

[54] **CRYOGENIC CURRENT LIMITING SWITCH**

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[56] **References Cited**

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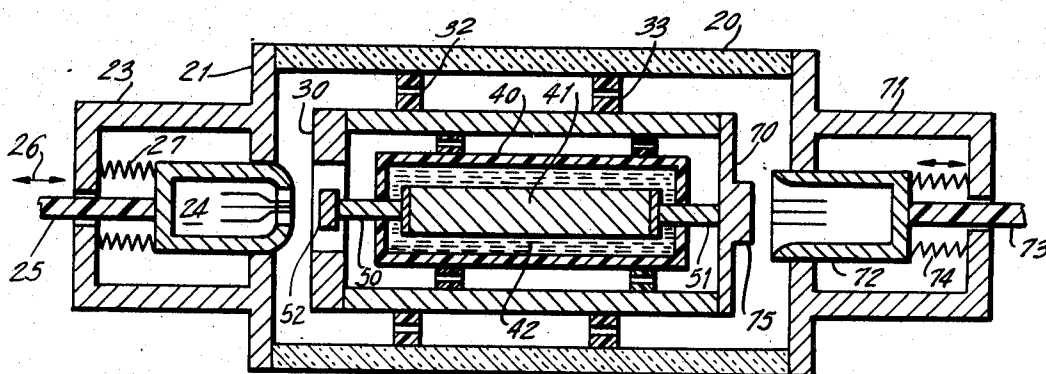
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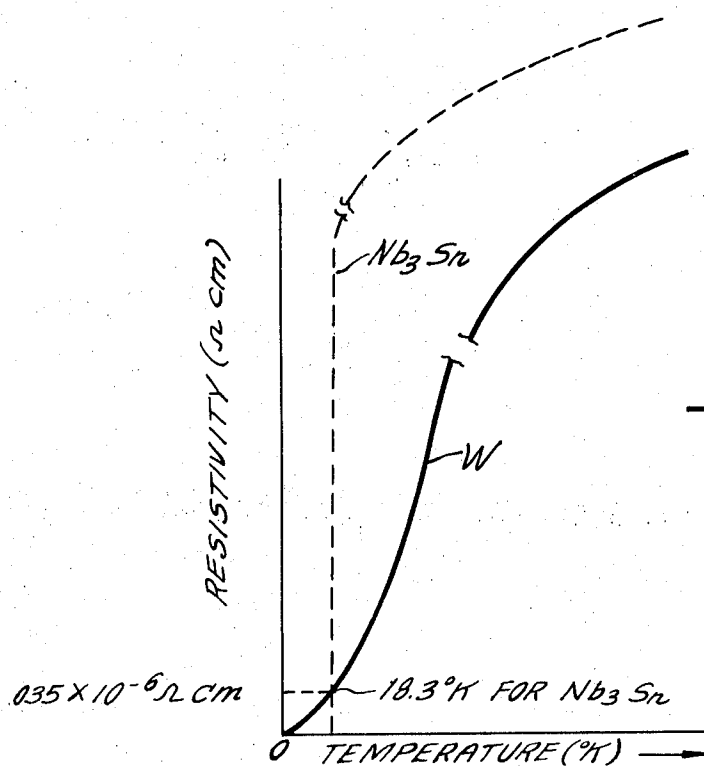
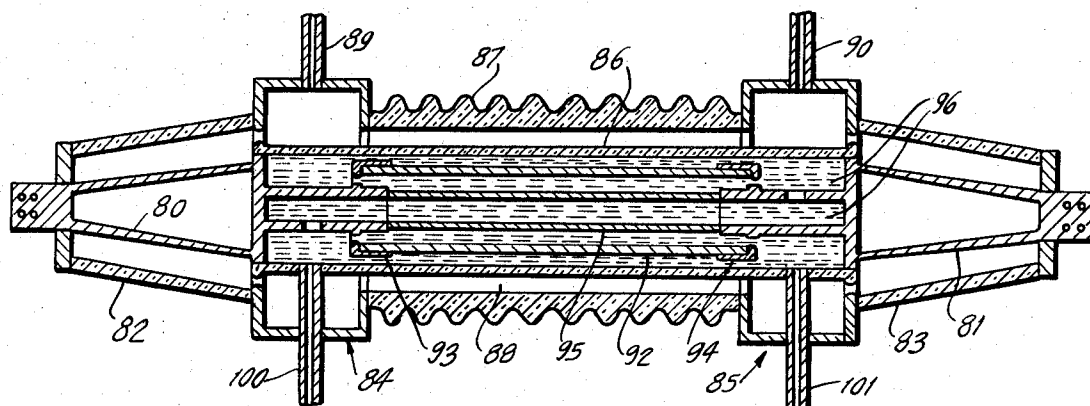
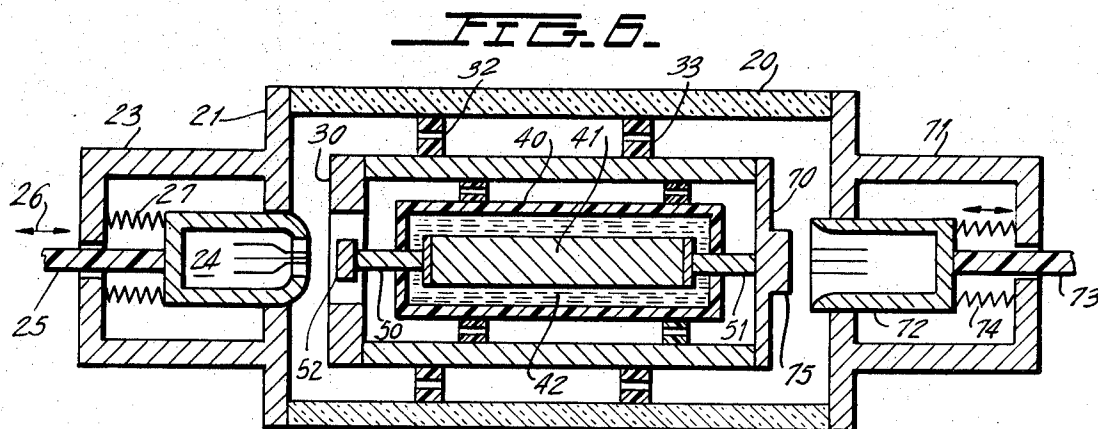
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[57] **ABSTRACT**

A superconductive element to be used for current limiting action is arranged in the interior of a tubular conductor and is in a substantially field-free region during normal current conduction. The vacuum used as thermal insulation for the superconductor element is further used as a switching medium for the contacts of switching devices associated with the superconductor. A non-linear resistor material such as pure tungsten is connected in parallel with the superconductor so that current commutates into the non-linear resistor when the superconductor switches to its normal conduction characteristics.

13 Claims, 8 Drawing Figures





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CRYOGENIC CURRENT LIMITING SWITCH

RELATED APPLICATIONS

This application is related to copending application Ser. No. 77,837, filed Oct. 5, 1970 entitled "Fault Current Limiter Using Superconductive Element", and assigned to the assignee of the present application.

BACKGROUND OF THE INVENTION

It is well known that certain materials exhibit superconductive characteristics when cooled to temperatures below some temperature characteristic of the particular material. The super-conducting state of the material is destroyed, with the material returning to its conventional resistive characteristics, when temperature rises above the critical temperature, and can also be destroyed when the magnetic field at the surface of the superconductor exceeds a given value.

These characteristics have been used to produce switching devices which can limit fault current. For example, U.S. Pat. No. 3,384,762 shows a circuit in which a superconducting element is used as a switching conductor in an electrical circuit. The superconducting material is in its superconducting state until the magnetic field at its surface, due to either an externally generated field or the field due to the current being carried, exceeds the critical value which destroys the superconductor properties and switches the superconductor to its normal and relatively high resistance condition, thereby modifying current flow in the circuit.

Using the magnetic field created by the current flow in the superconductor to cause switching from the superconductor state at a given current magnitude imposes limits on the design and rating capability of current limiting switches using superconducting elements in the circuit being protected. In order to overcome such rating problems, the device disclosed in U.S. Pat. No. 3,384,762 uses a superconductor having a relatively large diameter tube disposed coaxially around a central conductor. By making the tube large enough, the magnetic field at its surface will be reduced below the critical value for a given current magnitude being conducted. Moreover, such designs use particular alloys having higher than usual critical field intensities, such as niobium and niobium-containing alloys.

In accordance with a first aspect of the present invention, the superconductive element is disposed in a shielded, or substantially zero magnetic field environment, and, in particular, is disposed coaxially within a conductive tube of material which normally carries the rated current of the circuit being protected. When the circuit is to be interrupted, a switch is operated to commute current from the outer conventional tubular conductor, and into the superconductor. The superconductor will then have its superconductive state destroyed by the magnetic field now generated at its outer surface, thereby introducing a current limiting impedance into the circuit being interrupted. The operation of the superconductor may then be followed by the operation of a pair of isolating contacts in series with the superconductor. Since the magnetic field of the current in the outer tube is zero in the interior of the conductor, superconductors of very low critical fields may be employed. Moreover, the superconductor can now be physically small (since it need not carry normal load current, and can have a small outer diame-

ter), and can have a shape, such as a folded arrangement, to provide long length in a small volume, and to permit efficient cooling of the superconductor after power flow through the superconductor.

A further feature of the invention lies in the use of two disconnect contact pairs at either end of the superconductor member. The use of such an arrangement prevents heat input by conduction to one end of the superconductor wherein the circuit is in its open position by virtue of opening only one disconnect at one end of the superconductor.

While the use of a switch for commutating current from the outer conductive tube of the superconductor is desirable, it is possible to provide a direct connection between these components with current dividing in parallel between the two by the skin effect at higher current levels. Note, however, that the superconductor is not then in a completely field-free region, and absolute freedom of physical size and material choice for the superconductor is lost.

In constructing the cryogenic vessel, a relatively hard vacuum is employed for thermally insulating the vessel. A further important feature of the present invention is to employ this same vacuum as the interrupting medium for the contact elements used to effect interruption of the current limited by the superconductor after it is switched to its normal resistive state. At the same time, this vacuum defines the insulation between these contacts after they have opened. The same vacuum is used as the interrupting medium for the contacts used to effect switching of current from the outer tubular conductor and into the central superconductor.

By now appropriately sizing the normal condition resistance of the superconducting element, it is possible to use a vacuum switch of relatively low interrupting capability for circuits with high available fault currents. For example, in a 15 kV circuit, a vacuum switch with an interrupting capability of 5,000 amperes r.m.s. might readily be applied to circuits where the available fault current level is 50,000 amperes r.m.s., by employing a superconductive element whose normal condition resistance is 2 to 3 ohms.

The use of the vacuum of the vacuum switch as thermal insulation for the cryogenic vessel would also contemplate the use of non-superconductive materials as the current limiting material. For example, a highly non-linear resistor of the type shown in copending application Ser. No. 39,040, filed May 20, 1970, in the name of Fritz Kesselring, entitled "Current Limiting Switch Employing Low Temperature Resistor" [C-1532(ER)] could be placed in the cryogenic vessel, rather than the superconductor member.

As still another feature of the invention, a superconductor and non-linear resistor may be combined, and use a common cryogenic vessel, whereby the two are connected in parallel, with the superconductor normally carrying all load current. When the load current exceeds a given value, the magnetic field at the surface of the superconductor is sufficiently high to switch the superconductor to its resistive state. This then commutates current into the cold non-linear resistor (which has a cold resistance lower than the resistance of the superconductor when the superconductor is switched to its resistive state). The resistance of the non-linear resistor then increases to exert a current limiting action

on the fault current in the manner described in above-noted copending application Ser. No. 39,040. [C-1532(ER)]

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a longitudinal cross-sectional drawing of a current limiting circuit interrupter using a semiconductor member located in a magnetic field-free region, with the device contacts open.

FIG. 2 illustrates the device of FIG. 1 with the movable contact in a position to insert the superconductor in the circuit being protected.

FIG. 3 illustrates the device of FIGS. 1 and 2 with the disconnect contact in its closed position.

FIG. 4 is a cross-sectional drawing of FIG. 1 taken across the section lines 4—4 in FIG. 1.

FIG. 5 is a cross-sectional drawing of FIG. 1 taken across the section lines 5—5 in FIG. 1.

FIG. 6 illustrates an embodiment of the invention similar to that of FIG. 1 where disconnect contacts are provided at both ends of the superconductor.

FIG. 7 is a longitudinal cross-sectional diagram of an embodiment of the invention employing a parallel connected superconductor and non-linear resistor in a common cryogenic container.

FIG. 8 illustrates the relative changes in resistivity as a junction of temperature for the current limiter of FIG. 7.

DETAILED DESCRIPTION OF THE DRAWINGS

Referring first to FIGS. 1 to 5, there is shown an insulation housing 20 which has end conductive plates 21 and 22 secured, with vacuum seals, across its opposite ends. Conductive plate 21 has an extending chamber 23 which carries a movable contact 24 which is in sliding contact with a central opening in plate 21. Note that contact 24 has a plurality of separate contact fingers which may be spread away from one another, as will be described later. An operating rod 25, which may be of insulation material, is movable in the direction indicated by arrow 26 in FIG. 1 to move contact 24 between its fully open position of FIG. 1 to its fully closed position of FIG. 3. A steel bellows 27 is connected between contact 24 and a region surrounding rod 25 to form a vacuum-tight seal around the opening in member 23 which passes rod 25.

A stationary contact disk 30 is then mounted to cooperate with movable contact 24 and may, if desired, be a segmented contact containing finger sections biased inwardly for high-pressure contact with movable contact 24. Contact disk 30 is mounted on the end of conductive tube 31, which is supported from plate 22. To assist in the support of tube 31, insulation support disks 32 and 33 may be provided as shown. Note that these disks are perforated with suitable openings to permit a vacuum to be drawn within housing 20 without interruption by supports 32 and 33. It should be further noted that tube 31 and disks 32 and 33 may be formed of segmented sections, for ease of manufacture.

An inner hollow vessel 40 is then provided which contains the superconductor element 41 and a suitable liquified gas coolant 42, which is capable of reducing the temperature of superconductor 41 below its critical temperature. Vessel 40 may be supported within con-

ductive tube 31 by suitable permit spacers 43 and 44, which have openings therethrough to permit the draining of a vacuum in the chamber surrounding vessel 40. A suitable coolant supply 45 is connected to vessel 40 to maintain the coolant 42 therein at the desired low temperature. Superconductor 41 is then provided with terminals 50 and 51. Terminal 51 is connected to plate 22, and terminal 50 supports an intermediate stationary contact 52. Note that additional support structure (not shown) can be provided for the intermediate stationary contact 52. Contact 52 is so arranged that, when movable contact 24 opens from the position of FIG. 3, it first contacts contact 52 and then disengages from contact 30 (FIG. 2), and then disengages contact 52 (FIG. 3).

A suitable vacuum pump 60 is then connected to container 20 to evacuate the entire volume disposed within container 20 and the exterior of vessel 40. This vacuum is of the magnitude conventionally used for the thermal insulation of cryogenic vessels, and is further sufficiently hard that the contacts 24, 30 and 52 will operate in the manner of the contacts of a conventional vacuum switch.

The operation of the device of FIGS. 1 to 3 is as follows:

Assume that the contacts 24 and 30 are closed, as indicated in FIG. 3. Current flow then takes place from the conductive plate 21, which can form one terminal of the interrupter, through contact 24, contact 30, conductive tube 31, to conductive plate 22, and any terminal connected thereto. Note that there is no current flow through superconductor 41, which is in a superconducting state. Moreover, in accordance with the invention, the superconductor is in a region having no magnetic field (in the interior of tube 31) so that the material and design of superconductor 41 are free of the constraint of a critical magnetic field at the superconductor surface. Accordingly, the superconductor 41 may be relatively small in diameter, and can be a folded ribbon having a relatively long length to define a relatively high resistance when switched to a normal resistive state. Obviously, any desired superconductor material can be chosen which might be selected for relatively high critical temperature, economy, and the like, regardless of the critical field of the material. Thus, where the critical field of the device must be held low, materials such as niobium, and alloys thereof are used, whereby the temperature must be held below about 10°K. By freeing the use of materials to those having lower critical fields, as with the present invention, it is possible to select materials which exhibit superconductivity at relatively high temperatures. Thus, superconductors are presently available which exhibit superconductivity at temperatures up to 75°K. Other materials will, undoubtedly, become available which exhibit superconductivity at even higher temperatures. The use of such materials will, of course, reduce the requirements of equipment needed to hold the conductive material at temperatures below its critical temperature.

In order to open the interrupter, operating rod 25 is withdrawn, with contact 24 passing through the position of FIG. 2 toward the position of FIG. 1. This operation may be manual, or may be initiated in response to a fault. When the position of FIG. 2 is reached, the interior ends of the fingers of contact 24 engage contact

52. Accordingly, power current can now flow through the circuit including plate 21, contact 24, contact 52, superconductor 41, conductor 51, and plate 22, and current begins to transfer from conductive tube 31 to superconductor 41. The contact between movable contact 24 and contact 30 is opened while contact is still made to contact 52, in order to fully transfer current flow into the circuit containing superconductor 41. Note that by properly balancing the reactance of the two parallel circuits, essentially arcless transfer to the superconductor 41 can be achieved.

With current flow in the superconductor 41, its critical field is quickly reached, thereby switching the superconductor 41 to its resistive state. As previously indicated, the superconductor can now achieve a resistance of several ohms, which, in a high-voltage circuit, will drastically limit the available fault current in a circuit, and permit fault circuits to be cleared by relatively low current-rated switchgear.

Thus, with the maximum circuit current limited by the resistance of superconductor 41, movable contact 24 continues to open, to interrupt the remaining current flow in the manner of a vacuum switch having cooperating contacts 24 and 52 in the relatively hard vacuum used to insulate the cryogenic vessel 40.

In order to reclose the device of FIGS. 1 to 5, the contacts 24 and 52 first close, and contacts 24 and 30 thereafter close and contacts 24 and 52 open. Depending on the characteristics of the circuit containing the device of FIGS. 1 to 5, superconductor 41 may initially switch from its superconductive state to its resistive state. This action may be of advantage when switching loads having high inrush current, since these currents will be limited. However, it may be desired to not switch superconductor 41 while closing, as by providing a closing switch, not shown, in series with the circuit, which is held open until contacts 24 and 30 are closed.

FIG. 6 illustrates a modification of the device of FIGS. 1 to 5 where a second contact is arranged at the opposite end of the switch to serve as a means for totally isolating superconductor 41 from the line when the interrupter is open, and for permitting the reclosing of the device without causing conduction of superconductor 41. In FIG. 6, the conductive tube 31 of FIGS. 1 to 5 is modified and is provided with a stationary contact plate 70 at its right-hand end. In addition, conductive plate 22 of FIGS. 1 to 5 is replaced by a conductive movable contact housing 71, similar to contact housing 23 for movable contact 24. A movable contact 72, which may contain flexible contact fingers, is slidably mounted within housing 71, and is in continuous contact therewith. An operating rod 73, enclosed by bellows 74, completes the system.

It will be seen that movable contact 72 is movable into and out of engagement with stationary contact 75 on plate 74. Moreover, this region of contact is in the vacuum within container 20.

The device of FIG. 6 operates in substantially the same manner as described for the device of FIGS. 1 to 5. However, in FIG. 6, and after disconnection between contacts 24 and 52, contacts 72 and 75 are opened by operating rod 73. Therefore, the superconductor 41 is now isolated by the vacuum within container 20, and at its both ends, from the conductors of the circuit being

protected. Thus, heat flow into superconductor 41 is decreased, thereby easing the burden on the cooling equipment connection to cryogenic vessel 40.

Moreover, during reclosing, contacts 72 and 75 may close after contacts 24 and 30 close, so that closing current does not flow in superconductor 41.

The device of FIG. 6 may be further modified so that the movable contact 72 and stationary contact plate 70 are identical to stationary contact 30 and movable contact 24 on the left-hand side of the device. In addition, conductor 51 would be terminated by a contact 52 in the manner shown for conductor 50 at the left-hand end of the superconductor 41. With this type construction, the superconductor 41 will be isolated from the circuit in which the device is placed during the closed condition of the current-limiting interrupter. That is to say, the circuit will be closed by the engagement of the stationary contacts, such as contact 30, and movable contacts, such as movable contact 24, with the movable contact 24 being disconnected from contact 52 of the superconductor 41. Thus, with the above-noted modification of FIG. 6, superconductor 41 will be thermally isolated from the circuit in which it is connected when the device is either in its open or closed position.

In the embodiment of FIGS. 1 to 6, the element 41 has been described as a superconductor. It should be noted, however, that element 41 could be replaced by a more conventional material, exhibiting a positive resistance characteristic, as has been described in above-noted copending application Ser. No. 39,040, taking advantage of the insulating vacuum as the medium for receiving the cooperating contacts of the device. In such an embodiment, it is clear that the non-linear resistor need not be disposed within the normal conductor.

FIG. 7 shows an embodiment of the invention in which a non-linear resistor and superconductor are provided in parallel, and in a common cryogenic environment, where the superconductor is used to switch the non-linear resistor into a circuit responsive to a given current value.

The device of FIG. 7 is shown as a current limiter per se (without contacting equipment) and comprises a pair of main terminals 80 and 81, each being surrounded by thermal insulation bushings 82 and 83, respectively. Two end housings 84 and 85 are provided to receive the ends of terminals 80 and 81, and bushings 82 and 83, and to receive cryogenic insulation vessel 86. Housings 84 and 85 are further mounted on the ends of insulation casing 87. The interior regions of bushings 82 and 83 communicate with region 88 within casing 87 through suitable openings in housings 84 and 85. Vacuum lines 89 and 90 are then provided for housings 84 and 85, respectively, to permit the establishment of a hard vacuum within the device.

A tube 92, of superconducting material such as Nb_3Sn , is then supported between and connected to flanges 93 and 94 of terminals 80 and 81, respectively, while a tube 95 of nonlinear resistance material, such as pure tungsten, is connected to the opposing inner ends of terminals 80 and 81. Thus, superconductor tube 86 and non-linear resistor 95 are in parallel between terminals 80 and 81. The interior of vessel 86 is then filled with a suitable cryogenic liquified gas medium which circulates through suitable openings in

flanges 93 and 94 and openings in interior terminal sections so that the inner and outer surfaces of both tubes 92 and 95 are exposed to the same cryogenic medium. The cryogenic liquid supply may be circulated through supply lines 100 and 101 in housings 84 and 85, respectively.

The selection of materials for elements 92 and 95 and the design of the component shapes can be varied, depending on the desired application of the device of FIG. 7. In general, superconductor 92 should be designed such that, at rated load current, the magnetic field at its surface is below the critical field level for the material employed. Moreover, the critical field should be reached only at the current level where load current limitation is desired, for example, at two to three times normal load current level.

FIG. 8 shows the characteristics of two materials which could be selected for use in accordance with the invention, in particular, Nb₃Sn for superconductor 92 and pure tungsten for resistive conductor 95. In general, the superconductor 92 should have a fairly high critical temperature and critical field intensity and should exhibit a high rate of change of resistivity with temperature. The resistive conductor 95 should have a low resistivity at temperatures equal to or below the critical temperature of the superconductor 92. Moreover, its resistive-temperature characteristic should cross that of the superconductor at a low resistivity, compared to that of the superconductor at a temperature at or close to the critical temperature of the superconductor. This cross-over characteristic, shown in FIG. 8 at about 18.3°K, permits commutation of current of the superconductor 92 and into the resistive and current limiting conductor 95.

Resistive conductor 95 has a characteristic in which its resistivity increases by several orders of magnitude when passing through a given temperature range, due to heating by the current therethrough, which range extends from the superconductor temperature of element 92 to a maximum allowed temperature which is below the melting point of conductor 95. By way of example, tungsten will change in resistivity from about 0.0034×10^{-6} ohm cm. at -260°C to about 10×10^{-6} ohm cm. at 200°C, which is an increase of the order of 3,000 times.

A further important characteristic of conductor 95 is that it should have a lower resistivity than the superconductor throughout the operating range of temperatures. This insures that almost all heat input due to the through-current will be in conductor 95 to insure that superconductor 92 can be brought back to its essentially loss-less condition in a short time.

Clearly, the device of FIG. 7 may be provided with interrupting elements connected in series therewith, where such elements may be relayed in a conventional manner, or in response to a give voltage drop across the current limiting device.

Although this invention has been described with respect to particular embodiments, it should be understood that many variations and modifications will now be obvious to those skilled in the art, and it is preferred, therefore, that the scope of the invention be limited not by the specific disclosure herein, but only by the appended claims.

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

1. A current limiting device comprising, in combination:

a first elongated conductor of material having superconducting properties at temperatures below a given temperature;

a cryogenic vessel surrounding said first elongated conductor for cooling said first elongated conductor to a temperature below said given temperature;

a second elongated electrical conductor defining a hollow tubular shape surrounding said first elongated conductor, whereby said first elongated conductor is in a region substantially free of any magnetic field due to current conduction by said second elongated conductor; said second elongated conductor connectable at its opposite ends to a first and second terminal, defining the terminals of said current limiting device;

and first and second means connected to first and second ends of said first elongated conductor for connecting said first elongated conductor to said first and second terminals, respectively;

said first means comprising a switch means operable between an open and closed position, whereby, when said switch means is open, current conduction between said first and second terminals is through said second elongated conductor, and said first elongated conductor is maintained in a superconducting state independently of the magnetic field created by current flow in said second elongated conductor, and whereby a path for current flow, which can generate a magnetic field for switching said first elongated conductor to a resistive state, is defined through said first elongated conductor when said switch means is closed.

2. The current limiting device of claim 1 wherein said switch means is operable to switch all current flow between said first and second terminals from said second conductor to said first conductor responsive to operation thereof.

3. The current limiting device of claim 2 wherein said switch means is further operable to open the circuit between said first and second terminals after switching current flow from said second conductor to said first conductor.

4. The current limiting device of claim 2 wherein said second means connected to said second end of said first elongated conductor comprises second switch means operable between an open and a closed position.

5. The current limiting device of claim 1 which includes an external evacuated housing surrounding said cryogenic vessel and said second elongated conductor; said switch means being disposed within the vacuum of said evacuated housing.

6. The current limiting device of claim 2 which includes an external evacuated housing surrounding said cryogenic vessel and said second elongated conductor; said switch means being disposed within the vacuum of said evacuated housing.

7. The current limiting device of claim 3 which includes an external evacuated housing surrounding said cryogenic vessel and said second elongated conductor; said switch means being disposed within the vacuum of said evacuated housing.

8. The current limiting device comprising, in combination:

an elongated conductor of material having superconducting properties at temperatures below a given temperature;

cryogenic cooling means associated with said elongated conductor for cooling said elongated conductor to a temperature below said given temperature;

switch means connected to one end of said elongated conductor and in series with said elongated conductor;

first and second terminals for connecting said switch means and said elongated conductor in series with a circuit;

and a common evacuated housing surrounding said switch means and said elongated conductor, to serve as thermal insulation for said elongated conductor and as a vacuum medium for operating said switch means as a vacuum switch.

9. The device of claim 8 which includes a second switch means in series with said elongated conductor and connected to the end of said elongated conductor opposite to said one end.

10. A current limiting device comprising, in combination:

an elongated conductor of material having a positive temperature coefficient of resistance which changes value by at least several orders of magnitude when heated through a given temperature range;

switch means connected to one end of said elongated conductor and in series with said elongated conductor;

first and second terminals for connecting said switch means and said elongated conductor in series with a circuit;

and a common evacuated housing surrounding said switch means and said elongated conductor, to

serve as thermal insulation for said elongated conductor and as a vacuum medium for operating said switch means as a vacuum switch.

11. A current limiting device comprising, in combination:

a first elongated conductor of material having superconductor properties at temperatures below a given temperature;

a second elongated resistive conductor connected in parallel with said first elongated conductor;

a cooling means for said first and second elongated conductors for cooling at said first and second elongated conductors to a first temperature below said given temperature;

said first elongated conductor being switched out of its superconducting state to a resistive state responsive to the magnetic field of the current flow therethrough which exceeds a given value;

said second conductor having a resistance which is lower than the resistance of said first conductor at a temperature about equal to said first temperature and after said first conductor is switched from its said superconducting state; the resistance of said second conductor being lower than the resistance of said first conductor throughout a temperature range from said first temperature to a second temperature to which said second conductor is heated by the current therethrough.

12. The device of claim 11 wherein said first conductor has the form of a hollow conductive tube, and wherein said second conductor is disposed within said hollow conductive tube.

13. The current limiting device of claim 12 wherein said first and second conductors are immersed in a cryogenic cooling liquid; and an evacuated housing enclosing said cryogenic cooling liquid and said first and second elongated conductors.

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