

[54] **SATURATED CORE TRANSIENT
CURRENT LIMITER**

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[52] U.S. Cl.**317/20, 307/88 R, 323/9, 323/92, 336/110, 336/155**

[51] Int. Cl.**G05f 3/06**

[58] Field of Search**317/20, 50; 323/9, 92; 336/165, 110, 155; 307/88**

[56] **References Cited**

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[57] **ABSTRACT**

A transient current limiting device which includes a saturated core reactor having its windings in circuit with a power supply and a load. The magnetic core is biased into saturation for normal load currents and driven out of saturation by abnormally high transient load currents, such as currents caused by semiconductor loads which have been irradiated by high energy electromagnetic radiation. In one embodiment, the reactor comprises a magnetic core in the form of a wound toroid which exhibits a square loop hysteresis curve and includes a permanent magnet for biasing the core into saturation. A number of configurations are disclosed for placement of the permanent magnet relative to the core to saturate the magnetic element. The invention also permits automatic resetting of the magnetic flux density in the core to saturation when the abnormal load current is removed.

5 Claims, 16 Drawing Figures

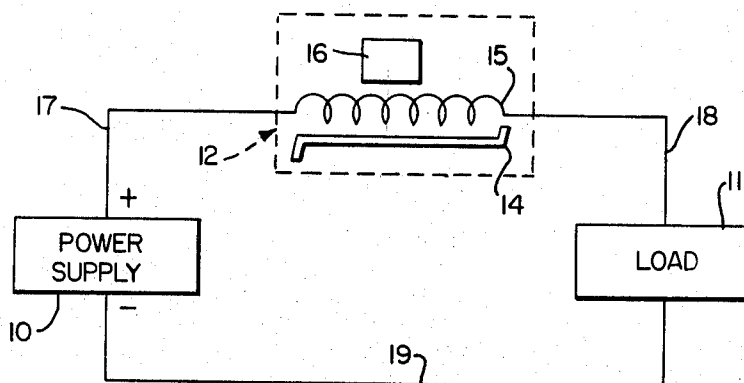


FIG. 1.

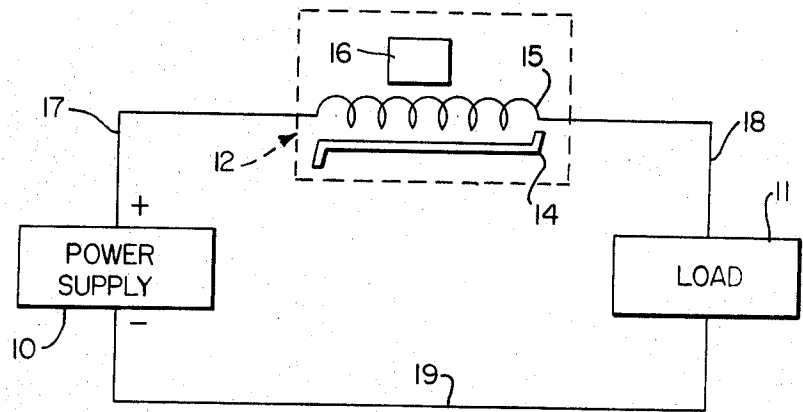


FIG. 2.

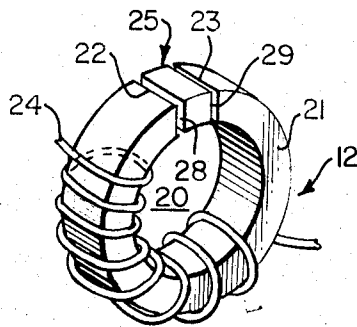


FIG. 3.

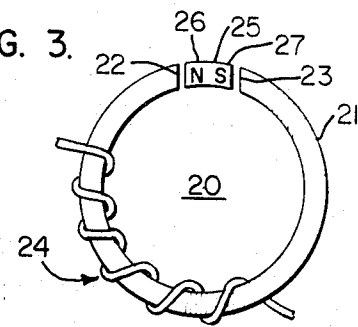


FIG. 4.

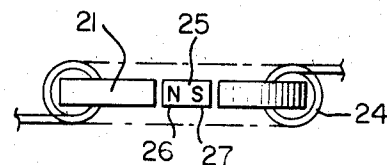
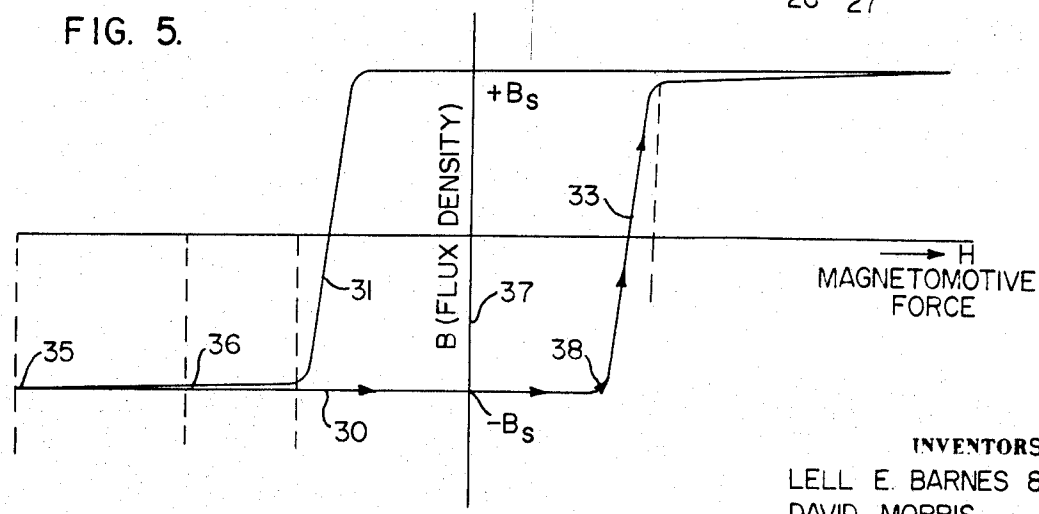


FIG. 5.



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FIG. 6.

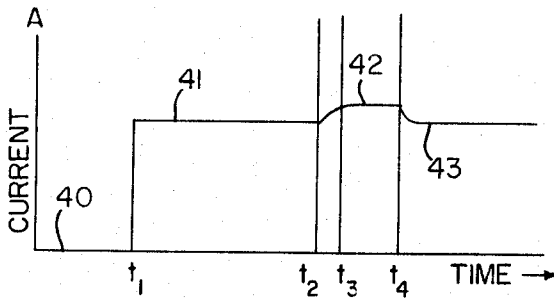


FIG. 7.

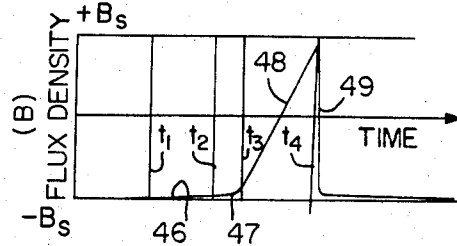


FIG. 8.

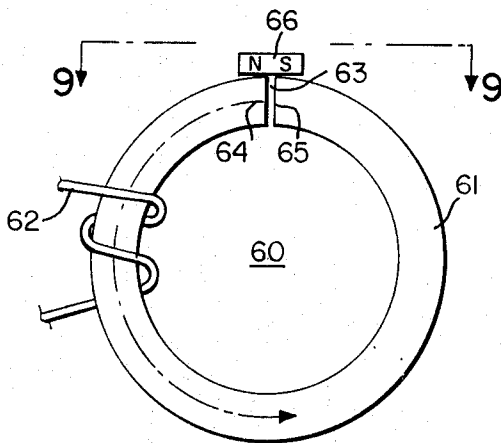


FIG. 10.

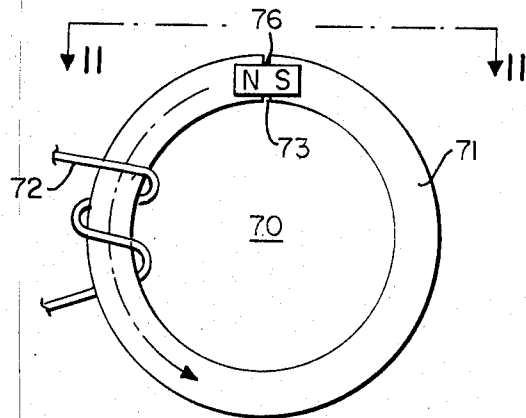


FIG. 9.

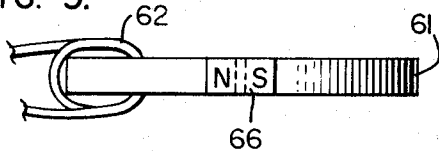


FIG. 11.

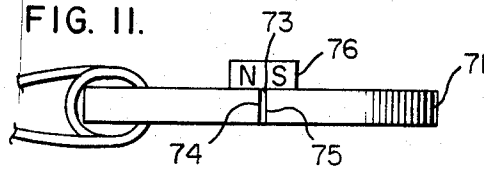


FIG. 12.

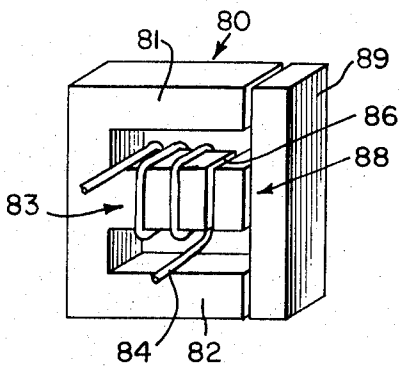
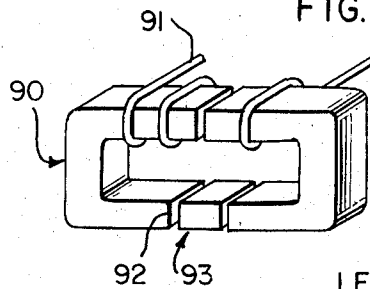


FIG. 13.



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FIG. 14.

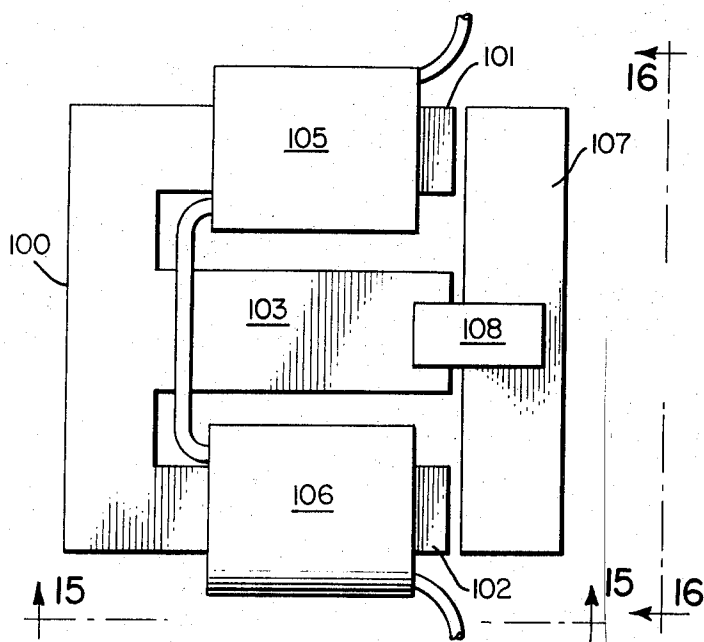


FIG. 16.

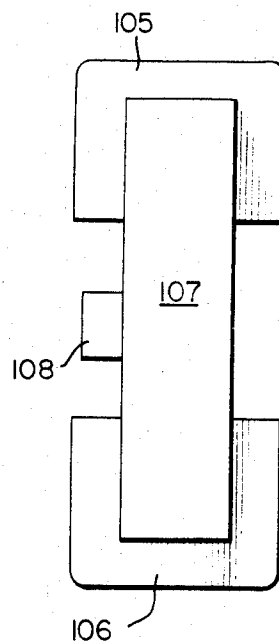
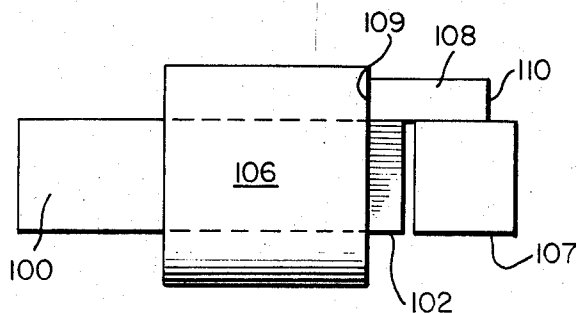


FIG. 15.



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SATURATED CORE TRANSIENT CURRENT LIMITER

BACKGROUND OF THE INVENTION

This invention relates to a transient current limiting device. More particularly, this invention relates to magnetic means in circuit with a power supply and a load to limit current delivered to the load under abnormal conditions. Still more particularly, this invention relates to a saturated core reactor having its winding in circuit with a power supply and a load wherein the reactor is biased into saturation for normal load currents, and is driven out of saturation by abnormally high transient load currents.

It has long been a problem in the electronic art, particularly since the advent of semiconductors, to limit the current delivered from a power supply to a load under abnormal conditions. A number of ways have been developed to solve the problem of limiting current under such transient conditions. Perhaps the best known is a fused arrangement which results in an open circuit when the current flow exceeds a predetermined level. Still other vacuum tube circuits, semiconductor circuits and magnetic amplifier circuits have been developed which will either disconnect the power supply from the load, or which will convert the power supply to a constant current source to avoid excessive current to the load. Generally, such approaches have produced complex circuitry and weighty circuit elements which are quite slow to react to the presence of an overload.

It is also known in the art that semiconductors and semiconductor circuitry may momentarily exhibit a short circuit to the power supply when a semiconductor is bombarded with high energy radiation, such as gamma rays. Essentially, the shorting effect is caused when the electromagnetic radiation frees electrons in the semiconductor material. The free electrons cause the semiconductor element to become a short circuit load as to the source. Many types of radiation will produce this effect, including bombardment with neutrons, electrons, laser beams and gamma rays.

While vacuum tubes and vacuum tube circuits are not generally as susceptible to electromagnetic radiation as semiconductors, vacuum tubes and vacuum tube circuits are not entirely satisfactory in protecting semiconductor circuitry from transient currents caused by radiation bombardment. In general, such vacuum tube devices are unsuitable because of the high power supply required and because of their relatively great weight which precludes their use in present day circuits.

Moreover, known solutions to current limiting problem are relatively slow to operate when considered in complex high-speed circuits, such as computer circuits or specialized communication circuits. In particular, it is a problem in this art to provide a transient current limiting device which will preclude delivery of abnormally high currents to the load in relatively fast times, such as in nanoseconds. For example, in one particular embodiment, it is known that the duration of transient currents caused by radiation on the load existed on the order of 1-10 microseconds so that in a very particularized environment, it was a problem to preclude transfer of the transient current to the load for a very short time.

Accordingly, it is an object of the invention to provide a transient current limiting device.

It is another object of the invention to provide magnetic means in circuit with a power supply in a load to limit the transfer of current therebetween under abnormal load conditions.

It is still a further object of this invention to provide a saturated core reactor which is biased into saturation for normal load currents and which is driven out of saturation for abnormally high currents.

It is another object of this invention to provide a transient current limiter which comprises a saturable core having a square loop hysteresis characteristic and which is biased by a permanent magnet.

It is another object of this invention to provide a current limiting device which includes a toroidal core having a square

loop hysteresis characteristic which is biased into saturation by a permanent magnet.

Other and additional objects of the invention will become apparent from the perusal of the accompanying drawings and the consideration of the detailed specification which follows.

SUMMARY OF THE INVENTION

Directed to a solution to the problem of limiting current between a power supply and load, particularly under the conditions previously discussed, this invention comprises a magnetic device which is connected in series with a load to limit current in the event of a transient short circuit. The magnetic device is a core biased into saturation for normal load currents and driven out of saturation for abnormally high load currents. As the flux in the core reverses from saturation in one direction to saturation in the other, the high load current is delayed, and thus limited, particularly due to the domain switching of the iron core.

In the disclosed embodiments, the winding about the magnetic core is in circuit with the source and the load. A permanent magnet is arranged to induce a biasing flux in a flux path in the magnetic core. Under normal operating conditions, the current delivered to the load causes a flux in the flux path in a direction opposite to that induced by the permanent magnet, but which maintains the core in its saturated state. Under abnormal conditions, the change in flux in the flux path follows the hysteresis characteristic of the iron core which, in a preferred embodiment, is a square loop characteristic. Thus, the saturated magnetic device provides a very low inductance to the circuit under normal load currents and a time delay for the delivery of a high load current under abnormal or short circuit conditions. The device is particularly useful in preventing high load current caused by shorts due to electromagnetic radiation because the device itself is not affected by such radiation. An additional advantage of the invention is that the protective circuit automatically resets once the abnormal condition is removed.

BRIEF DESCRIPTION OF THE DRAWINGS

In the Drawings:

FIG. 1 is a simplified circuit diagram incorporating the current limiting device according to the invention;

FIG. 2 is a perspective view of the reactor core showing the biasing permanent magnet located in a position coextensive with the geometry of the core;

FIG. 3 is a plan view of the core shown in FIG. 2;

FIG. 4 is an end view of the reactor core of FIG. 2 showing the position of the permanent magnet biasing means;

FIG. 5 shows the square loop B-H curve for the toroidal core, illustrating its operation under biasing, normal load, and abnormal load conditions;

FIG. 6 is a plot of the current supplied by the power supply versus time over a period including normal operation and abnormal conditions;

FIG. 7 is a plot of flux density in the core versus time under conditions shown in FIG. 5;

FIG. 8 is a reactor core similar to the reactor core shown in FIG. 2 wherein the permanent magnet is positioned radially adjacent to the core;

FIG. 9 is an end view of the reactor core of FIG. 8;

FIG. 10 is a view of the reactor core similar to that shown in FIG. 2 wherein the permanent magnet is positioned axially displaced from the core;

FIG. 11 is an end view of the reactor core of FIG. 10;

FIG. 12 illustrates the invention as applied to a E-I core arrangement in which the biasing permanent magnet is positioned in the middle leg;

FIG. 13 is a generally C-shaped core arrangement in which the permanent magnet biasing means is positioned in a portion of the core;

FIG. 14 depicts the variation of the core of FIG. 12 in which the windings are positioned on the legs of the E element and the permanent magnet is positioned adjacent the middle leg;

FIG. 15 is an end view of the structure shown in FIG. 14; and

FIG. 16 is a side view of the structure shown in FIG. 14.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

An electrical circuit is shown in FIG. 1 which illustrates one embodiment for incorporating the current limiting means according to the invention. A source 10 of power provides current in a series circuit by way of leads 17 and 18 to load 11. Current limiter 12, according to the invention, is in series circuit between the power supply 10 and load 11. Current limiter 12 is diagrammatically illustrated as including a core 14 of saturable magnetic material. Winding 15 on the core 14 is in series circuit with the source 10 and load 11. A permanent magnet 16 serves to bias the magnetic element into saturation for normal load currents. The core 14 will be driven out of saturation by abnormally high load currents flowing through the winding 15 such as would be caused, for example, by the presence of electromagnetic radiation on semiconductor load elements.

The current limiter 12 as shown in greater detail in FIG. 2 comprises a reactor 20 including toroid 21 of magnetically permeable material with winding 24 disposed thereon. In this embodiment, toroidal core 21 defines faces 22 and 23 to provide a gap in the toroid.

A permanent magnet 25 is positioned in the gap between faces 22 and 23 geometrically coextensive with the toroidal core 21. Air gaps of a predetermined width may be defined between the permanent magnet 25 and the core 21 according to the requirements of the magnetic circuit, or the poles of the permanent magnet 25 may be contiguous with the generally planar end faces 22 and 23 of the core 21.

As may be seen in FIGS. 3 and 4, the permanent magnet 25 has a magnetic north pole 26 and a magnetic south pole 27 and is positioned with respect to the toroidal core 21 so that poles 26 and 27 are coextensive with the planar faces 22 and 23 and with the geometrical configuration of the core.

In FIGS. 2 through 4 the core 21, the winding 24, and the magnet 25 correspond to the core 14, the winding 15, and the magnet 16 in the circuit of FIG. 1. As an alternate embodiment, the reactor core may be biased by the presence of an additional winding about the core having a predetermined number of turns in a manner resembling winding 24 instead of by a permanent magnet.

While the reactor core may be made from iron having conventional hysteresis characteristics which exhibit saturation levels of flux density, it is preferred that the core be of a material which exhibits a square loop hysteresis characteristic as shown by the plot of flux density B versus magnetomotive force H in FIG. 5.

When the power supply 10 is delivering no current to the load 11, the magnetomotive force on the reactor core provided by the permanent magnet 16 biases the core well into saturation to the position on the hysteresis loop designated by reference numeral 35 as shown in FIG. 5. The winding 15 is connected between the load 11 and the power supply 10 with a polarity so the magnetomotive force opposes that of the permanent magnet 16. Accordingly, when load current flows through the winding 15, the operating point on the hysteresis curve will move back along the lower portion 30 of the hysteresis loop toward zero magnetomotive force represented by the axis 37. When maximum normal power is delivered to the load, the resulting current through the winding 15 will move the operating point on the hysteresis loop to the position designated by the reference numeral 36. The core, however, remains in a saturated state. Variation in load current less than the maximum normal value will cause only small changes in the total flux in the core because the core will remain in saturation.

If the load should exhibit a momentary short circuit, the increased transient current flowing through winding 15 will cause the operating point to move along the lower portion 30 of the hysteresis loop past the knee 38 of the hysteresis loop

and into the leg 33 of the hysteresis loop, thus driving the core out of saturation. When the core has been driven out of saturation into the leg 33 of the hysteresis loop further increases in current will cause large changes in flux in the core. Thus, the winding 15 carrying the load current will exhibit a high value of inductance opposing further increases in load current. In this manner, the current limiter 12 prevents high transient current from flowing into the load during momentary shorting of the load 11.

The change in flux in the core follows the well known equation:

$$e = KNd\phi/dt$$

where K is a constant

N is the number of turns

e is the applied voltage

ϕ is the flux in the flux path of the reactor core, and

t is time

From equation 1 therefore:

$$\phi = 1/KN \quad edt$$

in which ϕ represents the change in flux over the time of the integral.

But $\phi = BA$, where B is the flux density in the flux path of the core and A is the cross sectional area of the core. Therefore, from equation (2):

$$B = 1/KNA \quad edt$$

in which B represents the change in flux density over the time of the integral.

For a predetermined number of turns and a predetermined cross-sectional area of the core, the change in flux density is given by the equation:

$$B = K_2 \quad edt$$

For the case in which the applied voltage e is a constant E equal to the power supply voltage the solution of the integral is:

$$B = K_2 Et = K_e t$$

When a momentary short in the load drives the core out of saturation into the leg 33 of the hysteresis loop, the flux density must change from $-B_s$ to $+B_s$, amounting to a total change of $2B_s$, before the core is driven all the way to the positive saturation level. Thus, from equation (5) in order for the total change in flux to equal $2B_s$, the time t must equal $2B_s/K_2$. Accordingly, if the time of the momentary short is less than $2B_s/K_2$, the current limiter will prevent the high transient current from being applied to the load. Thus, for short term transient currents, the device according to the invention provides an effective means for limiting transient currents for limited times.

FIG. 6, which shows a plot of the supply current from the power supply 10 against time, is exemplary of the operation of the circuit when a momentary short occurs. The portion 40 of the curve is the condition when no current is being delivered to the load. At $t = t_1$, the load is connected to the power supply and the current rises to a level represented by the portion 41 of the curve. At $t = t_2$ in the example of FIG. 6, the load exhibits a transient short circuit condition.

At a very short time thereafter, $t = t_3$, the start of the flux excursion time from $-B_s$ to $+B_s$, as shown in FIG. 5 occurs. The time difference between t_2 and t_3 is that necessary for the operating point 36 on the hysteresis loop of FIG. 5 to move from point 36 to the knee 38 of the hysteresis loop at which the core is driven out of saturation and begins to follow the leg 33 of the hysteresis loop. At time t_4 the short circuit ends before the core has been driven to positive saturation and the current only increases to the level 42 in response to the momentary short circuit. The core is then reset to negative saturation by the permanent magnet to a range between the points 35 and 36 on the hysteresis loop for normal load currents.

The plot of flux density in the core against time in the example described with reference to FIG. 6 is shown in FIG. 7. Prior to time t_1 before the load current is applied, the flux density is the negative saturation value $-B_s$. During the time interval from $t = t_1$ to $t = t_2$, when the circuit is operating normally, the flux density in the reactor core, as shown by the portion of the curve designated by the reference numeral 46, continues

at the negative saturation level. From $t = t_2$ to $t = t_3$, as shown by the portion of the curve designated by reference numeral 47, the flux density remains at the negative saturation level. But during the time from $t = t_3$ to $t = t_4$, during which the flux is going from negative saturation toward positive saturation as shown by the portion of the curve 48, the flux density changes rapidly from $-B_s$ toward the positive saturation level $+B_s$. At the end of the short on the load at time t_4 , the flux density returns, as shown by the portion of the curve 49 in FIG. 7, to its negative saturation level $-B_s$. Thus, FIG. 7 illustrates the ability of the circuit to reset after the removal of the short circuit on the load.

The speed of resetting is determined by the leakage reactance for the winding and the time required for magnetic domain rotation. In a toroidal winding, the leakage reactance may be considered negligible and may be made quite small by proper winding. Thus, the reset speed becomes nearly a direct function of the magnetic domain rotation from positive saturation to negative saturation. Such switching may occur in a very short time, such as in nanoseconds.

FIG. 8 depicts an alternate embodiment of the invention comprising a reactor 60 in the form of a toroidal core 61 having a winding 62 disposed thereon. Core 61 defines an air gap 63 between faces 64 and 65. Permanent magnet biasing means 66 are disposed adjacent to the outer cylindrical wall of the core, bridging the air gap 63. FIG. 9 is an end view of the core 61 illustrating the portion of the permanent magnet 66 with respect to the core 61.

The embodiment shown in FIGS. 10 and 11 comprises a reactor 70 in the form of a magnetic core 71 having winding 72 disposed thereon. A permanent magnet 76 is disposed adjacent to a radial wall of the core 71 bridging the air gap 73 defined by faces 74 and 75 of the core. An additional permanent magnet may be disposed adjacent to the other radial wall of the core 71 axially opposite the permanent magnet 76.

In the embodiments of FIGS. 8 and 10, the relationship of the various parameters of the magnetic circuit are such that cores 61 and 71 are biased into saturation according to the invention as previously discussed.

The embodiment of the invention as shown in FIG. 12 comprises an E-I lamination 80 including outer legs 81 and 82 and middle leg 83 having a winding 84 disposed thereon. Permanent magnet 88 is disposed in a gap between middle leg 83 and I section 89 to bias the reactor 80 into saturation as described above. As illustrated, the configuration of the permanent magnet 88 is such that it is geometrically coextensive with the face 86 of the middle leg 83. An air gap may be provided between end face 86 and the adjacent pole of permanent magnet 88, as well as between the opposite pole of permanent magnet 88 and the adjacent wall of the I section 89.

FIG. 13 is another embodiment of the current limiter comprising a C-shaped core 90 having winding 91 disposed thereon. The C-shaped core defines a gap in which a permanent magnet 93 is positioned. As in the preceding embodiments, the strength of permanent magnet 93 is such to bias the core 90 into saturation under normal operating conditions.

In the embodiment of the invention shown in FIGS. 14 through 16, an E-I lamination similar to that shown in FIG. 12 comprises a reactor 100 having outer legs 101 and 102 and

middle leg 103. Windings 105 and 106 are connected in a series aiding relationship and are disposed on legs 101 and 102 respectively. An I section 107 is disposed to bridge the end faces of the legs 101, 102 and 103 and a permanent magnet 108 is disposed bridging an air gap defined between middle leg 103 and I section 107.

The operation of the current limiter of FIGS. 12 through 15 is in accordance with the discussion of the FIG. 2 and the curves shown in FIGS. 5 through 7 and accordingly is not repeated in detail here.

Each of the above described current limiters will effectively protect against momentary short circuits in the load. The current limiters are particularly useful in protecting against short circuits caused by intense radiation such as gamma radiation because the current limiters themselves are virtually unaffected by such radiation.

What is claimed is:

1. An electrical circuit including:

a. a direct current source of power,

b. a load, and

c. magnetic means in circuit with said source and said load for limiting the current between said source and load in the event of a transient short circuit, wherein said magnetic means comprises an elongate discontinuous magnetic core ring member having a longitudinal axis and having a center portion and having a pair of axially spaced opposite end portions defining an air gap therebetween, a permanent magnet disposed adjacent to both said end portions of said core and arranged to provide an elongate flux path coaxially therewith and having sufficient strength for biasing said magnetic core into saturation for normal load currents, and a winding wound on said core center portion and connected between said source and said load and arranged to provide a second elongate flux path coaxially therewith, said second flux path being directed opposite to said first flux path and having sufficient strength so that said core is driven out of saturation by abnormally high load currents flowing through said winding.

2. The circuit as defined in claim 1 wherein said core is a toroidal element and said permanent magnet is disposed in said air gap in such a manner that said magnet is geometrically coextensive with said toroidal element.

3. The circuit as defined in claim 1 wherein said core is a toroidal element and said permanent magnet is positioned adjacent to the outer cylindrical wall of said toroidal element and bridges said air gap.

4. A circuit as defined in claim 1 wherein said core is a toroidal element and said permanent magnet is positioned adjacent to a radial wall of said toroidal element and bridges said air gap.

5. A circuit as defined in claim 1 wherein said core ring member is a portion of an assembly, said assembly including an I section element and a generally E-shaped magnetic element, said E-shaped element having an outer pair of legs and a middle leg, said winding being disposed about at least one of said legs, said E-shaped element and said I section element being spaced to define said air gap therebetween, and wherein said permanent magnet is located in said air gap.

* * * * *