising:

1. a first source of electrical energy;
2. a first silicon-controlled rectifier connected electrically in series with said first source and said electro-magnet;
3. first triggering means connected to said first silicon-controlled rectifier to render said silicon-controlled rectifier electrically conducting to produce a rise in current in said electromagnet to a predetermined value;
4. a second source of electrical energy;

5. a second silicon-controlled rectifier connected electrically in series with said second source and said electro-magnet;
6. current-sensing means connected to sense electric current in said electromagnet;
7. second triggering means responsive to said current-sensing means to trigger said second silicon-controlled rectifier in response to a signal generated from said current-sensing means to produce a constant current in said electromagnet;
8. a third silicon-controlled rectifier connected electrically to said electromagnet and to said first source of electrical energy in a polarity to effect discharge of stored electromagnetic energy in said electomagnet into said first source; and
9. third triggering means to render said third silicon-controlled rectifier conducting to effect discharge of said stored electromagnetic energy into said first source.

7. A method of generating a pulse of current in an inductive load comprising the sequential steps of:

1. generating in said inductive load, from a first source of electrical energy, a first current rising rapidly in magnitude to a predetermined value;
2. generating in said inductive load, from a second source of electrical energy, a second current remaining substantially constant at said predetermined value of said first current; and
3. discharging said second current to produce a rapid drop of said second current in said inductive load to a magnitude of zero.

8. The method of claim **7** wherein said step of discharging said second current comprises returning electrical energy associated with said second current to said first source of electrical energy.

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