United States Patent [19]

Long

[11] **3,786,310**

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[54] **HYBRID DC CIRCUIT BREAKER**

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[52] **U.S. Cl.** .... **317/11 C**, 307/136, 317/11 E

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

[58] **Field of Search** .... 317/11 E, 11 C; 307/136

[56] **References Cited**

UNITED STATES PATENTS

3,660,723	5/1972	Lutz et al.	317/11 C
3,641,358	2/1972	Lian et al.	307/136
3,678,289	7/1972	Lutz et al.	317/11 C

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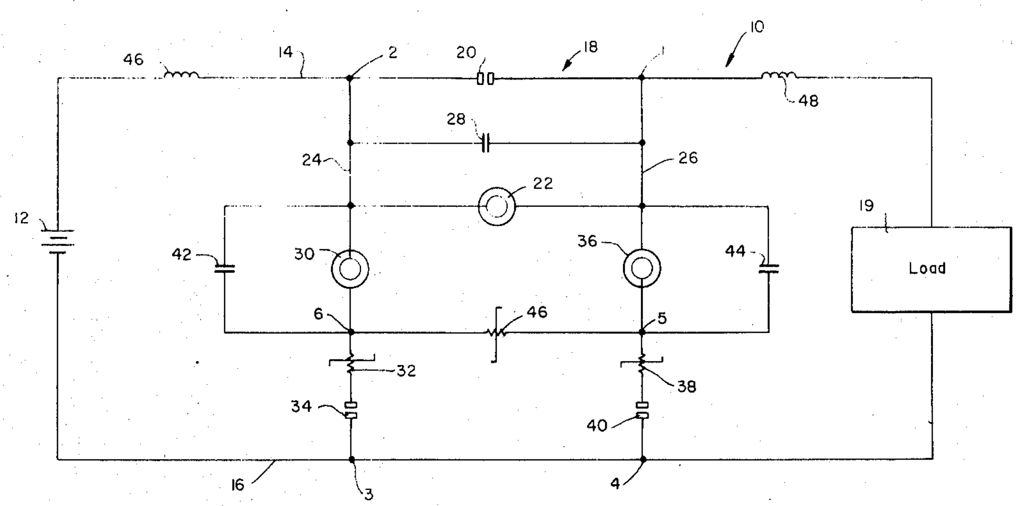
[57] **ABSTRACT**

DC circuit breaker has both in-line and line-to-ground components to limit in-line and line-to-ground voltages during load breaking and fault clearing. Impedance insertion forces down current.

15 Claims, 8 Drawing Figures



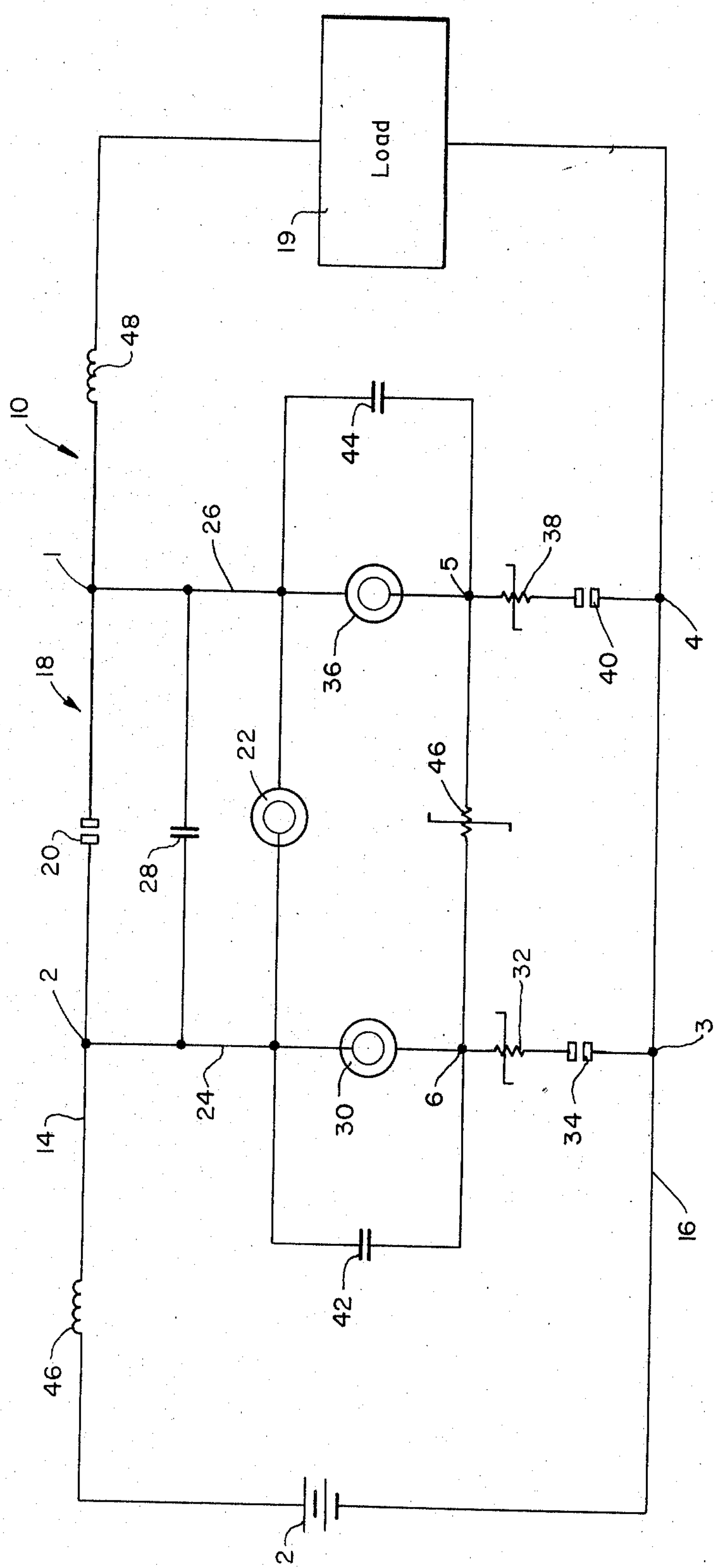


Fig. 1

Fig. 2.

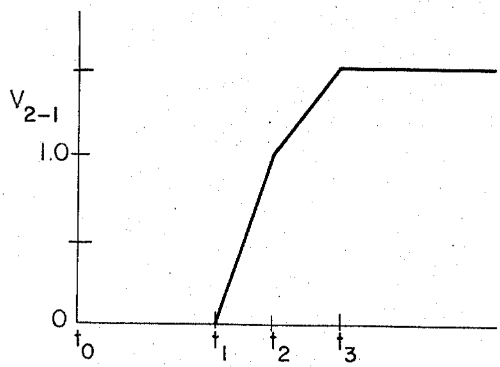


Fig. 3.

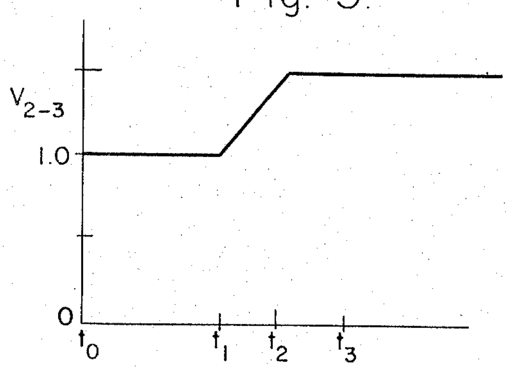


Fig. 4.

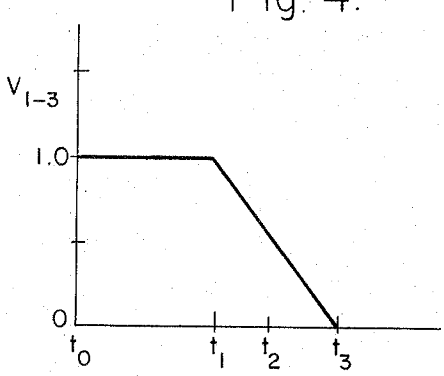


Fig. 5.

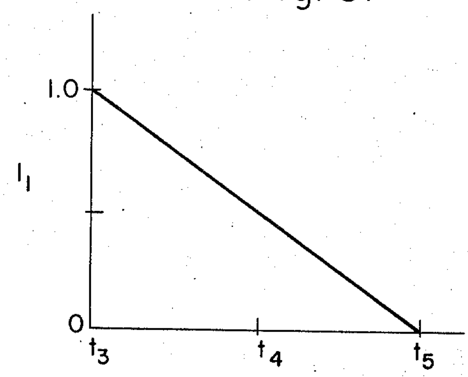


Fig. 6.

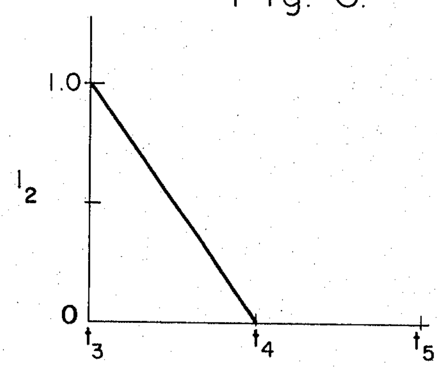


Fig. 7.

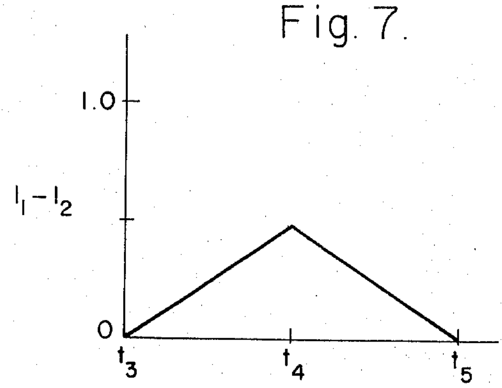
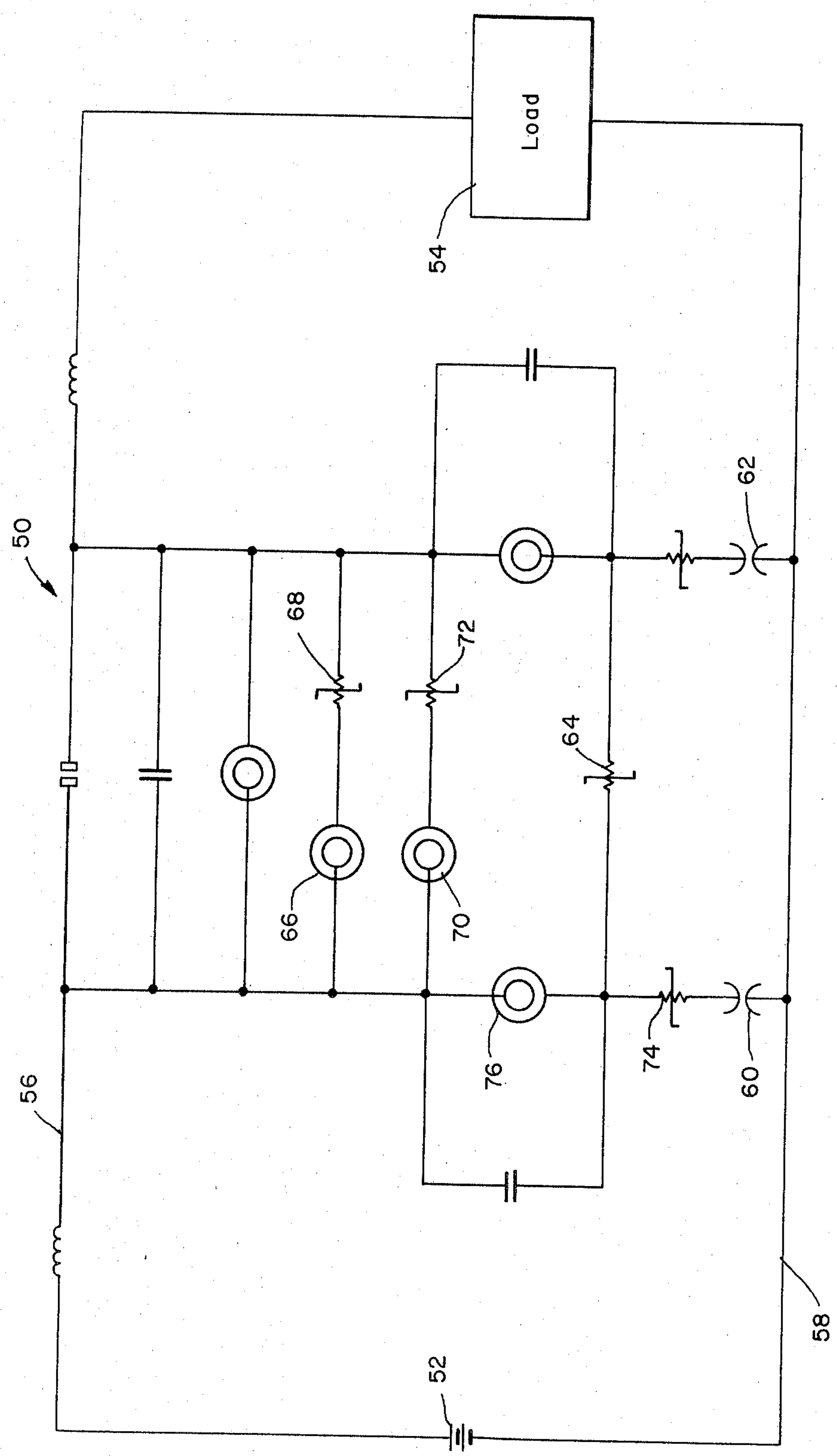


Fig. 8



HYBRID DC CIRCUIT BREAKER

Background of the Invention

This invention is directed to a hybrid DC circuit breaker which limits in-line and line-to-ground voltage.

The prior art consists of two fundamental configurations. In-line circuit breakers are those wherein current to be interrupted is diverted into a resistance in series with the load. One example of this is the sequential switching circuit breaker of K. T. Lian reissue patent RE-27,557. Another example is the series sequential circuit breaker of M. A. Lutz patent 3,660,723.

The other fundamental configuration of the prior art is the line-to-ground breaker wherein current is diverted into resistance between the line and ground, and the in-line circuit is open. Examples of this are A. N. Greenwood U.S. Pat. Nos. 3,390,305; 3,435,288; 3,476,978; and 3,489,951. The line-to-ground DC circuit breaker has an in-line switch and a series combination of a switch and a resistor connected to ground on each side of the in-line switch. The disadvantage arises that the voltage applied across the in-line switch is that sum of the voltage drop across the two line-to-ground resistors. This can be avoided by shorting the load side of the in-line switch to ground to eliminate the load side voltage to the in-line switch. However, this is not really acceptable in power systems.

Management of the voltage across components, both in-line and line-to-ground, is required for a circuit breaker of maximum utility. Furthermore, the circuit breaker should be able to open a load circuit, as well as interrupt a fault. It is the combined desirable objectives that the circuit breaker of this invention seeks to attain.

SUMMARY

In order to aid in the understanding of this invention, it can be stated in essentially summary form that is directed to a hybrid circuit breaker which comprises a line switch for serial interconnection between a power source and its load. The line switch is paralleled by a shunt switch which permits the line switch to open and deionize. Between the line side of the in-line switch and the ground is connected a series combination of a switch and a resistor with a connection point therebetween. Between the load side of the in-line switch and the connection point is connected a series combination of a switch and a resistor so that voltages are limited during off-switching and current is forced down.

It is thus an object of this invention to provide a hybrid circuit breaker which is capable of off-switching a normal load or breaking a fault. It is a further object to provide a hybrid circuit breaker which limits the voltage across components, including line-to-ground voltage, during all switching or fault breaking. It is still another object to provide a hybrid circuit breaker wherein no shorting to ground occurs. It is still another object to provide hybrid circuit breaker which is capable of off-switching high values of direct current against high voltages, so that load breaking and fault protection is available for high power direct current circuits.

Other objects and advantages of this invention will be understood from a study of the following specifications, the claims and the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic circuit diagram of a high voltage DC system showing the schematic arrangements of a high voltage DC hybrid circuit breaker connected therein for load breaking and fault protection;

FIGS. **2–4** are graphs showing voltages across various parts of the circuit breaker during load breaking;

FIGS. **5–7** are graphs showing the current through various portions of the circuit breaker during load breaking;

FIG. **8** is a schematic diagram showing another species of the hybrid circuit breaker of this invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

First referring to FIG. **1**, an electric system **10** is shown therein. The electric system comprises a power source **12** which is connected through power line **14** and ground line **16** to a load **19.** The hybrid DC circuit breaker **18** is connected in line **14** and between line **14** and ground **16** to control the flow of power to the load. A power system of this nature is disclosed in more detail in G. A. G. Hofmann U.S. Pat. 3,558,960. That patent describes the power source and load in more detail. Furthermore, that patent illustrates switching can be accomplished in a transmission line by switch **10*a***, and can be accomplished in a side tap arrangement from the main transmission line to a tapped load. Circuit breaker **18** of the present invention is capable of both line and side tap load switching. Furthermore, it is capable of load off-switching as well as fault breaking.

Circuit breaker **18** has in-line switch **20** connected serially in power line **14** between connection points **1** and **2.** In-line switch **20** can be a conventional mechanical switch which has a low impedance when closed, and when open can hold off the peak voltages between connection points **1** and **2.** In view of the fact that the in-line switch is in parallel with crossed-field switch device **22,** described in greater detail below, and it is necessary for such crossed-field switch devices to have a voltage impressed thereacross to begin conducting, it is desirable that the in-line switch device **20** be capable of developing adequate arc voltage to permit initiation of conduction in the crossed field switch device **22.** At present, about one kilovolt is necessary to start conduction. Therefore, in-line switch device **20** is preferably capable of developing a substantial arc voltage drop. Any conventional circuit breaker having these capabilities, such as a magnetic blowout, long arc path circuit breaker, is useful in this environment. Another particular structure which is useful is the switch disclosed in N. E. Reed U.S. Pat. No. 3,750,061 U.S. Pat. application Ser. No. 255,665 filed May 22, 1972.

Line **24** is connected from connection point **2** through connection point **6** to connection point **3** on ground line **16.** Similarly, line **26** is connected between connection point **1** through connection point **5** to connection point **4** on line **16.** Capacitor **28** is connected between lines **24** and **26** to control the rate of voltage rise when in-line switch **20** or crossed-field switch device **22** are off-switched. As previously stated, crossed-field switch device **22** is connected in parallel to in-line switch **20,** between lines **24** and **26.** Crossed-field switch device **22** is a switch device which is capable of passing direct current and off-switching direct current against high voltage. Crossed-field switch devices of this nature are disclosed in K. T. Lian U.S. Pat. RE-27,557, M. A. Lutz and R. C. Knechtli U.S. Pat. 3,638,061, R. E. Lund and G. A. G. Hofmann U.S. Pat. 3,641,384, G. A. G. Hofmann U.S. Pat. 3,604,977, G. A. G. Hofmann and R. C. Knechtli U.S. Pat. 3,558,960, G. A. G. Hofmann U.S. Pat. 3,714,510, M. A. Lutz and G. A. G. Hofmann U.S. Pat. 3,678,289 and several improvements thereon. From the study of this prior art, it is clear that crossed-field devices can carry large values of direct current and off-switch against high voltages.

In particular illustrative value, the power source **12** is capable of normal line voltages of 400 kilovolts at 2,000 amperes. These values will be considered to be the per-unit in the illustration, which is the 1 pu in this disclosure. For purposes of illustration, the values are normalized, with 1 pu voltage sources and initial currents. System inductance is shown lumped, and no transmission line or filter effect are included in the discussion. The non-linear resistors are considered ideal. With an overvoltage value $k = 1.5$, the non-linear resistors are treated as 1.5 pu DC sources in the voltage analysis.

For purposes of illustration, 1.5 pu is chosen as maximum overvoltage. Quite often in modern power transmission practice, an overload factor k of 1.7 is found. However, for purposes of this illustration, a value of 1.5 is chosen for illustrative purposes. If the equipment is designed for a different overvoltage factor, that factor would, of course, be employed in designing the circuit breaker for that system.

Modern non-linear resistors are structures which do not obey Ohm's Law, but the value of resistance varies with the amount of current. In the present case, a high resistance at low current and a lower resistance at high current is desired. The ideal non-linear resistance would have an infinite resistance value at zero current, but would break down and commence conducting when its breakdown voltage was reached. Modern non-linear resistors are made of silicon carbide, and do not reach the ideal goal. However, discussion of the present circuit breaker with ideal resistors therein aids in ease of description. The voltage and current curves would be less ideal, when a real non-linear resistor is employed.

In the operation, as described below, during off-switching or fault breaking, current is transferred from in-line switch **20** into crossed-field switch device **22**, by opening the switch **20** when crossed-field switch device **22** is conditioned to conduct. After in-line switch device **20** is opened and deionized, crossed-field switch device **22** is turned off. If there is too much energy in the circuit for a simple turnoff, a circuit can be connected and paralleled to crossed-field switch device **22** which comprises a series combination of another crossed-field switch device and an energy-absorbing resistor, optionally of non-linear characteristics. Such is shown in FIG. **8.** In that case, when crossed-field switch device **22** is turned off, the energy is reduced by diverting the current through the energy-absorbing resistor. Such additional energy-absorbing circuits are shown in K. T. Lian patent RE-27,557 and in M. A. Lutz patent 3,660,723.

Serially connected in line **24** between connection point **2** and connection point **3** are crossed-field switch device **30**, resistor **32**, which is illustrated as being non-linear, and switch **34**. Similarly, connected in line **26** between connection point **1** and connection point **4** is a series combination of crossed-field switch device **36**, resistor **38**, which is illustrated as being non-linear, and switch **40**. Capacitors **42** and **44** are respectively connected in parallel around crossed-field switch devices **30** and **36** to control the change of voltage with respect to time across the crossed-field switch devices. Resistor **46**, shown as being non-linear, is connected between lines **24** and **26** at connection points **5** and **6.**

Crossed-field switch devices **30** and **36** are identical to crossed-field switch device **22**, while switches **34** and **40** can be identical to in-line switch **20.** However, the requirements of switches **34** and **40** are somewhat different than the requirements of in-line switch **20**, so they could be of different design. Crossed-field switch devices, such as the devices **30** and **36** in the present state of the art, cannot reliably turn on in the proper mode when a voltage is initially impressed across them. For example, if switch **34** were absent from the circuit of FIG. **1**, crossed-field switch device **30** would be connected directly between the power line **14** and ground **16.** Therefore, the entire **1** pu would be impressed on the crossed-field device **30.** If an attempt was made to turn the crossed-field switch device **30** on under those circumstances, conduction in the arc mode rather than glow mode would sometimes result, so that it could not be turned off. Because of this condition, in the present state of development of such crossed-field switch devices, the switches **34** and **40** hold the power source voltage off of crossed-field switch devices **30** and **36** until their conduction is desired.

FIG. **2** illustrates the voltage between connection points **2** and **1** with respect to the time during off-switching. FIG. **3** illustrates the voltage between connection points **2** and **3** with respect to time. FIG. **4** illustrates the voltage between connection points **1** and **4** with respect to time. It is to be noted with respect to FIG. **4** that the connection point **3** is at the same potential as the connection point **4**, therefore the curve is labeled as the voltage between points **1** and **3.** Furthermore, since the sum of the voltages around the loop between the connection points **1, 2, 3, 4** and **1** must add up to **0**, the voltage between points **1** and **3** (FIG. **4**) is the difference between the voltages shown in FIGS. **3** and **2.**

To illustrate the operation of the breaker, it is assumed that in-line switch **20** is closed and there is normal current flow therethrough at **1** pu with a **1** pu voltage drop across the load. This is normal conduction, and load-breaking mode of operation will be illustrated, as contrasted to fault-clearing. During normal conduction, FIG. **2** illustrates the zero voltage drop across in-line switch **20**, between connection points **1** and **2**, with the **1** pu voltage drop between connection points **2** and **3**, and connection points **1** and **3.** It is seen that the voltage of FIG. **3** minus the voltage of FIG. **2** is the voltage of FIG. **4.** At t_0, the commencement of load-breaking, switches **34** and **40** are open, and crossed-field switch devices **22, 30** and **36** have no voltage thereacross, but crossed-field switch device is conditioned to conduct as soon as sufficient voltage is applied thereto. At time t_0, in-line switch **20** is opened and line current is transferred through crossed-field switch device **22.** The crossed-field switch device **22**, as presently known has about **500** volts drop, and such would not show on the idealized voltage curves. From time t_0

to t_1, in-line switch **20** is opened and deionized so that it can withstand its rated 1.5 pu voltage.

At time t_1, simultaneously, switches **34** and **40** are closed, and crossed-field switch device **22** is off-switched. Crossed-field devices **30** and **36** can be conditioned from t_0 to t_1 to conduct so that now, when switches **34** and **40** are closed, they become conductive. The voltage across the breaker, as shown in FIG. **2,** rises from t_1 to t_2 at a rate determined by the dv/dt limiting capacitance **28.** Assuming ideal non-linear resistors that do not conduct until the voltage reaches 1.5 pu, the voltage rise of FIG. **2** from t_1 to t_2, from 0 to 1.0 pu, is determined by the voltage rate of rise-limiting capacitors, as previously described. The capacitors must carry the current which was in the crossed-field tubes until the resistors conduct. Line current remains constant over this short time span, less than 1 ms.

As the voltage between connection points **2** and **3** reaches 1.5 pu at time t_2, as seen in FIG. **3,** the voltage between these connection points is clamped at 1.5 pu to limit the maximum voltage difference between power line **14** and ground **16.** Thus, interline insulation is not overstressed. As the voltage between connection points **2** and **1** rises, the voltage is taken across resistor **46** which begins conducting at time t_3 to clamp the voltage between points **2** and **1** at 1.5 pu, as is seen in FIG. **1.** By subtraction, the voltage across resistor **38,** between points **1** and **3,** reduces to zero so that resistor **38** never begins conducting. Switch **40** may just as well have been left open. Thus, in the circuit interruption so far described, the branch between connection points **4** and **5** is not necessary. However, it is shown and is employed when the circuit breaker operates the opposite way, such as when the source and the load might be exchanged and it is necessary to separate the reactance energy of both the line and load from the source. By this means, voltage is limited to 1.5 pu across the breaker connection points **1** and **2** and separately between breaker connection points **1** and **4** limiting the maximum voltage during off-switching.

With these voltages, the current is forced down from 1 pu, as is shown in FIGS. **5, 6,** and **7.** The current in the loop from power source **12** through line **14,** through connection points **2, 6** and **3** and back to power source is identified as I_1 and is shown in FIG. **5.** The current in the loop through load **19,** and through connection points **4, 3, 6, 5, 1** and back to the load is represented as current I_2, as is shown in FIG. **6.** For purposes of analysis, both power source **12** and load **19** are considered to be voltage sources valued at 1.0 pu. As previously discussed, system inductance is shown lumped, and no transmission line filter effects are included. The conducting non-linear resistors are considered ideal and are treated as 1.5 pu DC sources. Traversing the lefthand loop, it is seen that 0.5 pu is impressed across inductor **46** and thus the current will fall at a rate of 0.5 pu per-unit time, as indicated in FIG. **5** where the interval from 3 to t_4 is a time unit. Traversing the righthand loop of I_2, it is seen that the effective voltage of load **18** algebraically added to the equivalent voltages of non-linear resistors **32** and **46** is such that 1 pu appears across inductor **48** so that the rate of current decrease is 1.0 pu per-unit of time. Therefore, the current in that loop drops to 0 at time t_4.

The current through resistor **32** is the difference between I_1 and I_2. As shown in FIG. **7,** the current increases from zero at t_3 to 0.5 pu at t_4. Then it drops back to zero in the next time increment, ending at t_5. FIGS. **6** and **7** illustrate that the energy absorbed in resistors **32** and **46** is equal in this example.

Additional considerations applying to the circuit in relating this analysis of the ideal circuit to a real circuit include the fact that silicon carbide is not an ideal non-linear resistor. Its non-ideal characteristics require surge-absorbing capacitance. An appropriate location for this capacitance is between lines **24** and **26,** such as capacitance **28.** Thus, capacitor **28** should be calculated to include surge capacity for this purpose. Additionally, in a real circuit, where power source **12** is a rectifier and load **19** is an inverter, the system controls would affect the actual voltages. For example, the inverter controls would decrease the inverter voltage with respect to time so that I_2 would continue for a longer time.

Finally, the interruption is completed by off-switching crossed-field switch devices **30** and **36.** At the same time or slightly previously, switches **34** and **40** are opened so that off-switching of the respective crossed-field devices extinguishes the arcs in the switches **34** and **40.** Switches **34** and **40** can be triggered vacuum gaps instead of mechanical switch devices.

In fault clearing, the service is not so difficult as in load breaking, because the voltage between lines **14** and **16** is at a reduced value. In fault clearing, current at higher than 1 pu is to be interrupted and reduced to zero without exceeding the 1.5 pu voltage rating at any point in the circuit breaker. With the fault on the right side of the breaker and the voltage between the connection points **2** and **3** near zero, commencement of fault interruption by the breaker permits the voltage to rise. As it rises to 1.5 pu, it is clamped, as previously described. Similarly, the line and load reactance causes a rise in voltage through the right side of the breaker as current is reduced. Again, the voltage between points **1** and **2** is limited to 1.5 pu, so that overvoltages do not occur.

FIG. **8** illustrates circuit breaker **50** connected between power source **52** and load **54.** Connection is by means of power line **56** and ground line **58.** It is recognized that circuit breaker **50** is identical to circuit breaker **18,** except for two changes in detail. Gaps **60** and **62** are employed therein in place of switches **34** and **40,** respectively. They are precision spark gaps which break down and conduct when they reach a predetermined voltage. 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. In circuit breaker **50,** gap **60** holds off the voltage to prevent conduction through that branch until the voltage rises sufficiently above 1 pu, for example 1.5 pu, to cause the spark gap to arc over and conduct. Once conducting, the voltage drop across the branch is controlled by the current through the non-linear resistor in series with the conducting spark gap. Conduction continues until the crossed-field switch in that branch is turned off. Thereupon, the precision spark gap can recover its holdoff properties.

Another difference in detail between FIG. **8** and FIG. **1** is the showing of additional impedance steps to absorb the energy of diverting the line current into resistor **64**. Resistor **64** corresponds to resistor **46** in FIG. **1**. Two intermediate resistor-crossed-field switch stages are illustrated. Crossed-field switch **66** and its series resistor are connected in parallel to resistor **64**. Crossed-field switch **70** and its series resistor **72** are also connected in parallel to resistor **64**. These impedance stages are successively switched off to successively increase impedance to transfer the line current through resistor **64**. In most cases, only one such intermediate stage is expected to be needed. However, two are shown as an example.

As a further alternative, a triggered vacuum gap could be employed in each of the locations of gaps **60** and **62**, shown in FIG. **8**. In the case of the triggered vacuum gap, it would not need to precisely break down at a given voltage, but instead, triggering of conduction in the gap would be controlled by appropriate voltage sensors. In that way, the gap begins conducting at an appropriate condition in the breaker. Such a gap is shown in J. M. Lafferty U.S. Pat. No. 3,290,542.

As still another possible alternative structure, instead of a serial connection of an on-switching device such as switch **34** or gap **60**, together with a resistor such as non-linear resistor **32** or **74** and an off-switching device such as crossed-field switch device **30** or **76**, a single unit which accomplishes these functions could be employed. For example, a lightning arrestor structure is a prospective candidate structure for employment in such use. However, the presently known DC lightning arrestor structures are incapable of adequate energy absorption for the present purpose, and furthermore, they do not reliably isolate when the current is turned off. Thus, as presently known, they are not practical for performing this service. However, further development in that art may produce DC lightning arrestors of accurate onswitching, adequate energy absorption, sealing off at a proper voltage and proper voltage holdoff recovery when current is stopped.

This invention having been described in its preferred embodiment, it is clear that it is susceptible to numerous modifications 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.

What is claimed is:

1. A circuit breaker for connection between first and second lines for the carrying of direct current and for the interruption of current in said first line, comprising:

a switch in said first line between a first connection point and a second connection point in said first line for opening said first line between said first connection point and said second connection point;

first means capable of conducting direct current and off-switching direct current connected in parallel to said switch in said first line for providing a parallel circuit to said first switch for receiving current when said first switch is opened to permit said first switch to deionize and for off-switching direct current through said first means after said first switch has been deionized;

second means for on-switching direct current and for absorbing energy from direct current passing therethrough and for off-switching direct current passing therethrough connected between said second connection point and said second line so that voltage between said second connection point and said second line can be limited to be maintained below a predetermined value;

third means for absorbing energy from direct current passing therethrough and for off-switching direct current connected between said first connection point and said second means so that voltage between said first and second connection points can be limited to be maintained below a predetermined value.

2. The circuit breaker in claim **1** wherein said first means is a crossed-field switch device connected between said first and second connection points.

3. The circuit breaker of claim **2** wherein said second means is a serial connection of a crossed-field switch device for off-switching direct current and means for on-switching and absorbing energy from direct current flowing therethrough.

4. The circuit breaker of claim **3** wherein said means for on-switching and absorbing energy comprises an on-switching device and a separate resistor.

5. The circuit breaker of claim **1** wherein said second means is a serial connection of a crossed-field switch device for off-switching direct current and means for on-switching and absorbing energy from direct current flowing therethrough.

6. The circuit breaker of claim **5** wherein said means for on-switching and absorbing energy comprises an on-switching device and a separate resistor.

7. The circuit breaker of claim **1** wherein said third means is a serial connection of a crossed-field switch device and a resistor.

8. The circuit breaker of claim **3** wherein said third means is a serial connection of a crossed-field switch device and a resistor, said serial connection being connected at one end at said first connection point and at the other end between the crossed-field switch device of said second means and its energy-absorbing means.

9. The circuit breaker of claim **5** wherein said third means is a serial connection of a crossed-field switch device and a resistor, said serial connection being connected at one end at said first connection point and at the other end between the crossed-field switch device of said second means and its energy-absorbing means.

10. The circuit breaker of claim **1** wherein said circuit breaker has its second connection point connected to a power supply and has its first connection point connected to a load, said power supply and load also being connected to said third connection point.

11. The circuit breaker of claim **7** wherein said circuit breaker has its second connection point connected to a power supply and has its first connection point connected to a load, said power supply and load also being connected to said third connection point.

12. The circuit breaker of claim **8** wherein said circuit breaker has its second connection point connected to a power supply and has its first connection point connected to a load, said power supply and load also being connected to said third connection point.

13. The circuit breaker of claim **9** wherein said circuit breaker has its second connection point connected to a power supply and has its first connection point connected to a load, said power supply and load also being connected to said third connection point.

14. The circuit breaker of claim 1 further including means for on-switching direct current and for absorbing energy from direct current connected between said third means and said third connection point.

15. The circuit breaker of claim 14 wherein said circuit breaker has its second connection point connected to a power supply and has its first connection point connected to a load, said power supply and load also being connected to said third connection point.

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