# United States Patent

**Knauer**

[15] **3,657,607**

[45] **Apr. 18, 1972**


## [54] IMPEDANCE-INCREASING METHOD AND APPARATUS AS PART OF A HVDC CIRCUIT BREAKER


[72] Inventor: **Wolfgang Knauer,** Malibu, Calif.

[73] Assignee: **Hughes Aircraft Company,** Culver City, Calif.



[22] Filed: **Mar. 9, 1971**

[21] Appl. No.: **122,396**

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

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

[58] **Field of Search** .....317/11 A, 11 C, 11 E; 307/133, 307/136; 200/144 AP



[56] **References Cited**

UNITED STATES PATENTS

2,849,659 8/1958 Kesselring.....317/11 A

3,198,986 8/1965 Luehring et al. .....317/11 E

3,534,226 10/1970 Lian.....317/11 C



*Primary Examiner*—James D. Trammell

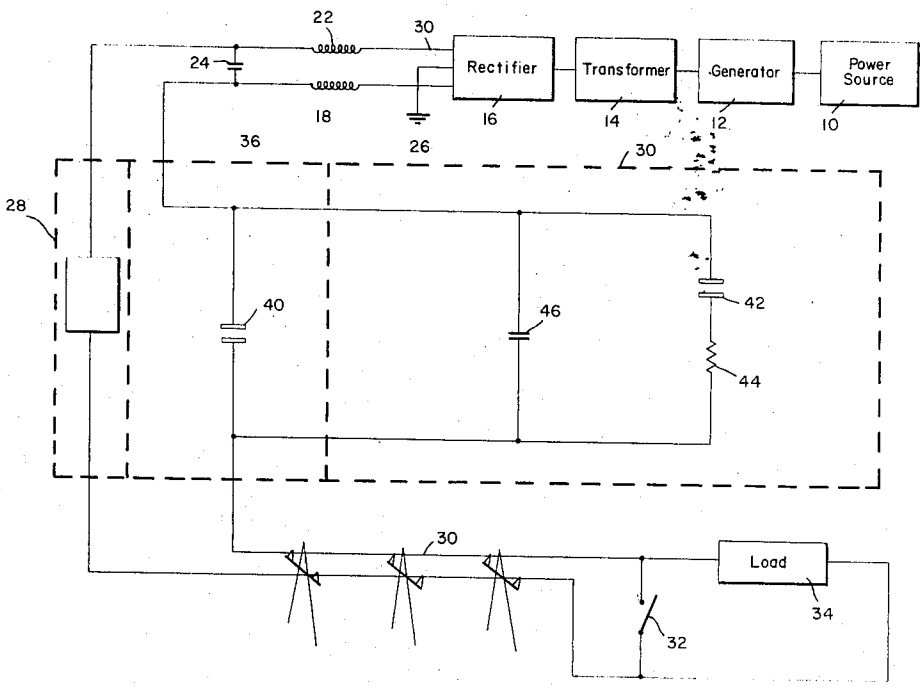
*Attorney*—W. H. MacAllister, Jr. and Allen A. Dicke, Jr.



[57] **ABSTRACT**

The high voltage DC circuit breaker must generate a variable impedance which increases gradually from negligibly small, when the breaker is closed, to infinitely large, after it has been opened. This invention describes a novel impedance-increasing method comprising serially connected resistance and switch means and a capacitor which shunts both. The switch means, which must be capable of opening and closing a high voltage, is programmed to rapidly switch on and off with increasing offtime so that the time averaged impedance of the DC circuit is increased to an offswitched condition.


**10 Claims, 9 Drawing Figures**



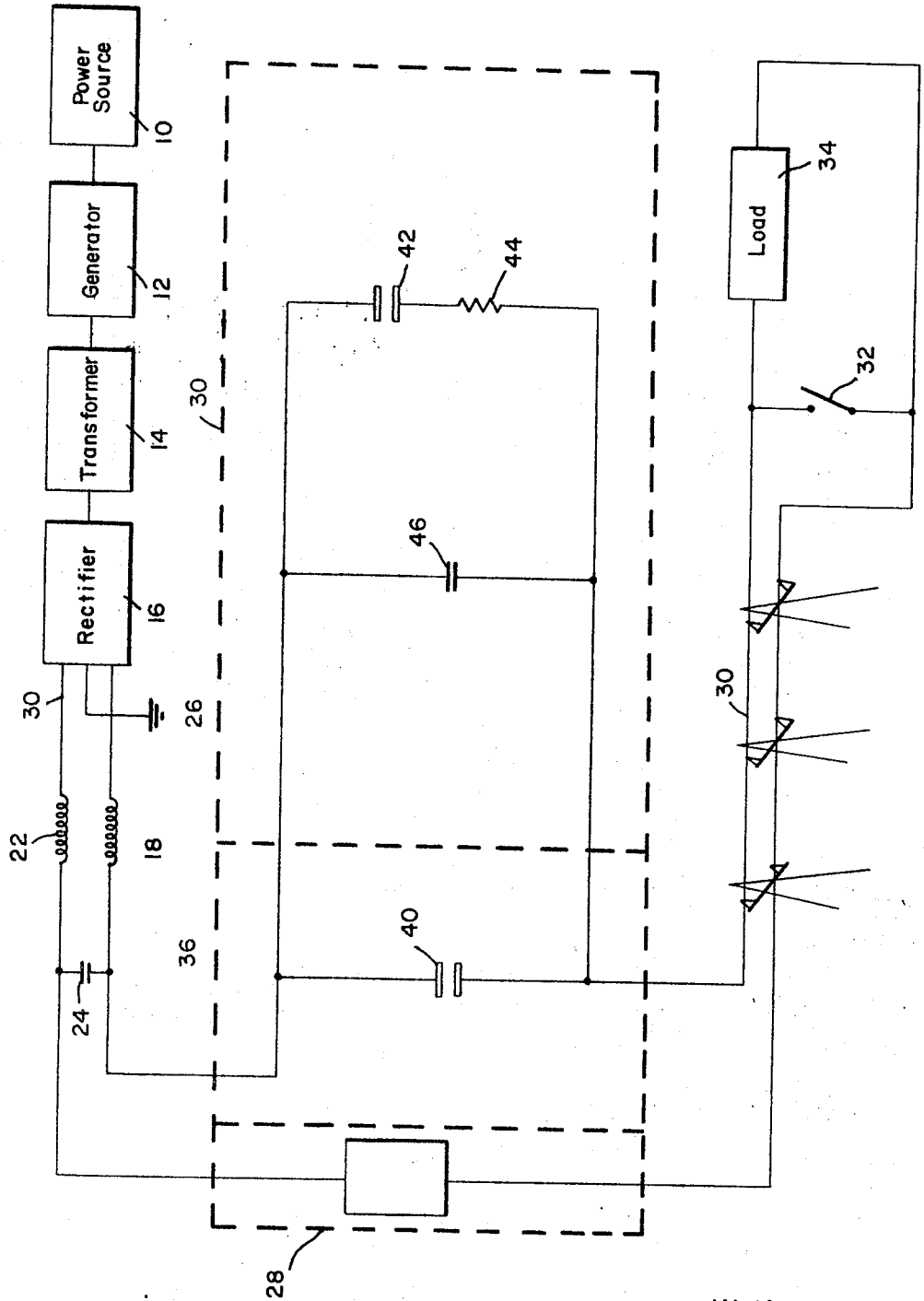



Fig. 1.

Wolfgang Knauer,
INVENTOR.
BY.
ALLEN A. DICKE, Jr.,
AGENT.

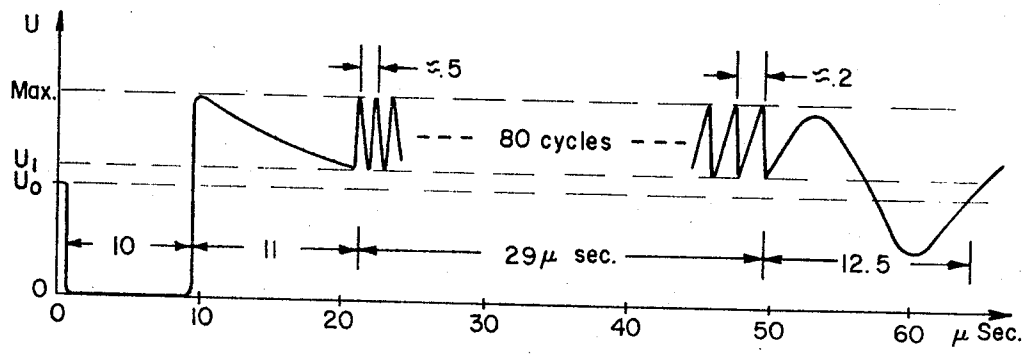



Fig. 2.

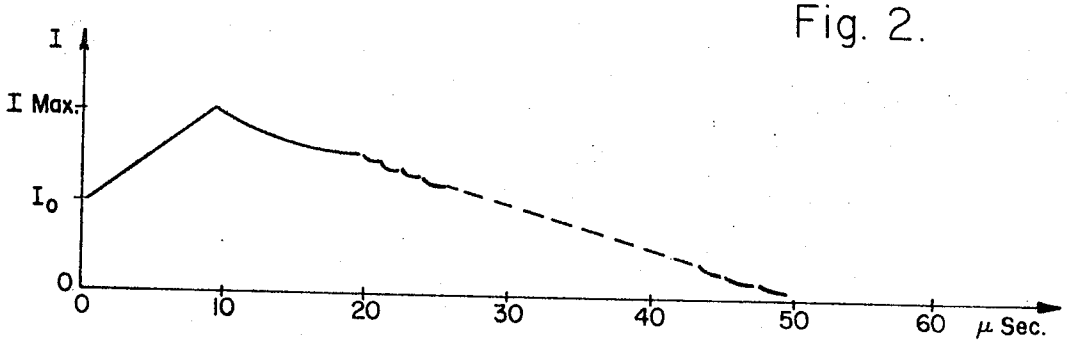



Fig. 3.

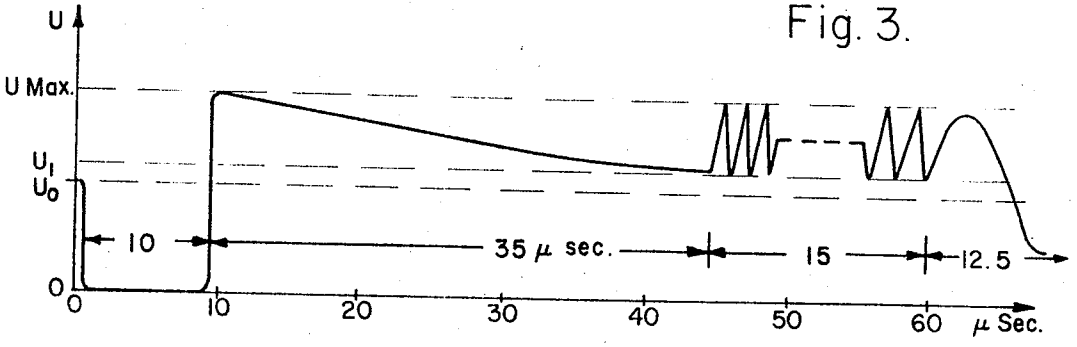



Fig. 4.

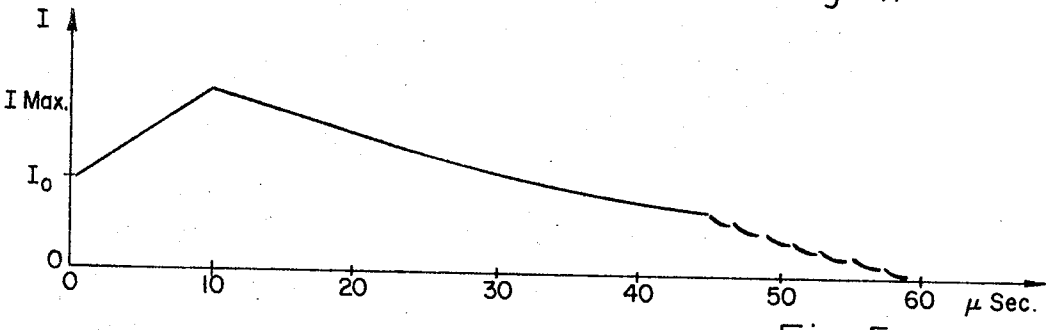



Fig. 5.

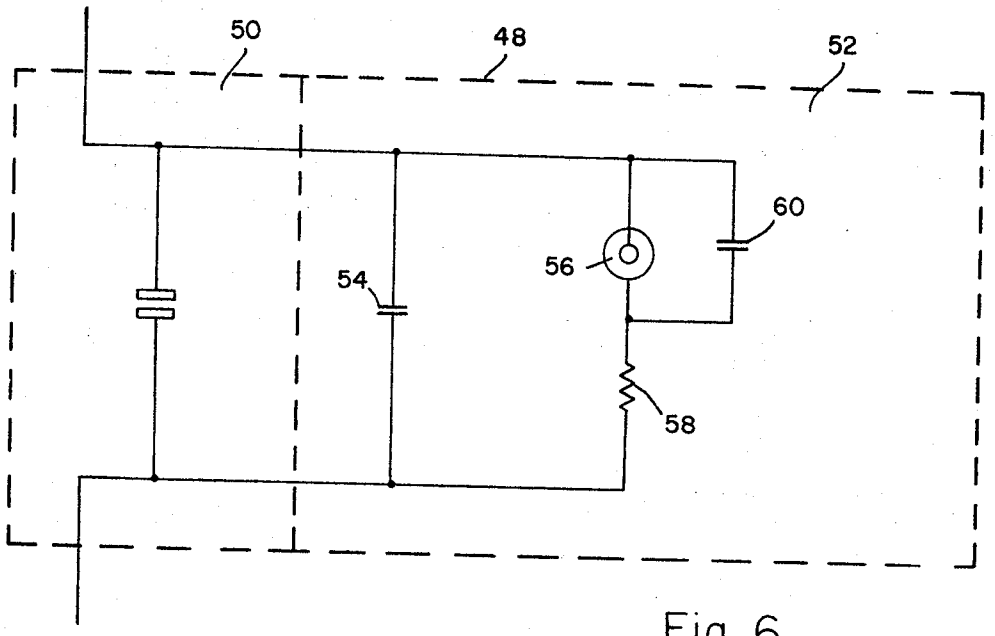



Fig. 6.

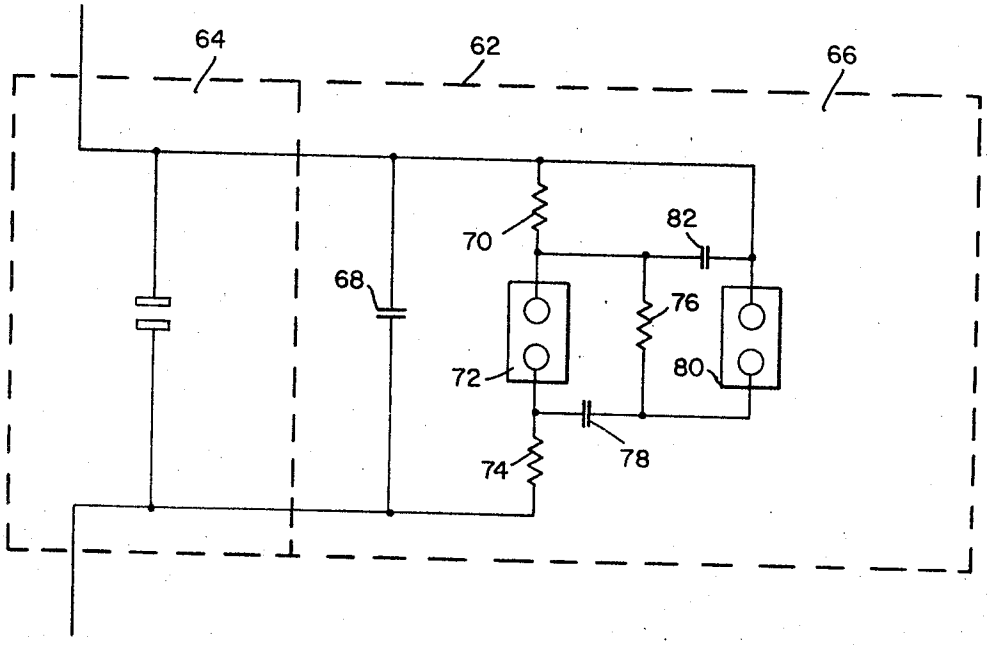



Fig. 7.

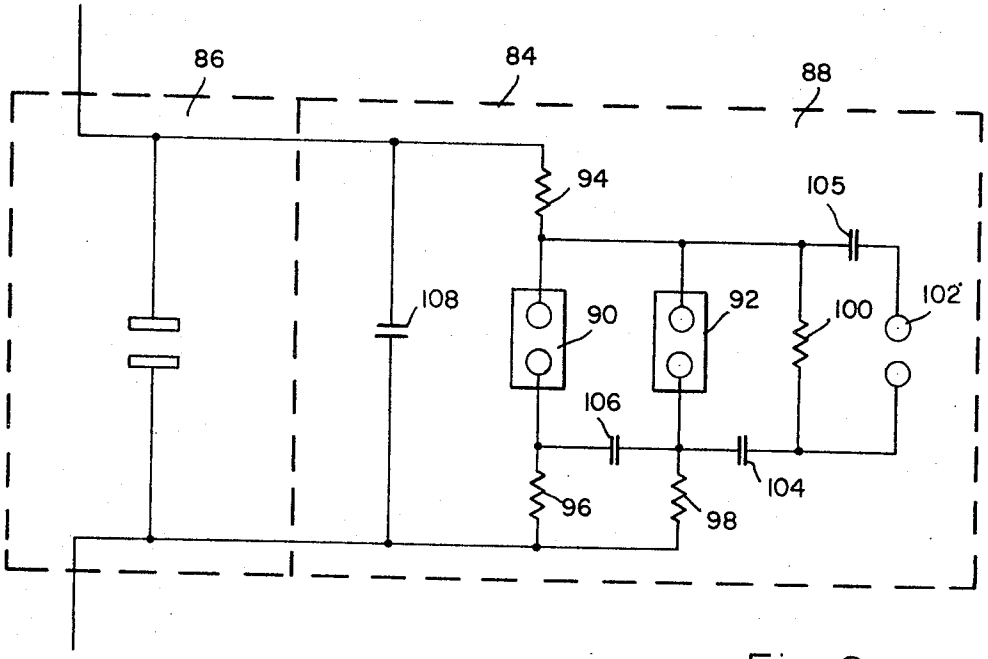

86
84
88
94
105
108
90
92
100
102
106
104
96
98

Fig. 8.

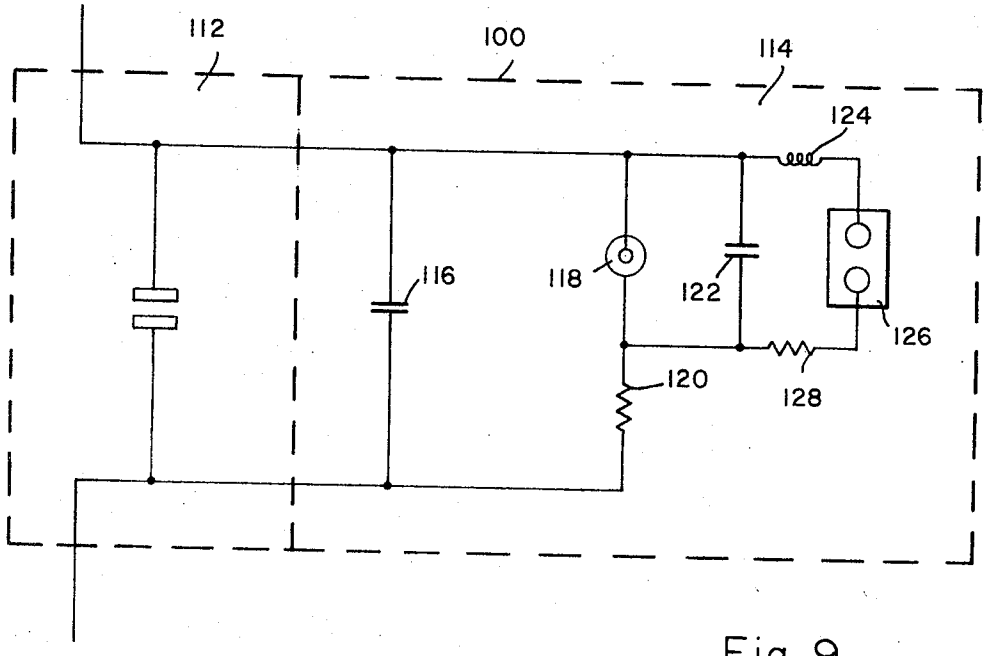

112
100
114
124
116
118
122
126
120
128

Fig. 9.

# IMPEDANCE-INCREASING METHOD AND APPARATUS AS PART OF A HVDC CIRCUIT BREAKER

## BACKGROUND

This invention is directed to an impedance-increasing method and apparatus of a high voltage DC circuit breaker which operates in conjunction with an in-line switch. To initiate offswitching, the in-line device which carries the normal current flow, is opened and the current flow is transferred to the impedance-increasing section of the circuit breaker.

The prior art includes Kenneth T. Lian U.S. Pat. No. 3,534,226, wherein it was first recognized that a high voltage DC circuit breaker may comprise an in-line device which carries normal circuit current when it is closed and thus presents low impedance to the current flow, and an impedance-increasing section to which the DC current is transferred from the in-line device as the in-line device becomes nonconductive. The impedance-increasing section can comprise several different characterizations of impedance-increasing circuitry. The above-mentioned Lian U.S. Pat. No. 3,534,266 teaches the increase of impedance by employing a plurality of resistors and a switch in connection with each of the resistors. The net circuit impedance is increased as the switches are successively opened. Thus, circuit impedance has a progressive net increase to finally permit cutoff of the current flow.

Both the Lian invention and this invention are capable of being used as AC offswitching circuit breakers. However, since alternating current has a natural current zero, the offswitching thereof is a less complex situation than found in DC circuitry. It would be useful to employ this invention only where it is desired that offswitching occur before the next current zero is attained.

Contrasted to the Lian patent, which utilizes a number of resistance and switch means in a timed sequence, this invention is directed to the repetitive resistance and employment of switch means which cyclically open and close with increasing nonconductive time so that the time averaged impedance progressively increases, together with a capacitor which receives the circuit current when the switch is open.

## SUMMARY

In order to aid in the understanding of this invention, it can be stated in essentially summary form that it is directed to an impedance-increasing method and apparatus as part of a high voltage DC circuit breaker. The impedance-increasing apparatus comprises switching means having a resistance device serially connected therewith and a shunt capacitor. The switching device is driven on and off with an increasing proportion of offswitched time so that the short time averaged circuit impedance is progressively increased to a point where full offswitching can be accomplished. During off-periods, the current passes into the capacitor, thus preventing excessive voltage buildup. The method comprises the utilization thereof.

Accordingly, it is an object of this invention to provide a DC circuit breaker for the offswitching of direct current circuits. It is a further object to provide a circuit breaker which employs a combination of in-line device and impedance-increasing device. It is still another object to provide an impedance-increasing device wherein a switch, resistance, and capacitor are connected so that cyclic operation of the switch with varying on/off switch time ratios provides an increasing line impedance. It is still another object to progressively increase the circuit impedance until the circuit current is decreased to zero and the circuit is fully opened.

Other objects and advantages of this invention will become apparent from a study of the following portion of the specification, the claims, and the attached drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic drawing of a high voltage DC circuit, showing one embodiment of the impedance-increasing method and apparatus as part of a high voltage DC circuit breaker therein.



FIG. 2 is a graph showing line voltage to ground versus time during a circuit breaker opening cycle, when the circuit breaker resistance is linear.

FIG. 3 is a graph showing line current versus time for the opening cycle of FIG. 2.

FIG. 4 is similar to FIG. 2, but showing the voltage curve with the employment of a non-linear resistor in the circuit of this invention.

FIG. 5 is a curve showing the line current versus time for the curve of FIG. 4.

FIG. 6 is a schematic diagram of a further circuit breaker, in accordance with this invention.

FIG. 7 is a schematic diagram of a further circuit breaker of this invention.

FIG. 8 is a schematic diagram of a further circuit breaker, in accordance with this invention.

FIG. 9 is a schematic diagram of a further circuit breaker, in accordance with this invention.

## DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, the DC power which is to be offswitched by the circuit breaker of this invention having an impedance-increasing means therein is conventionally derived at power source **10** which delivers power to AC generator **12**. Generator **12** delivers its output to transformer **14** by which the voltage is raised to suitable transmission line voltage. From the transformer, the power is rectified by rectifier **16**. Rectifier **16** has positive and negative output lines **18** and **20** respectively. Inductance **22**, connected in the lines and capacitance **24**, connected between the lines, serve as conventional DC filtering and smoothing equipment. They are preferably connected at the output of the rectifier, as shown. In certain circumstances, the reactance of the transmission system may be sufficient to provide adequate smoothing for economic power transmission.

Circuit breaker **26** is serially connected in line **18** between the rectifier **16** and transmission system **30**, while an identical circuit breaker **28** is connected in line **20** therebetween. Bipolar circuit breakers are thus provided, because of the high voltages in the exemplary embodiment of employment of the circuit breaker. In lower voltage systems, only one circuit breaker might be necessary.

In high voltage DC systems, it is customary to have a line potential such that one line is above ground potential, while the other is below. This equalizes the amount of transmission line insulation between the two lines and ground. Either one of the lines, through the transmission system or at the load, may fault to each other, as by exemplary fault switch **32**, or can fault to ground. Thus, independent line protection is necessary, as by breakers **26** and **28**.

Circuit breaker **26** comprises line switch means **36** and impedance-increasing means **38**. Line switch means **36** comprises switch **40** which is serially connected in power line **18** between rectifier **16** and the load **34**. Line switch means **36** is of such nature that, as it opens, sufficient voltage drop is generated thereacross to transfer the current from the low impedance path through normally closed switch **40** into the impedance-increasing means **38**. Different devices suitable for employment as switch **40** include conventional circuit breakers, of which Westinghouse Circuit Breaker Type 1150 SF 10000 is an example. This circuit breaker is rated for 115 KVRMS at 2,000 amperes continuous current. Two of such breakers in series would be suitable as a switch in the 200 KV example given below. A vacuum relay, such as Allis Chalmers part No. VSC–15, can serve as switch **40**, provided that it is equipped with circuitry which induces an artificial current zero so that the metal arc therein is permitted to deionize. A particular current transfer circuit of this nature is disclosed in Michael A. Lutz and Willis F. Long patent application, entitled "Current Transfer Circuit As Part of High Voltage DC Circuit Breaker," filed concurrently herewith, Ser. No. 122,395. The entire disclosure of that application is incorporated herein by this reference.

In any event, the line switch means **36** is conductive during normal conduction so as to provide for a very low impedance normal conduction path. Upon fault detection, or for voluntary circuit opening, switch **40** is opened and the current flowing therethrough is transferred to the impedance-increasing means **38**, which is thereafter actuated to increase the circuit impedance between the source and the load to ultimately cut off the circuit continuity.

FIG. **1** illustrates a simple impedance-increasing means **38** to show the most simple form of the method and apparatus of this invention. Cyclic switch **42** is serially connected to energy-absorbing resistance **44**. It is understood that, as cyclic switch **42** is opened and closed, with an increasing ratio of open time to closed time, the time averaged impedance of these circuits increases. In order to receive the current during offswitch time and limit surges, smoothing capacitor **46** is paralleled around cyclic switch **42** and its energy-absorbing resistor **44**.

The mathematical relationship between the various circuit components can be readily computed, using the impedance-increasing circuit **38** of FIG. **1** as a model.

At first, the optimum time dependence for the effective impedance of a circuit breaker is derived. Assume that the transmission line has the inductance $L$, operates at normal line voltage $U_o$ and ordinarily carries normal maximum current $I_o$. It is insulated for maximum voltage $U_{max}=f\cdot U_o$ where f is greater than 1, and can tolerate a maximum short circuit current $I_{max}$. If a sudden short circuit develops, the current varies with time as

$$I=I_o+\frac{U_o}{L}t$$

Thus, offswitching must be initiated not later than at time $t_{max}$

$$t_{\max}=(I_{\max}-I_o)\frac{L}{U_o}$$

The maximum resistance which can be inserted at time $t_{max}$ is given by

$$R_o=\frac{U_{\max}}{I_{\max}}$$

If a resistance larger than $R_o$ is used, the voltage will rise above the insulation level of the line; with a smaller $R$, the voltage will remain below $U_{max}$. In the latter case, the short circuit current decreases at a rate slower than with $R_o$, as follows: from

$$\frac{dI}{dt}=\frac{U-U_o}{L}$$

Accordingly, the shortest offswitching time $t_{min}$ is obtained with $U=U_{max}$. This time $t_{min}$ is given by

$$t_{\min}=\frac{I_{\max}}{U_o}\frac{L}{f-1}$$

It is evident that, during offswitching, the load impedance must increase with time in order that the voltage can be kept constant at $U_{max}$. With the help of several of the above relations, the resistance can be computed to vary as

$$R=\frac{R_o}{1-\frac{f-1}{f}\frac{R_o}{L}t}$$

Thus, for $t=t_{min}$, the resistance $R$ goes to infinity, as must be the case for a totally disrupted circuit. It is concluded that, for circuit breakers which offswitch in minimum time and which therefore pass the minimum energy, the design objective should be to reach a temporal dependence of $R$ equivalent to that given by the last equation.

Control means for the cyclic switch **42** is provided to switch it substantially in the time dependance given in the above equation. FIGS. **2** and **3** show a representative switching sequence for the circuit shown in FIG. **1**. The numerical values chosen for this example are: line inductance $L=2$ Henry, operating voltage $U_o=200$ KV, operating current $I_o=1{,}000$ amperes, over-voltage factor $F=1.7$, maximum short circuit current $I_{max}=2{,}000$ amperes. The parameters of the switch circuit are: the impedance of resistance **44** $R_o=170$ ohms. Similarly, capacitance C of the capacitor **46** equals 2 microfarads. The curves of FIG. **2** represent the voltage in line **18** at the output of rectifier **16** with respect to ground. FIG. **3** represents the current in line **18** at the output of the rectifier. At zero time in these curves, the voltage and current are normal at full load. At about 1 millisecond, the fault occurs and, between 1 millisecond and 10 milliseconds, the current is transferred from the line switch means **36** into the impedance-increasing means **38**, and line switch **40** is opened and deionized. The switching sequence of these figures was arbitrarily timed to let the voltage drop to $1/e$ of the over-voltage $U_{max}$ minus $U_o$ during each cycle. The first drop in voltage to about 21 milliseconds has a shallower slope than subsequent switching cycles because the line current still has a large value and thereby keeps the capacitor **46** charged. From about 21 milliseconds, for the next 29 milliseconds, cyclic switch **42** is cycled so that the voltage varies between $U_{max}$ and $U_1$. At the beginning of this period, the cycle period is about 0.5 milliseconds and at the end, is about 2 milliseconds. There are about 80 cycles of cyclic switch **42** in this 29 millisecond cycling period. Finally, at 50 milliseconds, cyclic switch **42** can be opened without the surge voltage exceeding $U_{max}$, so that the circuit breaker is finally opened. FIG. **3** illustrates the progressive decrease in current with the progressively increasing time averaged impedance provided by cyclic switch **42** and its energy-absorbing resistor **44**.

It has been shown above that, if the load impedance increases with time, so that the voltage is kept constant at $U_{max}$, the cyclic offswitching time is decreased. Thus, when a current-dependent resistor, for example a "thyrite" is employed as the resistor **44** and the value thereof is about $R=CI^{-3}$, fewer switching cycles and a shorter switching time is obtained. This is illustrated in FIGS. **4** and **5**, which represent the offswitching of the circuit of FIG. **1** when resistance **44** is a current-dependent resistor of the value noted above. In FIGS. **4** and **5**, it takes 35 milliseconds from the initial closure of cyclic switch **42** for the current and voltage to drop so that $U_1$ is reached. Thereafter, only about 15 cycles of the cyclic switch **42** are required to bring the current down so that cyclic switch **42** can be permanently opened without circuit overvoltage.

The circuit breaker **26** of FIG. **1** is a fairly simplified device which illustrates the theory of operation. Going now to various embodiments of circuit breakers which are operated in accordance with these teachings, FIG. **6** illustrates circuit breaker **48** which comprises line switch means **50** and impedance-increasing means **52**. The line switch means **50** is identical to line switch means **36** and the impedance-increasing means is similar in that it comprises a capacitor **54** across the circuit to be opened, which is paralleled by switch **56**, which has resistor **58** in series therewith. The resistor **58** corresponds to resistor **44**, and either may be linear or nonlinear, as previously indicated. The preferred switch in this embodiment is a crossed field tube. The offswitching of the crossed field tube **56** against rising high voltages requires a parallel capacitor **60**, which limits the rate of voltage rise to about 2 kilovolts per microsecond. For interruption of 2,000 amperes, suitable numerical values for the circuit of FIG. **6** are as follows. Capacitor **54** is 2 microfarads, capacitor **60** is 1 microfarad, and resistor **58** is 170 ohms. The crossed field tube **56** is basically an offswitch and is disclosed in more detail in the above-mentioned Lian U.S. Pat. No. 3,534,226. It can be turned on with the proper magnetic field and a high voltage applied together with a suitable triggering method, such as the use of a plasma gun into the inter-electrode space. Details of this onswitching are disclosed in patent application Ser. No. 122,397, filed by Gunter A. G. Hofmann concurrently herewith, and entitled "Method and Apparatus for Ignition of Crossed Field Switching Device for Use in a HVDC Circuit Breaker", the entire disclosure of which is incorporated

herein by this reference. The crossed field tube described above has among its antecedents those described in Penning U.S. Pat. No. 2,182,736; Boucher U.S. Pat. Nos. 3,215,893 and 3,215,939; and Wasa U.S. Pat. No. 3,405,300.

Another embodiment of the circuit breaker, in accordance with this invention, is illustrated in FIG. 7, wherein the circuit breaker is identified at **62**. Circuit breaker **62** comprises line switch means **64**, which is identical to line switch means **36**, and impedance-increasing means **66**.

Impedance-increasing means **66** has capacitor **68** paralleled across the line switch, to control the rate of voltage rise, as described above. Also connected between the lines, or in the circuit of the circuit breaker, is a series combination of resistor **70**, triggered vacuum gap **72**, and resistor **74**. Paralleled around triggered vacuum gap **72** is a series combination of resistance **76** and capacitor **78**. Triggered vacuum gap **80** is connected to the breaker input line and to the capacitor **78**. Capacitor **82** is connected between the breaker input line and triggered gap **72**.

The triggered vacuum gaps **72** and **80** are of the nature described in Lafferty U.S. Pat. No. 3,290,542. Such a triggered vacuum gap is basically an onswitch. In conduction, they operate in a metal arc mode with a fairly low (50 volt) voltage drop. In order to turn them off, one must force the current to zero. One of the ways in which forced commutation can be accomplished is by the circuit shown in FIG. 7, in association with the triggered vacuum gaps. Triggered vacuum gap **72** is the main switch which must be periodically opened and closed. Assuming that triggered vacuum gap **72** is conductive, then the current passing through resistor **70** charges capacitor **82**. Now, if triggered vacuum gap **80** is made conductive, a negative voltage pulse is transmitted through capacitor **78** to the other pole of triggered gap **72**. This forces the current to zero and triggered gap **72** deionizes and becomes nonconductive. Triggered tap **80** continues to conduct, since the charging current of capacitor **78** passes through it. If triggered gap **72** is fired again, the plus pole of triggered gap **80** is pulsed negatively via the charged capacitor **78**. Thus, triggered gap **80** extinguishes and the next cycle can begin. It must be noted that only triggered gap **72** must withstand the maximum circuit voltage. Triggered gap **80** can have a relatively low voltage rating. Thus, impedance-increasing means **66** can be cycled to obtain a progressively increasing time average impedance into the circuit breaker circuit.

Suitable component values for the circuit of FIG. **7** are as follows: capacitor **68**, 2 microfarads; capacitor **78**, 1 microfarad; and capacitor **82** is 10 microfarads and can be of low voltage. Furthermore, resistance **74** is 170 ohms, resistance **70** is 10 ohms, and resistance **76** is 10 ohms.

FIG. **8** illustrates the circuit breaker **84** which comprises line switch means **86** and impedance-increasing means **88**. The line switch means **86** is identical to line switch means **36**. The impedance-increasing means is arranged to cyclically insert resistance into the circuit breaker circuit so that the time averaged impedance progressively increases to previous current flow. The impedance-increasing means **88** is another circuit with a triggered vacuum gap. Here, triggered gaps **90** and **92**, identical to triggered gaps **72** and **80**, are connected through resistance **94** to one line and are respectively connected through resistances **96** and **98** to the other line.

Resistance **100** is connected in parallel to spark gap **102** to one line of the circuit breaker and, on the other end, they are both connected through capacitor **104** to the bottom of triggered gap **92**. Additionally, the bottoms of these two triggered vacuum gaps **90** and **92** are connected together through capacitor **106**. Again, capacitor **108** is connected between the lines to control the rate of voltage rise.

In FIG. **8**, the two triggered vacuum gaps **90** and **92** alternately carry the current. Assuming that triggered vacuum gap **90** is initially conductive and triggered vacuum gap **92** is nonconductive, then capacitor **106** charges. Now, if triggered vacuum gap **92** is made conductive, capacitor **106** pulses triggered vacuum gap **90** to force commutate zero current therein. This causes deionization and nonconduction of triggered vacuum gap **90**. Now, capacitor **106** charges in the opposite direction. Thus, by alternate triggering, the other triggered vacuum gap is force commutated. When line current has sufficiently decreased, triggered vacuum gap **92** can be force commutated to become nonconductive (while triggered vacuum gap **90** is already nonconductive) by the firing of the triggered spark gap **102**.

In this circuit, both triggered vacuum gap devices **90** and **92** must have full voltage ratings, but only triggered vacuum gap **90** must be able to handle full current. Triggered vacuum gap **92** can be rated for currents about 1 order of magnitude smaller. Triggered spark gap **102** can be designed for comparatively small voltages.

Suitable values for the components shown in FIG. **8** are as follows. Capacitor **108** is 2 microfarads, capacitor **106** is 1 microfarad, capacitor **104** is 1 microfarad, capacitor **105** is 10 microfarads (at low voltage). Resistance **96** is 170 ohms, resistance **98** is 2,000 ohms, and resistances **94** and **100** are each 10 ohms.

FIG. **9** illustrates circuit breaker **110** which has a line switch means **112** and an impedance-increasing means **114**. The line switch means **112** is identical to the line switch means **36**. The impedance-increasing means **114** combines a triggered vacuum gap and a crossed field tube. Capacitor **116** is connected across the lines of the circuit breaker to control rate of voltage rise. Crossed field tube **118** and energy-absorbing resistor **120** are serially connected and they are connected between the lines of the circuit breaker. A crossed field tube **118** with ordinary ignition characteristics, without a plasma trigger, can be employed. Paralleled around the crossed field tube is capacitor **122**. Paralleled around capacitor **122** is a series combination of inductance **124**, triggered vacuum gap **126**, and resistance **128**.

The crossed field tube **118**, without plasma trigger, is of such nature that it becomes conductive only if a relatively low voltage is applied to its electrodes, in the presence of the necessary magnetic field. Assuming that the crossed field tube **118** is initially noncondutive, then capacitor **122** is charged. Now, the triggered vacuum gap **126** is fired and a damped oscillation is initiated in the resonant circuit constituted by capacitor **122**, inductance **124**, and resistance **128**. At the first current zero, the triggered vacuum gap **126** extinguishes. At this time, capacitor **122** is charged in the reverse direction. However, current passing through resistor **120** tends to restore the original charge. As the capacitor voltage passes through zero, the crossed field tube ignites, when the magnetic field is appropriately on. After a period of conduction, the crossed field tube **118** can be offswitched and a new cycle begins.

In FIG. **9**, suitable values of the components are: capacitor **116**, 2 microfarads; capacitor **122**, 1 microfarad; resistance **120**, 170 ohms; and resistance **128**, 10 ohms. Additionally, inductance **124** is $10^{-3}$ Henrys.

This invention having been described in its preferred embodiment, it is clear that is 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.

What is claimed is:

**1**. A high voltage DC circuit breaker, said circuit breaker comprising a line switch and an impedance-increasing means connected in parallel to said line switch so that, when said line switch is opened, current is transferred to said impedance-increasing means, the improvement comprising:

said impedance-increasing means comprising a cyclically operable switch and an energy-absorbing resistor in series with said cyclically operable switch and means to operate said cyclically operable switch, a rate of voltage rise limiting capacitor connected in parallel to said series combination of said cyclically operable switch and said energy-absorbing resistor, so that the time averaged impedance of said impedance-increasing means increases as

said cyclically operable switch is operated to have an increasing ratio of offswitch time.

2. The circuit breaker of claim 1 wherein said cyclically operable switch is a crossed field switch device.

3. The circuit breaker of claim 2 wherein a rate of voltage rise limiting capacitor is connected in parallel to said crossed field switching device.

4. The circuit breaker of claim 3 wherein a triggered gap switching device has reactance means in series therewith, said triggered gap switching device and said reactance means being connected in parallel to said capacitor in parallel to said crossed field switching device so that onswitching of said triggered gap causes resonant pulsing of said crossed field switching device.

5. The circuit breaker of claim 1 wherein said switch means comprises a triggered vacuum gap switch device having said energy-absorbing resistance in series therewith.

6. The circuit breaker of claim 5 wherein there are first and second triggered vacuum gap switch devices connected in parallel to each other through reactance means so that said second triggered vacuum gap switch device induces a current zero in said first triggered vacuum gap switch device.

7. The circuit breaker of claim 6 wherein said reactance means comprises capacitive means connected between said first and second triggered vacuum gap switch devices so that said capacitive means is charged by voltage drop in said circuit breaker and said charge on said capacitive means is discharged through one of said triggered vacuum gap switch devices to impress a current zero on the other of said triggered vacuum gap switch devices.

8. The process for increasing the impedance in a high voltage DC circuit breaker comprising the steps of:

cyclically opening and closing a switch having a resistance in series therewith, through which switch and resistance pass the current in the circuit breaker to be interrupted, with increasing ratio of switch open time to switch closed time; and

reactively damping current flow through the switch and the resistance to limit rate of voltage rise upon opening of the switch.

9. The process of claim 8 wherein said reactively limiting step comprises the step of capacitively limiting rate of voltage rise.

10. The process of claim 9 wherein closing is accomplished by the step of causing an electric discharge between spaced electrodes and switch opening is accomplished by the step of terminating the electric discharge between the spaced electrodes.

* * * * *