

[54] **CIRCUIT BREAKER AND METHOD**

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[51] Int. Cl. **H02h 7/22**

[58] Field of Search **317/11 C, 11 E, 11 A;**
307/136; 200/144 AP

[56] **References Cited**

UNITED STATES PATENTS

3,611,031	10/1971	Lutz	317/11 C
3,590,319	6/1971	Baltensperger	317/11 C
3,522,472	8/1970	Breitholtz	317/11 C

3,641,358	2/1972	Lian	317/11 C
3,657,607	4/1972	Knauer	317/11 C

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[57] **ABSTRACT**

Direct current is interrupted against a high voltage by opening an in-line switch and switching the current into an impedance-increasing section of the circuit breaker. The impedance-increasing section comprises an electronic switching device such as a crossed-field tube serially connected with at least two impedance-increasing resistors. There is a gap in parallel to each of these resistors, except one. As voltage builds up across an impedance-increasing resistor so that the total voltage drop will exceed the desired maximum, the gap breaks down to reduce voltage drop.

9 Claims, 3 Drawing Figures

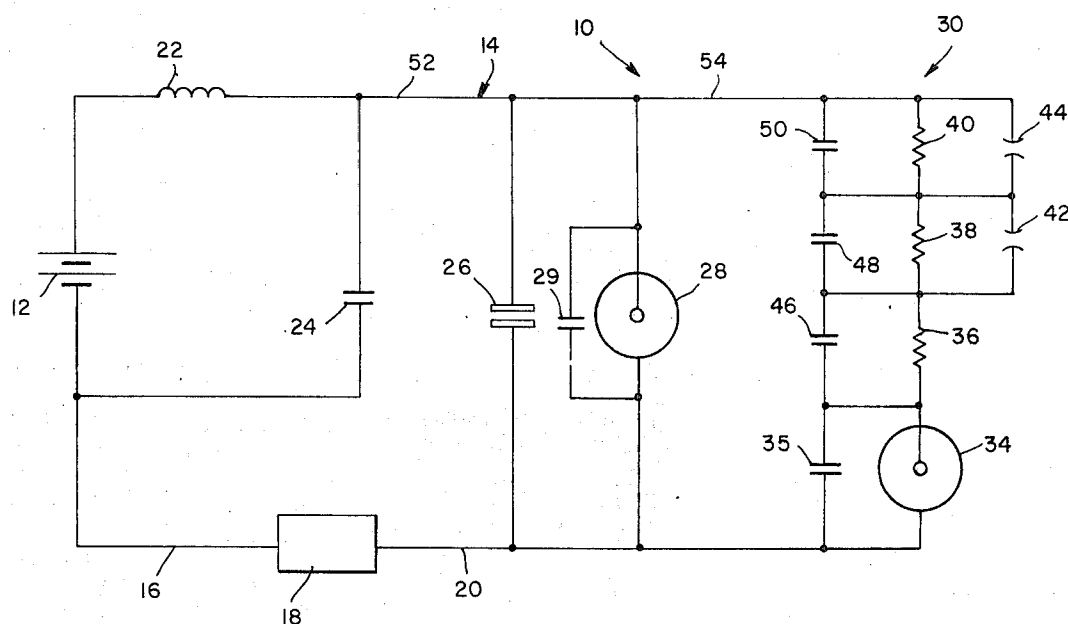


Fig. 1.

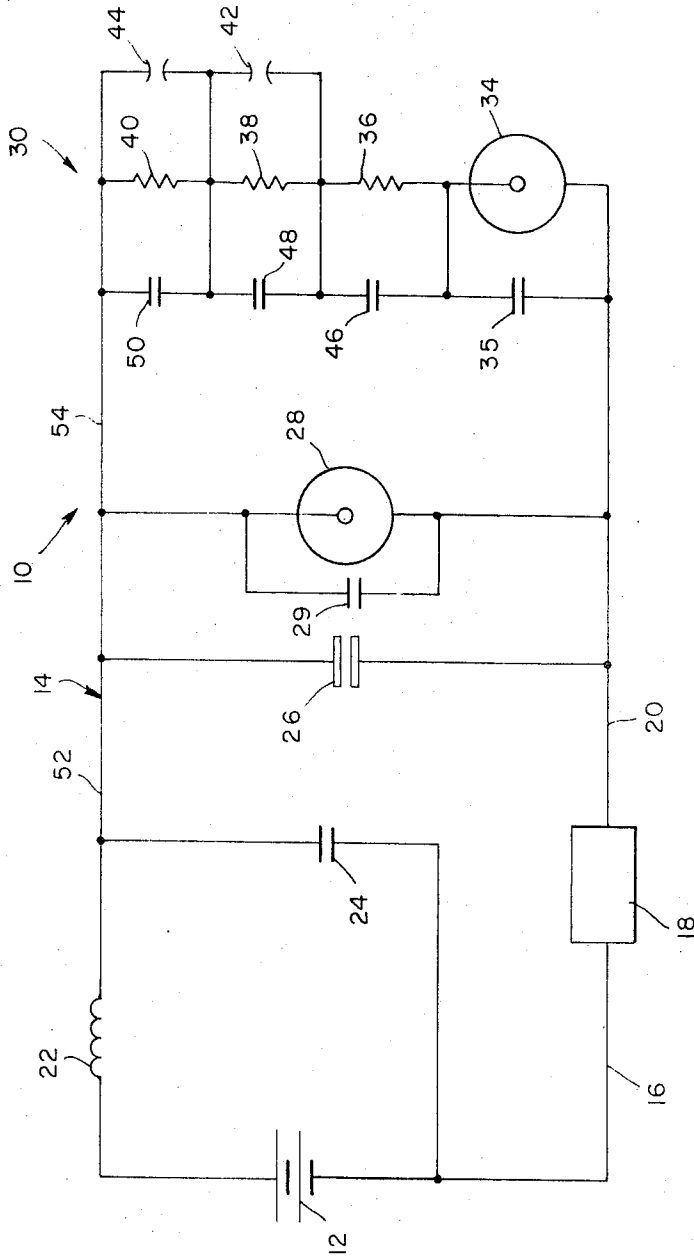


Fig. 2.

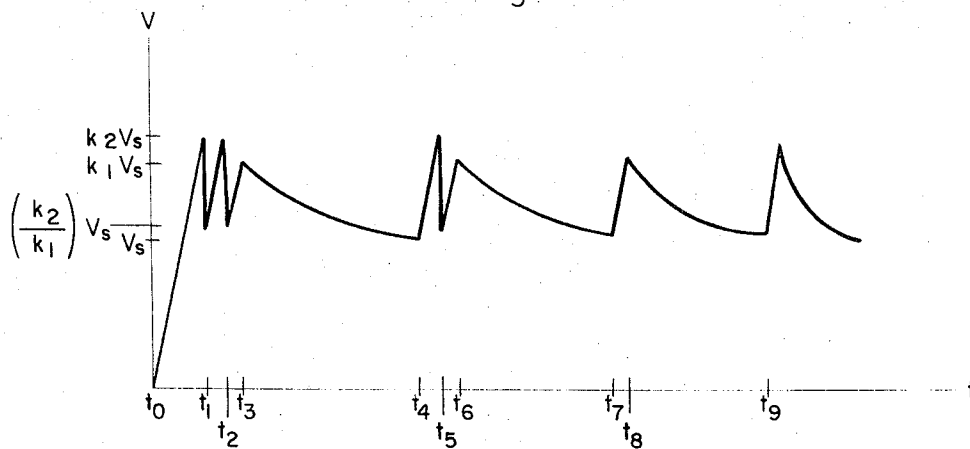
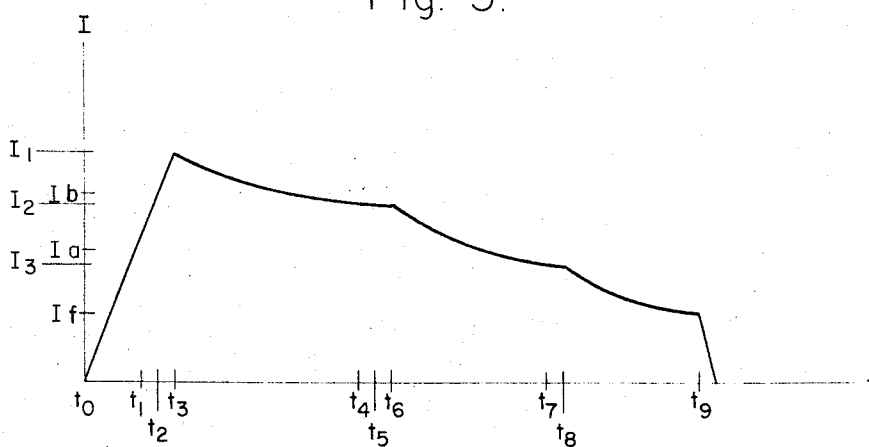


Fig. 3.



CIRCUIT BREAKER AND METHOD

BACKGROUND

1. Field of the Invention

This invention is directed to a circuit breaker, and particularly a circuit breaker for interrupting direct current against high voltage.

2. The Prior Art

The prior art includes patents such as K. T. Lian U.S. Pat. No. 3,534,226 which requires an offswitching electronic switch for each branch in the impedance-increasing section of the circuit breaker. This patent teaches the transfer of line current from the normally conducting interrupter portion of the circuit breaker into the impedance-increasing section of the circuit breaker. However, each branch of the impedance-increasing section requires an electronic switch. On the other hand, W. Knauer U.S. Pat. No. 3,657,607 requires onswitching against high voltage.

Electronic offswitching devices are known in the art. However, there are few electronic offswitching devices which can off switch large direct current flow against high voltage. One class of such a device is a liquid metal cathode device in which the envelope is maintained at a relatively low pressure so that arcing occurs in the vacuum arc mode. This type of offswitching device is shown in FIG. 7 of K. T. Lian U.S. Pat. No. 3,534,226. This type of device is also shown in W. O. Eckhardt U.S. Pat. No. 3,659,132 and K. T. Lian U.S. Pat. No. 3,662,205.

However, the preferred type of electronic switching device is a crossed-field switching device such as is shown in FIG. 8 of K. T. Lian U.S. Pat. No. 3,534,226. Further embodiments of improvements of this crossed-field type of switching device are found in G. A. G. Hofmann and R. C. Knechtli U.S. Pat. No. 3,558,960; M. A. Lutz and R. C. Knechtli U.S. Pat. No. 3,638,061; M. A. Lutz and G. A. G. Hofmann U.S. Pat. No. 3,678,289; and R. E. Lund and G. A. G. Hofmann U.S. Pat. No. 3,641,384. As used with respect to this invention, the term electronic switch means either the vacuum arc mode discharge from liquid metal or the crossed-field type of device indicated above. However, the specification details a structure in which the crossed-field type of device is applied. The entire disclosures of these background patents are incorporated herein by this reference.

SUMMARY

In order to aid in the understanding of this invention, it can be stated in essentially summary form that it is directed to a DC circuit breaker and method. The DC circuit breaker includes an in-line switch through which the current normally flows, and an impedance-increasing section parallel to the in-line switch and into which the current is transferred when the in-line switch is opened. The impedance-increasing section comprises an electronic switch and two resistors serially connected to the electronic switch. A spark gap is in parallel around one of the resistors so that, when circuit breaker voltage approaches the maximum desired value, the gap breaks down to prevent system over-voltages. The circuit breaking method comprises the operation of these components.

It is thus an object of this invention to provide a circuit breaker which is capable of offswitching high voltage DC circuits. It is a further object to provide a

method for offswitching high voltage DC circuits. It is a further object to provide a circuit breaker which employs a minimum number of offswitching devices so that the circuit breaker can be economically and reliably manufactured. It is yet another object to provide a circuit breaker which is of simple design and construction. It is a further object to provide a circuit breaker which is self-adaptive in inserting the maximum amount of impedance possible for particular circuit conditions. It is yet another object to provide a circuit breaker which applies crossed-field switching devices for offswitching the current, and arranged so that the crossed field switching devices need be onswitched only against a lower value of voltage than maximum voltage. Other objects and advantages of this invention will become apparent from the study of the following portion of this specification, the claims, and the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic circuit diagram of the circuit breaker of this invention.

FIG. 2 is a graph of voltage across the buses of the circuit breaker versus time during offswitching of the circuit breaker.

FIG. 3 is a graph of current through the circuit breaker versus time during offswitching of the circuit breaker.

DESCRIPTION

Referring to FIG. 1, the circuit breaker 10 of this invention is schematically shown therein, as part of a direct current power system. The system includes a direct current power source 12. Power source 12 is schematically illustrated as being a battery, but this represents a power generation and distribution system. A generation and distribution circuit, including a load, is shown in more detail in M. A. Lutz and W. F. Long U.S. Pat. No. 3,660,723, the entire disclosure of which is incorporated herein by this reference. The power source 12 is merely schematically illustrative of such a generation and distribution circuit. The power source 12 is connected to buses 14 and 16 to supply the power to load 18 wherein the power is received, absorbed, and the voltage drop takes place during normal circuit operation. The other side of load 18 is connected to bus 20. The inductance and capacitance of the power source and distribution circuit are represented by inductor 22 and capacitor 24.

In-line switch 26 is connected between the buses 14 and 20. In normal circuit operation, in-line switch 26 is closed and carries the normal circuit current. In-line switch 26 can be any type of normal circuit breaker which is capable of carrying the load current, and which is capable of drawing an arc in excess of 1 KV when open. Thus, switch 26 can be a standard SF₆ filled circuit breaker or can be a switch, as described in Noel E. Reed U.S. Pat. application Ser. No. 255,665, the entire disclosure of which is incorporated herein by this reference.

Electronic switch 28 is connected between buses 14 and 20 in parallel with in-line switch 26. Electronic switch 28 is either a liquid metal cathode switch device which operates in the vacuum arc mode, or a crossed field switch device. Both of these types of devices are described above, in patents incorporated herein by reference. The crossed-field type of device, schematically

illustrated, is the preferred embodiment of the electronic switch 28. In-line switch 26 and electronic switch 28 together comprise the interrupter section of the circuit breaker 10. When in-line switch 26 is opened, electronic switch 28 is in the conductive condition and the increasing voltage drop due to the opening of in-line switch 26 causes electronic switch 28 to conduct. When switch 28 is conductive, in-line switch 26 stops arcing and deionizes so that it can hold off the full voltage. Now, electronic switch 28 is turned off to force the current into the impedance-increasing section 30 of circuit breaker 10.

Impedance-increasing section 30 comprises electronic switch 34 serially connected with resistors 36, 38 and 40 between buses 14 and 20. Electronic switch 34 is of the type described above, and is preferably a crossed-field switch device. Resistors 36, 38 and 40 are of suitable current-carrying capacity and energy dissipation for the particular service, such as the example described below. They may be linear resistors, but nonlinear resistors which have a higher resistance at lower current are preferred. Nonlinear resistors of such characteristics can reduce the number of stages required. Spark gaps 42 and 44 are connected in parallel to resistors 38 and 40. These spark gaps are each a conventional spark gap and are particularly designed so that the voltage at which the gap breaks down and begins arcing is as close to the same value as possible for each breakdown. The gaps 42 and 44 are substantially identical, and preferably have the same breakdown voltage. Each can be in the form of a gap in a vacuum envelope or a gap in an envelope filled with SF_6 . In the case of vacuum or SF_6 gaps, gap recovery is rapid upon cessation of arcing. Each of the gaps 40 and 42 is of sufficient current capacity to carry the full load current. A suitable gap is described in an article in *IEEE Transactions on Power Apparatus and Systems*, Volume PAS-91 No. 5, September-October 1972, at pages 2104-2112 entitled "Separation of Gap Functions - A New Concept in Station Class Lighting Arrestor Design" by Joseph C. Osterhout of Westinghouse Electric Company, Bloomington, Indiana. The article discusses pressurized preionized gaps with accurate voltage breakdown repeatability.

Capacitors 46, 48 and 50 are respectively paralleled across resistors 36, 38 and 40. These capacitors have sufficient voltage rating to equal the voltage drop through the resistance across which they are individually paralleled.

Referring to FIGS. 1, 2 and 3, when a fault occurs which bypasses load 18, the current in bus 14 at section 52 thereof rises rapidly. The rise is detected and electronic switch 28 is turned on, preferably at the same time electronic switch 34 is turned on. Thereupon, in-line switch 26 is opened and, when it is deionized, electronic switch 28 is turned off, thereby completing the interrupter action. It is the current in section 54 of bus 14 which is indicated in FIG. 3. The offswitching of crossed-field switch 28 is being accomplished from time t_0 to t_3 and thus the current rises in section 54 from zero to I_1 . Thus the initial rise in current in FIG. 3 is not the rise in current in section 52 as a result of the fault occurring, but represents fault current being transferred from the interrupter section to the impedance-increasing section 30.

Current in the impedance-increasing section flows through now conducting crossed-field switch 34, resis-

tor 36, resistor 38 and resistor 40. Capacitors 46, 48 and 50 charge up, in accordance with the voltage drop upon the resistors with which they are in parallel. At time t_1 the current I_n , see FIG. 3, produces a voltage drop $k_2 V_s$ which approaches the maximum permissible system hold off voltage. When V_s is a normal system voltage, k_2 is typically 1.7. At this time, the current flow I_n through resistor 40 produces sufficient voltage drop so that gap 44 breaks over, thus shorting out resistor 40. At this time, capacitor 50 discharges through arcing gap 44. Resistor 40 is of higher value than resistor 38 and thus produces a higher voltage drop. Thus gap 44 is the first to break down. Now, the current flow is through crossed-field switch 34, resistor 36, resistor 38 and arcing gap 44 so that, with this lower value of resistance, the current flow does not produce a total voltage drop in excess of that tolerable by the system. Current transfer into the impedance-increasing branch still continues and the current rises. At time t_2 , current has risen to I_b . The sum of series resistances 36 and 38 is such that, with a current flow I_b therethrough, the voltage drop again approaches $k_2 V_s$, which is the system limit. At this point, the voltage drop across resistance 38 causes gap 42 to break down to remove resistance 38 from the series string, and discharge capacitor 48. Current transfer continues until t_3 with a maximum current flow I_1 . This results in a voltage drop across resistor 36 of $k_1 V_s$. Current transfer is completed and the voltage drop across resistor 36 is greater than the source voltage of V_s . Therefore, current flow in the system is forced down and the voltage reduces on an RL transient curve t_3 to t_4 . At t_4 the current is reduced to I_2 .

System stability is approached as current reaches I_2 where that current through resistor 36 produces a voltage drop which approaches V_s at t_4 . It should be noted that the time scales in FIGS. 2 and 3 are distorted for clarity. The voltage surges, e.g., t_1 to t_2 , are only tens of microseconds apart, while the RL transients, e.g., t_3 to t_4 are tens of milliseconds long. Now crossed-field tube 34 is switched off for a sufficient length of time to permit gaps 42 and 44 to cease arcing and deionize. This would be expected to be about 10 microseconds.

Crossed-field switch device 34 is thereupon on-switched. Onswitching permits the current to flow through this series combination of resistors 36, 38 and 40, charging the paralleled capacitors 46, 48 and 50. These capacitors charge, causing the slope to the voltage curve of FIG. 2 from t_4 to t_5 . Again, as the current through the series combination of resistors 36, 38 and 40 causes a voltage drop which is approaching $k_2 V_s$ at t_5 , the voltage drop due to this current through resistor 40 reaches the breakdown of gap 44, thereby shorting out resistor 40. As the current through crossed-field switch 34 continues to charge capacitors 46 and 48, the voltage builds up respectively across resistors 36 and 38 to the value of $k_1 V_s$ at t_6 . The current I_2 through these resistors causes the voltage drop greater than V_s so that current is reduced down an RL transient curve, as shown in FIG. 3, and voltage across the impedance-increasing section moves down a similar curve from $k_1 V_s$ and approaches V_s .

The end of this curve is reached at t_7 , at which time crossed-field switch 34 is turned off. Gap 44 ceases arcing and deionizes, and crossed field switch 34 is again turned on. It is difficult to properly turn on a crossed-field switch of this nature against high voltage, but the

capacitors 35, 46, 48 and 50, as well as the system capacitance, prevent a rapid rise of voltage across the crossed field switch 34 when it is turned off. As an example, the crossed-field tube is turned off only about 10 microseconds; in this time, the voltage can only rise a few kilovolts. Thus, this crossed-field switch 34 can be turned on against only a few kilovolts, and thus can successfully conduct in the glow mode. When crossed-field switch 34 is turned on at t_n , the current I_3 is below the value of current I_a at which gap 44 breaks down. Therefore, neither gap 42 nor 44 breaks down and all three resistors 36, 38 and 40 remain in the circuit to provide maximum impedance. The current is reduced and, with the reduction in current, the voltage drop across the series combination of resistors 36, 38 and 40 reduces and approaches V_s .

Capacitor 29 is connected in parallel to switch 28. Capacitor 29 represents system capacitance, and where the system capacitance is small, capacitor 29 can be an actual capacitor. Both capacitors 29 and 35 provide dv/dt protection for the offswitching crossed-field switch devices. When dv/dt is high, the crossed-field switches will arc. Thus these capacitors limit dv/dt for this purpose.

Capacitor 35 must be of small value so that the gaps can quickly deionize when switch 34 is turned off. Capacitor 29 is of large value to limit the final voltage surge.

As the final step in the circuit breaker operation, switch 34 is turned off at t_g . The current is driven to zero and the final voltage surge is taken in the capacitors, particularly capacitor 29.

In a specific example of operation, the following relationships hold for the components of the system. Numerical values are given for an exemplary system:

$$V_s = 100 \text{ kV}$$

$$V_{gap} = V_s (k_1 - 1) k_2 / k_1 = 66 \text{ kV}$$

$$k_2 = 1.7$$

$$k_1 > 1.0 \text{ and less than } k_2, \text{ e.g., } 1.6$$

$$I_{normal} = 1,000 \text{ A}$$

$$I_1 = 2,000 \text{ A}$$

$$R_{36} = k_1 V_s / I_1 = 80 \Omega$$

$$R_{38} = (k_1 - 1) R_{36} = 48 \Omega$$

$$R_{40} = k_1 (k_1 - 1) R_{36} = 77 \Omega$$

$$I_a = V_{gap} / R_{36} = 860 \text{ A}$$

$$I_2 = V_s / R_{36} = 1,250 \text{ A}$$

$$I_b = I_2 k_2 / k_1 = 1325 \text{ A}$$

$$I_3 = V_s / (R_{36} + R_{38}) = V_s / (k_1 R_{36}) = 781 \text{ A}$$

$$I_f = V_s / (R_{36} + R_{38} + R_{40}) = V_s / (k_1^2 R_{36}) = 488 \text{ A}$$

It is thus seen that the circuit breaker 10 has a minimum number of electronic offswitching devices. Furthermore, onswitching of the crossed-field tubes against high voltage is not required. Nonlinear resistors, that have higher resistance at lower current are preferably employed to minimize the number of resistors and gaps. The circuit breaker is adaptive in that it will automatically insert the highest possible value of resistance for the level of the current interrupted. The above example gives operation during a maximum current situation. If the fault current is lower, such as I_2 , more resistance will stay in the circuit. While a particular example of linear resistances in series with the crossed-field switch is given, the circuit breaker can incorporate any number of linear or nonlinear resistance stages required for the particular circumstances. These circumstances depend upon the value of k_2 and the system capacitance.

While described with respect to a DC power system, it is clear that this circuit breaker can insert impedance into or break an AC circuit between natural current zeros.

This invention having been described in its preferred embodiment, it is clear that it is susceptible to numerous modifications and embodiments within the ability of those skilled in the art and without the exercise of the inventive faculty. Accordingly, the scope of this invention is defined by the scope of the following claims.

We claim:

1. A circuit breaker for a circuit comprising:

an interrupter section, said interrupter section being capable of continuously carrying the normal circuit current, and interrupting circuit current;

an impedance-increasing section connected in parallel to said interrupter section so that, when said interrupter section interrupts current therethrough, the current is transferred to said impedance-increasing section;

said impedance-increasing section comprising a switch capable of offswitching current passing therethrough, first, second and third resistors serially connected with said electronic switch, a first spark gap connected in parallel to said second resistor and a second spark gap connected in parallel to said third resistor, said first and second spark gaps having different breakdown voltage so that, when current flow through said second resistor produces a voltage drop in excess of the first spark gap breakdown voltage, said first spark gap breaks down and bypasses said second resistor and when current flow through said third resistor produces a voltage drop in excess of the second spark gap breakdown voltage, said second spark gap breaks down and bypasses said third resistor.

2. The circuit breaker according to claim 1 wherein said interruptor section comprises an in-line switch and a crossed-field switch in parallel to said in-line switch, and said switch in said impedance-increasing section comprises a crossed-field switch.

3. The circuit breaker of claim 1 wherein said impedance-increasing section further includes a first capacitor in parallel to said first resistor a second capacitor in parallel to said second resistor and a third capacitor in parallel to said third resistor, said first, second and third capacitors respectively limiting rate of voltage rise across said first, second and third resistors.

4. The circuit breaker according to claim 3 wherein said interruptor section comprises an in-line switch and a crossed-field switch in parallel to said in-line switch, and said switch in said impedance-increasing section comprises a crossed-field switch.

5. The circuit breaker of claim 1 wherein said second and third resistors have different values so that said first and second spark gaps break down at different current.

6. The circuit breaker of claim 5 wherein said resistors are nonlinear resistors.

7. The circuit breaker of claim 5 wherein said circuit breaker further comprises first and second buses, each of said buses being connected to both said interruptor section and said impedance-increasing sections, one of said buses being connected to a load and the other of said buses being connected to a power supply, said power supply also being connected to said load.

8. The method of off-switching a DC circuit including a power supply and a load, with a circuit breaker con-

connected to interrupt current flow from said power supply, said circuit breaker comprising an interruptor section and impedance-increasing section, said impedance-increasing section comprising an electronic switch and first and second serially connected resistors with a spark gap connected in parallel to said second resistor, comprising the steps of:

- opening the interruptor section to transfer current from the power supply to the impedance-increasing section with the current through the impedance-increasing section increasing so that the voltage drop across the second resistor exceeds the breakdown voltage of the spark gap so that the spark gap breaks down and short circuits the second resistor;
- reducing the current flow through the impedance-increasing section by developing a larger voltage drop across the first resistor than the power supply voltage to a current value less than the value of current through the second resistor which breaks down the spark gap;
- offswitching the electronic switch to permit the spark gap to cease arcing; and
- turning on the electronic switch to connect both the first and second resistors in series with the power supply to result in increased impedance and reduced current flow.

9. The method of offswitching a circuit including a power supply and a load, with a circuit breaker connected to interrupt current flow from said power supply, said circuit breaker comprising an interruptor section and impedance-increasing section, said impedance-increasing section comprising an electronic switch and first, second and third serially connected resistors in series with the electronic switch and first and second spark gaps respectively connected in parallel to the second and third resistors, comprising the steps of:

- opening the interruptor section to transfer current from the power supply to the impedance-increasing section with the current through the impedance-increasing section increasing so that the voltage

drop across the second resistor exceeds the breakdown voltage of the first gap so that the first spark gap breaks down and short-circuits the second resistor, and so that the current through the impedance-increasing section increases so that the voltage drop across the third resistor exceeds the breakdown voltage of the second spark gap so that the second spark gap breaks down and short-circuits the second resistor;

- reducing the current flow through the impedance-increasing section by developing a larger voltage drop across the first resistor than the power supply voltage to a current value less than the value of current through the third resistor which breaks down the second spark gap;

offswitching the electronic switch to permit both the first and second spark gaps to cease arcing;

turning on the electronic switch to connect the first, second and third resistors in series with the power supply to result in increased impedance and reduced current flow with the current flow being at a value that the voltage drop across the third resistor does not exceed the breakdown voltage of the second spark gap but the voltage drop across the second resistor exceeds the breakdown voltage of the first spark gap so that the first spark gap breaks down and short-circuits the second resistor;

- reducing the current flow through the impedance-increasing section by developing a larger voltage drop across the serially connected first and third resistors than the power supply voltage to a current value less than the value of current through the second resistor which breaks down the first spark gap;
- offswitching the electronic switch to permit the first spark gap to cease arcing; and

turning on the electronic switch to connect the first, second and third resistors in series with the power supply to result in an increased impedance and reduced current flow.

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