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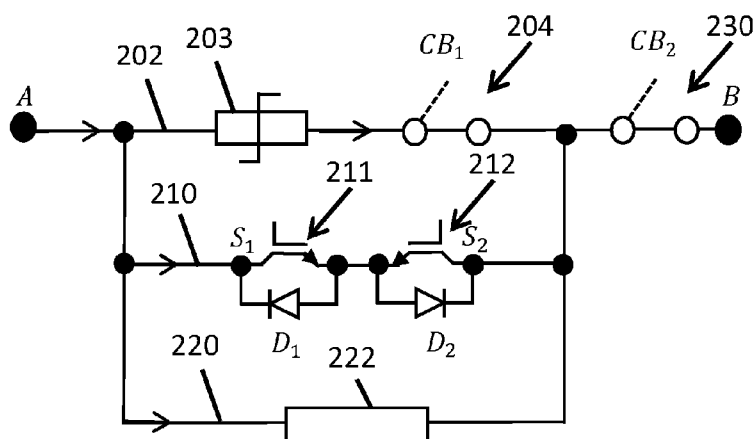
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- (54) **Title:** APPARATUS AND METHOD FOR CONTROLLING A DC CURRENT



(57) **Abstract:** A circuit breaker and method of controlling Direct Current is disclosed. The circuit breaker has a primary conduction path comprising a positive temperature coefficient (PTC) device with a positive temperature coefficient of resistance and a mechanical switch is connected in series with the PTC device. There is a secondary conduction path with a semiconductor switch arranged in parallel with the PTC device. The PTC device is arranged to commutate current to the secondary conduction path in response to an increase in current through the primary conduction path. The semiconductor switch device is controllable to break current flow through the secondary conduction path.

FIGURE 2

APPARATUS AND METHOD FOR CONTROLLING A DC CURRENT

[0001] This invention relates to a circuit breaker and method of controlling Direct Current (DC).

BACKGROUND

5 **[0002]** A circuit breaker makes and interrupts both load and fault currents, unlike other forms of switchgear which are not designed to interrupt fault current. In the closed position, circuit breakers provide a passage for load current, whereas in the open position they provide electrical isolation. In the event of a fault, the circuit breaker must be capable of interrupting a fault current which is in excess of the load current. Current DC circuit
10 breakers can be classified as resonant circuit breakers, a solid-state circuit breakers or hybrid circuit breakers. DC resonant circuit breakers inherently have a mechanical switch contact breaker with a relatively slow reaction time. In contrast, DC solid-state circuit breakers have one or more semiconductor switches and do not necessarily require a mechanical switch contact breaker. Consequently, solid-state circuit breakers have a
15 relatively rapid reaction time. DC Hybrid circuit breakers comprise three conduction paths connected in parallel. One of the paths includes a mechanical switch contact breaker, a second path includes one or more semiconductor switches and a third path includes a surge arrestor device.

[0003] Current hybrid circuit breakers have a relatively long circuit breaking reaction
20 time and solid state circuit breakers have relatively large steady state losses compared to some hybrid circuit breakers. However, although hybrid circuit breakers have a relatively fast breaking reaction time, with low steady state losses, their cost and size may be relatively high due to external control requirements and additional high power rated circuit components.

25 **[0004]** It is an object of embodiments of the invention to at least mitigate one or more of the problems associated with prior art DC circuit breakers.

BRIEF SUMMARY OF THE DISCLOSURE

[0005] In accordance with an embodiment of the present inventions there is provided a DC circuit breaker comprising: a primary conduction path comprising a positive
30 temperature coefficient (PTC) device, having a positive temperature coefficient of resistance, a mechanical switch member connected in series with the PTC device, the mechanical switch member configured to provide a low impedance path in a first configuration and a high impedance path in a second configuration; and a secondary

conduction path arranged in parallel with at least the PTC device of the primary conduction path, the secondary conduction path comprising at least one semiconductor switching device, wherein the PTC device is arranged to commutate current to the secondary conduction path in response to an increase in current through the primary conduction path;
5 and wherein the at least one semiconductor switching device of the secondary conduction path is controllable to break current flow through the secondary conduction path.

[0006] In accordance with another embodiment of the present inventions there is provided a method of controlling a DC current, comprising: a first conduction path for the DC current through a positive temperature coefficient (PTC) device having a positive
10 temperature coefficient of resistance and a mechanical switch member connected in series with the PTC device; commutating the DC current to a secondary conduction path comprising at least one semiconductor switching device by the PTC device in response to an increase in the current through the primary conduction path; and controlling the at least
15 one semiconductor switching device to break the current through the secondary conduction path.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Embodiments of the invention will now be described by way of example only, with reference to the accompanying figures, in which:

[0008] Figure 1 is a schematic block diagram of a DC circuit breaker according to a
20 general embodiment of the invention;

[0009] Figures 2 to 5 are schematic circuit diagrams of DC circuit breakers according to embodiments of the invention;

[0010] Figure 6 is a schematic circuit diagram of a circuit breaker system according to an embodiment of the invention;

25 **[0011]** Figures 7A to 7D and 8A to 8C are schematic circuit diagrams of DC circuit breaker commutating elements according to further embodiments of the invention;

[0012] Figures 9 to 14 schematic circuit diagrams of further DC circuit breakers according to embodiments of the invention;

30 **[0013]** Figure 15 is a schematic circuit diagram of a modular DC circuit breaker according to an embodiment of the invention; and

[0014] Figure 16 a flow chart illustrating a method of controlling a DC current according to an embodiment of the invention.

DETAILED DESCRIPTION

[0015] Embodiments of the present invention provide a hybrid circuit breaker capable of rapidly interrupting a DC fault current without generation of an electrical arc.

[0016] Figure 1 is a schematic block diagram outline illustration of a high power DC circuit breaker 100 according to a general embodiment of the present invention. The circuit breaker 100 is arranged to be connected to a high voltage line 102 carrying a DC current 110, and having an inherent inductance. The DC circuit breaker 100 consists of three potential conduction paths connected in parallel; a primary conduction path 106, a secondary conduction path 108, and an energy absorbing conduction path 104.

[0017] In normal operation, the line current 110 flows through the primary conduction path 106, which presents a low impedance path through the circuit breaker for the line current 110. As will be explained, the primary conduction path 106, changes to a high impedance path without the need for an external control signal. This change in impedance commutates the line current 110 from the primary conduction path 106 to the secondary conduction path 108. As the circuit breaker acts to interrupt a fault current, the voltage across the circuit breaker will rise until the voltage across the energy absorbing path 104 exceeds a pre-determined level, at which point the energy absorbing path 104 begins to conduct a surge current, thereby absorbing energy from the high voltage line 102.

[0018] An example secondary conduction path 108 in accordance with embodiments of the invention consists of a semi-conductor member with turn-off capability. The semi-conductor member provides a relatively low impedance path conditions or a high impedance path depending on the state of a control signal. The low impedance is greater than the impedance of the primary conduction path at a normal (without fault) line current. The semi-conductor member may contain one or more semiconductor switches with turn-off capability of any suitable type, for example gate turn-off (GTO) thyristors, insulated gate bipolar transistors (IGBT) or integrated gate commutated thyristors (IGCT). The semi-conductor switches may be connected in series and/or parallel and/or anti-parallel. The semiconductors may also have appropriate circuitry to evenly share the voltage across each device and snubber circuits to reduce losses.

[0019] The primary conduction path 106 comprises a device having a positive temperature coefficient (PTC) of resistance. The device may comprise one or more PTC

elements, whose resistance increases when the line current 110 exceeds a predetermined "normal" current.

5 **[0020]** The primary conduction path 106 comprises a mechanical switch member which provides a low impedance path in the closed position, and blocks the majority of the voltage across the primary conduction path 106 in the open position. The mechanical switch member contains one or more mechanical breakers connected in series and/or parallel, which can withstand the maximum permissible voltage which may occur across the mechanical switch member.

10 **[0021]** The function of the energy absorbing conduction path 104 is to limit the voltage across the secondary conduction path 108 to a pre-determined maximum level and de-energize part of the transmission system. The energy absorbing conduction path 104 contains one or more individual devices (e.g. varistors), which may be connected in series and/or parallel. In some embodiments, the secondary conduction path 108 and the energy absorbing conduction path 104 may be configured so that a varistor is coupled across
15 each semi-conductor switch in the secondary conduction path 108 or a varistor is coupled in parallel to a number of semi-conductor switches.

20 **[0022]** In operation, secondary conduction path 108 may be duly controlled to be in a low conduction state before, during or after the positive temperature coefficient (PTC) of resistance of the primary conduction path 106 increases during the presence of a current surge. Upon occurrence of a fault in the HVDC transmission system, the increase in current through the primary conduction path causes the resistance of the PTC device to increase which commutates the current to the secondary conduction path 108 which now provides a lower impedance path than the primary conduction path 106.

25 **[0023]** Once the line current 110 has been commutated to the secondary conduction path 108, there will be substantially lower current flowing through the mechanical switch member and the contacts of the mechanical switch member may be separated without generating an electrical arc. The secondary conduction path 108 may then be controlled to turn off the current through the circuit breaker 100.

30 **[0024]** In other embodiments, as will be explained, the secondary conduction path is arranged in parallel across only the PTC device and the semiconductor device(s) of the secondary conduction path are controlled to reduce the current 110 flow prior to opening the mechanical switch member, as will be explained.

[0025] The main advantage of this circuit breaker is the improved operating time compared to other hybrid circuit breaker designs. For High Voltage Direct Current (HVDC) applications very fast operating times are required due to the very rapid rise of fault current. In principle, faster designs may also result in significant smaller breakers, due to the reduced current carrying requirements. As many of the breakers will also be on offshore platforms, any reduction in size and weight will have extra effects on reducing the costs.

[0026] The passive nature of the commutation method means that the operation time will be reduced, as the commutation will occur without a specific active detection requirement.

[0027] If the PTC is a superconducting element, then this will also perform the commutation faster than any semi-conductive switch equivalent circuit breaker. This will also decrease the operating time of the breaker.

[0028] On state losses are also significantly reduced compared to semi-conductive circuit breakers. This is due to the lack of semi-conductors exposed to normal current flow and the low resistance of the positive temperature coefficient element.

[0029] Negligible arcing takes place in any of the mechanical devices, which results in less damage to the mechanical switches. The fact that no arc forms also means that the mechanical breakers do not need to be made using hazardous gases such as sulphur hexafluoride, which removes the environmental concern of the gas leaking.

[0030] The passive nature of the commutation also means that this breaker is more robust and is not affected by as many internal faults as other designs, which require active measurement and control to perform the commutation.

[0031] Figure 2 is a schematic block diagram of a DC circuit breaker 200 according to an embodiment of the invention. The circuit breaker 200 has a primary conduction path 202 comprising a positive temperature coefficient (PTC) device 203 (also referred to as a commutating element) having a positive temperature coefficient of resistance. The primary conduction path also has a mechanical switch member (CB₁) 204, connected in series with the PTC device 203. The mechanical switch member 204 is typically an isolating electromagnetically actuated switch; however other switching mechanisms may be used. The mechanical switch member 204 is configured to provide a low impedance path in a first configuration (closed contacts) and a high impedance path in a second configuration (open contacts).

[0032] There is a secondary conduction path 210 arranged in parallel with at least the PTC device 203 of the primary conduction path 202. The secondary conduction path 210 comprises semiconductor switching devices, which in this embodiment are a first IGBT (S_1) 211 with a parallel connected reversed biased diode D_1 , and a second IGBT (S_2) 212 with a parallel connected forward biased diode D_2 . Also, when a current flows in the direction as illustrated, with suitable gating the secondary conduction path 210 may allow for DC current flow through the first IGBT 211 and forward biased diode D_2 . Alternatively, if current flow is in the opposite direction to that illustrated, with suitable gating the secondary conduction path 210 may allow for DC current flow through the second IGBT 212 and diode D_1 .

[0033] There is also an energy absorption branch 220, in parallel with the primary conduction path 202 and the secondary conduction path 210. This energy absorption branch 220 includes a varistor 222 coupled across the secondary conduction path 210. The DC circuit breaker 200 also includes another mechanical switch member (CB_2) 230 that may be used for power supply isolation as will be apparent to a person skilled in the art. Hence, mechanical switch member (CB_2) 230 provides additional isolation and breaks any leakage current that flows from paths 202, 210 and 220.

[0034] During normal (fault-free) operation the secondary conduction path 210 is turned on. However, the majority of current flows through the primary conduction path 202 since the PTC device 203 and the mechanical switch member (CB_1) 204 have a lower resistance than the semiconductor devices of the secondary conduction path 210.

[0035] When a fault occurs in a load fed through the circuit breaker 200, the load current starts to rise. This increase in current heats the PTC device 203 thereby increasing its resistance dramatically. This increase in resistance causes the current to commutate into the secondary conduction path 210 and current flows through the first IGBT 211 and diode D_2 . During this transition the voltage across the PTC device 203 is limited (clamped) by the first IGBT 211 and diode D_2 .

[0036] Once the current has fallen to zero or sufficiently reduced within the mechanical switch member (CB_1) 204, it can be opened without causing arcing across its contacts. Once the mechanical switch member (CB_1) 204 is fully open, the secondary conduction path 210 can be turned off. The line energy is dissipated within varistor 222, which also limits the transient recovery voltage. The mechanical switch member (CB_1) 230 can then be opened and used to break any residual current and provide full isolation. In this embodiment, as with all other embodiment in this disclosure, there is a controller coupled to each control gate (or base) of the semiconductor devices which in this embodiment are

the first IGBT 211 and second IGBT 212. Such a controller also controls the opening and closing of the mechanical switch member (CB_2) and the controller monitors the current flow in the circuit breaker circuitry by detecting changes in voltage across the PTC device 203.

[0037] Figure 3 is a schematic block diagram of a DC circuit breaker 300 according to an embodiment of the invention. The circuit breaker 300 has a primary conduction path 302 comprising a positive temperature coefficient (PTC) device 303 (also referred to as a commutating element), having a positive temperature coefficient of resistance. There is a secondary conduction path 310 is arranged in parallel with at least the PTC device 303 of the primary conduction path 302. The secondary conduction path 310 comprises semiconductor switching devices, which in this embodiment are a first IGBT (S_1) 311 with a parallel connected reversed biased diode D_1 , and a second IGBT (S_2) 312 with a parallel connected forward biased diode D_2 . Also, when a current flows in the direction as illustrated, with suitable gating the secondary conduction path 310 may allow for DC current flow through the first IGBT 311 and forward biased diode D_2 . Alternatively, if current flow is in the opposite direction to that illustrated, with suitable gating the secondary conduction path 310 may allow for DC current flow through the second IGBT 312 and diode D_1 .

[0038] There is also an energy absorption branch 320, in parallel with the primary conduction path 302 and the secondary conduction path 310. This energy absorption branch 320 includes a varistor 322 coupled across the secondary conduction path 310. The DC circuit breaker 200 also includes a mechanical switch member (CB_2) 304 connected in series with the PTC device 303, the mechanical switch member 304 being a switch configured to provide a low impedance path in a first configuration (closed contacts) and a high impedance path in a second configuration (open contacts). In this embodiment there is also a snubber circuit comprising a parallel coupled capacitor 330 and high impedance resistor 332 coupled across the first and second conduction paths 302, 310.

[0039] When a fault occurs in a load fed through the circuit breaker 300, the load current starts to rise. This increase in current heats the PTC device 303 thereby increasing its resistance dramatically. This increase in resistance causes the current to commute into the secondary conduction path 310 and current flows through the first IGBT 311 and diode D_2 . During this transition the voltage across the PTC device 303 is limited (clamped) by the first IGBT 311 and diode D_2 .

[0040] Once the current has through the PTC device 303 has fallen to zero, or is sufficiently reduced, the secondary conduction path 310 can be turned off. The line energy is partly dissipated within varistor 322, partly stored in capacitor 330 and partially

dissipated in resistor 332 which also limits the transient recovery voltage. The mechanical switch member (CB₂) 304 is then opened to break any residual current and provide full isolation.

[0041] Figure 4 is a schematic block diagram of a DC circuit breaker 400 according to an embodiment of the invention. The circuit breaker 400 has a primary conduction path 402 comprising a positive temperature coefficient (PTC) device 403 (also referred to as a commutating element), having a positive temperature coefficient of resistance. The primary conduction path 402 also has a mechanical switch member (CB₁) 404 connected in series with the PTC device 403, the mechanical switch member 404 being a switch configured to provide a low impedance path in a first configuration (closed contacts) and a high impedance path in a second configuration (open contacts).

[0042] There is a secondary conduction path 410 arranged in parallel with at least the PTC device 403 of the primary conduction path 402. The secondary conduction path 410 comprises semiconductor switching devices, which in this embodiment are a first IGBT (S₁) 411 with a parallel connected reversed biased diode D₁, and a second IGBT (S₂) 412 with a parallel connected forward biased diode D₂. Also, when a current flows in the direction as illustrated, with suitable gating the secondary conduction path 410 may allow for DC current flow through the first IGBT 411 and forward biased diode D₂. Alternatively, if current flow is in the opposite direction to that illustrated, with suitable gating the secondary conduction path 410 may allow for DC current flow through the second IGBT 412 and diode D₁.

[0043] There is also an energy absorption branch 420, in parallel with the primary conduction path 402 and the secondary conduction path 410. This energy absorption branch 420 includes a varistor 422 coupled across the secondary conduction path 410. The DC circuit breaker 400 also includes another mechanical switch member (CB₃) 430 that may be used for power supply isolation as will be apparent to a person skilled in the art.

[0044] The DC circuit breaker 400 also includes a switched snubber circuit 450 comprising anti-parallel thyristors S_A, S_B coupled across the PTC device 403 and a series coupled resistor and capacitor circuit R₁, C₁ coupled across the mechanical switch member 404. The switched snubber circuit 450 allows the secondary conduction path 410 to be turned off earlier resulting in a shorter breaking time of the circuit breaker 400.

[0045] Figure 5 is a schematic block diagram of a DC circuit breaker 500 according to an embodiment of the invention. This circuit breaker 500 is similar to that of circuit

breaker 400 but has a further mechanical switch member (CB₂) 514 in the secondary conduction path 410 which is in series with the first IGBT 411 and second IGBT 412. Consequently, the first IGBT 411 and second IGBT 412 do not need to be rated for the full DC link voltage as will be apparent to a person skilled in the art.

5 **[0046]** During normal operation the majority of current flows through the primary conduction path 402. When a fault occurs on the system, the increase in current causes a change in resistance in the positive temperature coefficient (PTC) device 403. This change in resistance commutates the current into the secondary conduction path 402. The mechanical switch member (CB₁) 404 is then opened. Once CB₁ is in the process of
10 opening, the first IGBT 411 is turned off. The mechanical switch member (CB₂) 514 is then opened and thyristor S₄ is turned on. Capacitor C₁ now starts to charge to the system voltage, the rate of increase is limited to be slower than the recovery rate of the dielectric material in the mechanical switch members.

[0047] Figure 6 is a schematic circuit diagram of a circuit breaker system 600 according
15 to an embodiment of the invention. The system 600 as illustrated includes any one of the circuit breakers as described herein such as circuit breaker 200. The system 600 includes a rectified Z Source with series connected first and second inductances 610, and 612 in series with an input node of the circuit breaker 200 and input terminal A of the system 600. There is also a third inductance 614 in series with an output node of the circuit
20 breaker 200 and an output terminal B of the system 600. The system 600 also includes series connected thyristors S₁, S₃ and series connected thyristors S₂, S₄ coupled across the input and output nodes of the circuit breaker 200. There is also an output capacitor 620 coupling a common node of the thyristors S₂, S₄ to and the output terminal B. There is also an input capacitor 630 coupling a common node of the inductances 610, 612 to a common
25 node of the thyristors S₂, S₄. During normal operation current flows from terminal A to terminal B. When a fault is detected, switches in the form of thyristors S₃ and S₂ are turned on. Current now flows via the capacitors in the reverse direction to normal current flow, resulting in a net lower current within the circuit breaker. When the current in the capacitors drops to zero, switches (thyristors) S₃ and S₂ are turned off and switches
30 (thyristors) S₄ and S₁ are turned on. The current now reverses direction within the capacitors, but still flows in the opposing direction to normal current flow within the circuit breaker 200. The frequency of oscillations is determined by inductor 610 and the capacitors 620, 630.

[0048] Figures 7A to 7D illustrates embodiments of various DC circuit breaker
35 commutating elements, which could replace the positive temperature coefficient (PTC)

device 203, 303 or 403 (which can also be also referred to as an R_{sc}) according to further embodiments of the invention. In figure 7A there is shown a series connected capacitor C_1 and anti-parallel thyristors T_1 , T_2 are connected in parallel across a mechanical switch member CB_4 which is a switch configured to provide a low impedance path in a first configuration (closed contacts) and a high impedance path in a second configuration (open contacts).

[0049] In figure 7B there is shown a series connected capacitor C_1 and semiconductor switching devices, which in this embodiment are a first IGBT S_1 with a parallel connected reversed biased diode D_1 , and a second IGBT S_2 with a parallel connected forward biased diode D_2 . The series connected capacitor C_1 and semiconductor switching devices are connected in parallel across a mechanical switch member CB_4 which is a switch configured to provide a low impedance path in a first configuration (closed contacts) and a high impedance path in a second configuration (open contacts). In figure 7C there is shown a series connected capacitor C_1 and semiconductor diode device D_1 connected in parallel across a mechanical switch member CB_4 which is a switch configured to provide a low impedance path in a first configuration (closed contacts) and a high impedance path in a second configuration (open contacts).

[0050] In figure 7D there is shown a series connected capacitor C_1 and a parallel circuit of a semiconductor diode device D_1 and high impedance resistor R_1 . The branch comprising the capacitor C_1 with the parallel circuit of the semiconductor diode device D_1 and high impedance resistor R_1 are connected in parallel across a mechanical switch member CB_4 .

[0051] Figure 8A to 8C show additional possible embodiments of a replacement positive temperature coefficient (PTC) device 203, 303 or 403 (which can also be also referred to as an R_{sc}). In Figure 8A there is illustrated a semiconductor device in the form a Gate Turn Off thyristor GTO1 connected in parallel across a mechanical switch member CB_4 .

[0052] In Figure 8B there is illustrated a semiconductor device in the form a diode D_1 connected parallel with an IGBT S_1 . Both the diode D_1 and IGBT S_1 are connected in parallel across a mechanical switch member CB_4 .

[0053] In Figure 8C there is illustrated a capacitor C_1 connected parallel across a mechanical switch member CB_4 .

[0054] Figure 9 is a schematic circuit diagram of a DC circuit breaker 900 according to an embodiment of the invention. The DC circuit breaker 900 is similar to that of circuit breaker 200. Additionally, the circuit breaker 900 comprises a capacitor 940 coupled across the first and second conduction paths 202, 210, a capacitor 950 arranged in parallel across the mechanical switch member (CB₁) 204 and an inductor 960 in series with the first and second conduction paths 202, 210.

[0055] After the mechanical switch member (CB₁) 204 is opened and the secondary conduction branch 210 is turned off, current then starts to flow into capacitor 940. The voltage will rise very quickly across capacitor 940 until it reaches the varistor's 222 limit voltage. When the varistor voltage is reached, the varistor will start to conduct a proportion of current and start to dissipate all the energy stored in the inductance 960. At this time the voltage across capacitor 940 is the varistor voltage and the current flowing into the breaker 900 is (or at least partly) flowing through the varistor 222. The voltage across the capacitor 940 is the same as the voltage across the mechanical switch member (CB₁) 204. The voltage across the mechanical switch member (CB₁) 204 will grow towards the voltage across the varistor 222 governed by an RC time constant. The voltage across the varistor 222 acts like a voltage source for the primary conduction path 202. This results in the initial rate of rise of voltage across the mechanical switch member (CB₁) 204 being much lower than the initial rate of rise of voltage across the secondary conduction path 210. As the current that flows through the capacitor 940 is of an exponential form, the restrictions on equivalent series inductance and resistance of the capacitor 940 are reduced.

[0056] This embodiment decouples the mechanical switch member (CB₁) 204 voltage from the rest of the circuit; hence the demands on the mechanical switch member (CB₁) 204 design are significantly reduced. Each of the components within this embodiment can be made from a single device or a number of devices connected in series and/or parallel. This device can also be connected in series for a modular embodiment. Discharge or isolation circuits may be utilised to limit the capacitance charging during operation. Additional circuits may also be utilised to discharge any capacitance before the circuit breaker is reclosed.

[0057] Figure 10 is a schematic circuit diagram of a DC circuit breaker 1000 according to an embodiment of the invention. The DC circuit breaker 1000 is similar to that of circuit breaker 200. Additionally the circuit breaker 1000 comprises a snubber circuit 1050 coupled in parallel across the mechanical switch member (CB₁) 204. The snubber circuit 1050 comprises antiparallel thyristors S_A, S_B in series with a capacitor 1060. The snubber circuit 1050 limits the rate of voltage rise across the mechanical switch CB₁ 204. The

snubber circuit 1050 will also allow the secondary conduction path 210 to be turned off earlier, resulting in a shorter breaking time.

[0058] Figure 11 is a schematic circuit diagram of a DC circuit breaker 1100 according to an embodiment of the invention. The DC circuit breaker 1100 is similar to that of circuit breaker 400. In this embodiment the snubber circuit 450 is replaced with a snubber circuit 1150. The snubber circuit 1150 is a modified version of the snubber circuit 450 in which the resistor R_1 has been replaced by a wire. During normal operation current flows from points A to point B primarily through the primary conduction path 402. Also, with suitable gating the secondary conduction path 410 may allow for DC current flow through the first IGBT 411 and forward biased diode D_2 . When a fault occurs, the fault current increases and causes the PTC device 403 to increase its impedance once the quench current level has been reached. The voltage across the PTC device 403 will now rise and can be used to trigger the appropriate snubber switch (S_A and/or S_B), or a threshold can be set before the quench current of the commutating element is reached and the secondary conduction path 410 turned on prior to quenching of the PTC device 403.

[0059] The current in the commutating element 403 will now circulate through the semiconductor switch (S_A and/or S_B) and the commutating element. Any current flowing in the line or source inductance will be commutated into the secondary conduction path 410.

[0060] Once the current in the mechanical switch member (CB_1) 404 is zero or sufficiently close to zero, the mechanical switch member (CB_1) 404 will be opened. If an arc forms the circuit can then wait for the arc to be extinguished. Further time may be added to allow the mechanical switch member (CB_1) 404 to open.

[0061] The secondary conduction path 410 can then be turned off as well as the trigger switch to switch S_A . Current will now commutate into switch S_A for a short period of time until a current zero is forced in the switch resulting in complete turn off of the switch S_A . This transient commutation into switch S_A is only for semiconductor devices which do not have full turn-on and turn-off capability.

[0062] Current now flows through the commutating element and the capacitance across the mechanical switch member (CB_1) 404. The commutating element will be predominately resistance and inductance; hence the voltage across this system will build much slower than a circuit without a snubber circuit 1150.

[0063] The energy absorbing conduction path 420 includes voltage limiting comprising varistor(s) or a switched resistance, or a combination thereof. This could be used to limit

the voltage across the entire breaker 1100 and/or allow capacitor C_1 to be discharged via S_A or S_B .

5 **[0064]** Figure 12 is a schematic circuit diagram of a DC circuit breaker 1200 according to an embodiment of the invention. The DC circuit breaker 1200 is similar to that of circuit breaker 1100. In this embodiment the snubber circuit 1150 is replaced with a snubber circuit 1250. The snubber circuit 1250 is arranged across the entire circuit breaker 1200 to allow the earlier turn off of the secondary conductive path 410. The snubber circuit is used to control the rate of rise of the voltage across the entire circuit breaker 1200.

10 **[0065]** Figure 13 is a schematic circuit diagram of a DC circuit breaker 1300 according to an embodiment of the invention. The DC circuit breaker 1300 is similar to that of circuit breaker 400. In this embodiment the snubber circuit 450 is replaced with an active snubber circuit 1350. The active snubber circuit 1350 is a modified version of the snubber circuit 450 in which the resistor R_1 has been replaced by anti-parallel thyristors S_C , S_D . The active snubber circuit 1350 will prevent oscillations between the snubber capacitance C_1 and
15 other elements in the transmission network by isolating the capacitance during normal operation of C_1 .

[0066] Figure 14 is a schematic circuit diagram of a DC circuit breaker 1400 according to an embodiment of the invention. The DC circuit breaker 1400 is similar to that of circuit breaker 1200 and includes a resistor R_1 coupled across the anti-parallel thyristors S_A , S_B .
20 The resistor R_1 is used to help control the recharge rate of the capacitor C_1 . Resistor R_1 will also reduce transient voltage overshoots across the commutating element or to reduce the power demands of the superconducting element. Resistor R_1 may be a fixed resistor value or a non-linear resistor, such as a varistor or a switched resistor.

25 **[0067]** Figure 15 is a schematic circuit diagram of a modular DC circuit breaker 1500 according to an embodiment of the invention. In this embodiment the secondary conduction path and energy absorbing paths have been designed in a modular fashion comprising N modules, in Figure 15 $N=3$. Modularizing the secondary branch allows each module M_1 , M_2 , and M_3 to be selectively turned off and on individually.

30 **[0068]** Current flows through the primary conduction path, via the PTC device R_{SC} and the mechanical switch CB_1 . During a fault the PTC device R_{SC} will quench, the secondary conduction path is thus turned on and current commutates from the primary conduction path into the secondary conduction path. The mechanical switch CB_1 is then opened, or starts to open. Instead of turning off all of the modules M_1 , M_2 , and M_3 together, the modules M_1 , M_2 , and M_3 are turned off one at a time or several at a time. Turning off the

modules M_1 , M_2 , and M_3 one at a time results in the peak superconductor voltage (V_{SC}) being reduced and the initial rate of rise of the mechanical switch voltage (V_{mech}) being reduced. The time between each module M_1 , M_2 , and M_3 turning off is related to the time constant of the RC snubber circuit which includes C_2 and R_{SC} . This results in the initial
5 rate of rise of the mechanical switch voltage being reduced by the number of modules (N). As the peak superconductor voltage is reduced, the maximum current the superconductor is exposed to during the turn off process is also reduced. Secondary conduction path semiconductors S_{11} to S_{31} can be turned off individually at different times when breaking current flow, or in groups of series and/or paralleled devices.

10 **[0069]** For any of the further embodiments detailed that contain semi-conductor components the type of device does not represent an innovative step. The devices could be IGBTs, GTOs, Photoconductive Elements, BJTs, MOSFETs, thyristors, diodes or IGCTs. Positive temperature coefficient resistances and superconductors materials could also be used to form the commutating element. Nonlinear elements, such as non-linear
15 capacitors and nonlinear resistors could also be used in parallel with mechanical or semi-conductive switches to form the commutating element. It must be noted that any individual device may be made from a number of series or paralleled, or series and paralleled devices to construct a device with a higher voltage and current rating.

[0070] Figure 16 is a flow chart illustrating a method 1600 of controlling a DC current
20 according to an embodiment of the invention. The method 1600 by way of a non-limiting example will be illustrated with reference to the circuit breaker 200. At a block 1610, the method 1600 provides a first or primary conduction path 202 for the DC current through the positive temperature coefficient (PTC) device 203 the mechanical switch member (CB1) 204. The method 1600 monitors for a fault (current surge) condition at block 1615
25 by monitoring a change in resistance across the positive temperature coefficient (PTC) device 203. When a fault is detected the method 1600 proceeds to a block 1620 and commutates the DC current to a secondary conduction path 210 comprising at least one semiconductor switching device by the PTC device in response to an increase in the DC current through the primary conduction path 202. There is then performed, at a block
30 1625, a process of controlling the semiconductor switching device (the first IGBT 211) to break the current through the secondary conduction path 210. In response to the controlling the semiconductor switching device at block 1625, the circuit breaker 200 is in a non-conductive state when the primary conduction path and secondary conduction path are both in a non-conductive state.

[0071] Advantageously embodiments of the present invention provide for use of temperature dependent impedances to force current commutation typically by passively commutating current to the secondary conduction path. Consequently, embodiments of the invention provide for commutation without necessarily requiring the need for external control. The snubber circuits are also beneficial in which in some embodiments the commutating element impedance may be part of the snubber circuit. Furthermore, the embodiments described herein are configured so that the semiconductor switching device(s) of the secondary conduction path is/are controllable to break current flow through the secondary conduction path to zero current flow. Accordingly, the circuit breaker of any of the embodiments described herein is configured to be in a non-conductive state when the primary conduction path and secondary conduction path are both in a non-conductive state.

[0072] It will be appreciated that embodiments of the present invention can be realised in the form of hardware, software or a combination of hardware and software. Any such software may be stored in the form of volatile or non-volatile storage such as, for example, a storage device like a ROM, whether erasable or rewritable or not, or in the form of memory such as, for example, RAM, memory chips, device or integrated circuits or on an optically or magnetically readable medium such as, for example, a CD, DVD, magnetic disk or magnetic tape. It will be appreciated that the storage devices and storage media are embodiments of machine-readable storage that are suitable for storing a program or programs that, when executed, implement embodiments of the present invention. Accordingly, embodiments provide a program comprising code for implementing a system or method as claimed in any preceding claim and a machine readable storage storing such a program. Still further, embodiments of the present invention may be conveyed electronically via any medium such as a communication signal carried over a wired or wireless connection and embodiments suitably encompass the same.

[0073] All of the features disclosed in this specification (including any accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive.

[0074] Each feature disclosed in this specification (including any accompanying claims, abstract and drawings), may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic series of equivalent or similar features. It will also be understood that the term "commutated",

“commutating” or versions thereof includes the meaning transferring or partially transferring current flow. It will also be apparent to a person skilled in the art that only the first IGBT 211 and diode D1 need be employed in the secondary conduction paths of any of the embodiments.

- 5 **[0075]** The invention is not restricted to the details of any foregoing embodiments. The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims, abstract and drawings), or to any novel one, or any novel combination, of the steps of any method or process so disclosed. The claims should not be construed to cover merely the foregoing embodiments, but also
- 10 any embodiments which fall within the scope of the claims.

Claims

1. A DC circuit breaker, comprising:
 - a primary conduction path comprising a positive temperature coefficient (PTC) device, having a positive temperature coefficient of resistance,
 - 5 a mechanical switch member connected in series with the PTC device, the mechanical switch member configured to provide a low impedance path in a first configuration and a high impedance path in a second configuration; and
 - a secondary conduction path arranged in parallel with at least the PTC device of the primary conduction path, the secondary conduction path comprising at least one
10 semiconductor switching device,
 - wherein the PTC device is arranged to commutate current to the secondary conduction path in response to an increase in current through the primary conduction path; and
 - wherein the at least one semiconductor switching device of the secondary
15 conduction path is controllable to break current flow through the secondary conduction path.
2. The circuit breaker of claim 1, wherein the circuit breaker is configured to be in a non-conductive state when the primary conduction path and secondary conduction path are both in a non-conductive state.
- 20 3. The circuit breaker of claim 1 or claim 2, wherein in the first configuration the primary conduction path has a lower impedance than the secondary conduction path.
4. The circuit breaker of claim 3, wherein the primary conduction path has a lower impedance than the secondary conduction path when conducting less than a predetermined current.
- 25 5. The circuit breaker of any preceding claim, wherein the PTC device comprises a superconductor material.
6. The circuit breaker of any preceding claim, wherein the PTC device is arranged to commutate the current to the secondary conduction path without a control signal.

7. The circuit breaker of any preceding claim, wherein the secondary conduction path is arranged in parallel with the PTC device and the mechanical switch member.
8. The circuit breaker of any of claims 1 to 5, comprising an energy absorbing conduction path in parallel with the secondary conduction path.
- 5 9. The circuit breaker of claim 8, wherein the energy absorbing conduction path comprises one or more varistors.
10. The circuit breaker of any preceding claim, wherein the secondary conduction path comprises a passive member.
11. The circuit breaker of claim 10, wherein the passive member comprises a
10 capacitive passive member.
12. The circuit breaker of any preceding claim, wherein the secondary conduction path comprises one or more semiconductor switches.
13. The circuit breaker of claim 12, wherein the secondary conduction path comprises two or more semiconductor switches arranged in series and/or in parallel.
- 15 14. The circuit breaker of claim 12 or 13 wherein the one or more semiconductor switches comprise one or more of a gate turn-off thyristor, an insulated gate bipolar transistor, and/or an integrated gate commutated thyristor.
15. The circuit breaker of any of claims 12 to 14, wherein the one or more semiconductor switches are arranged to cause current and voltage to be shared evenly
20 across all the semiconductor switches.
16. The circuit breaker of any preceding claim, wherein the mechanical switch member comprises one or more fast acting mechanical switches or breakers.
17. The circuit breaker of any preceding claim, further including a snubber circuit connected in parallel across at least part of the primary conduction path.
- 25 18. The circuit breaker of any preceding claim, wherein the snubber circuit is an active snubber circuit.
19. The circuit breaker of claim 17, wherein the snubber circuit is connected in parallel across all of the primary conduction path.

20. The circuit breaker of claim 17, wherein the snubber circuit is connected in parallel across only the mechanical switch member.
21. The circuit breaker of claim 17, wherein the commutating element impedance is part of the snubber circuit.
- 5 22. The circuit breaker of any preceding claim, wherein the secondary conduction path comprises more than one said semiconductor switching device and each said semiconductor switching device is configured to be turned off at different times when breaking current flow.
- 10 23. The circuit breaker of claims 1 to 21, wherein the secondary conduction path comprises more than one said semiconductor switching device and each said semiconductor switching device is in a group of at least one switching devices that are to be turned off at different times from other said groups when breaking current flow.
24. A method of controlling a DC current, comprising:
- 15 providing a first conduction path for the DC current through a positive temperature coefficient (PTC) device having a positive temperature coefficient of resistance and a mechanical switch member connected in series with the PTC device;
- commutating the DC current to a secondary conduction path comprising at least one semiconductor switching device by the PTC device in response to an increase in the current through the primary conduction path; and
- 20 controlling the at least one semiconductor switching device to break the current through the secondary conduction path.
25. The method of claim 24, wherein in response to the controlling the circuit breaker is in a non-conductive state when the primary conduction path and secondary conduction path are both in a non-conductive state.
- 25 26. The method of claim 24 or 25, further comprising switching the mechanical switch member into a high impedance configuration.
27. The method of claim 25 or 26, wherein the controlling of the at least one semiconductor switching device is performed following the switching of the mechanical switch member into the high impedance configuration.

28. The method of claim 26, wherein the controlling of the at least one semiconductor switching device is performed prior to the switching of the mechanical switch member into the high impedance configuration.

29. The method of any of claims 24 to 28, wherein the current is passively commutated
5 to the secondary conduction path.

30. The method of any of claims 24 to 29, wherein the controlling of the at least one semiconductor device is performed to reduce the current through the secondary conduction path substantially to zero.

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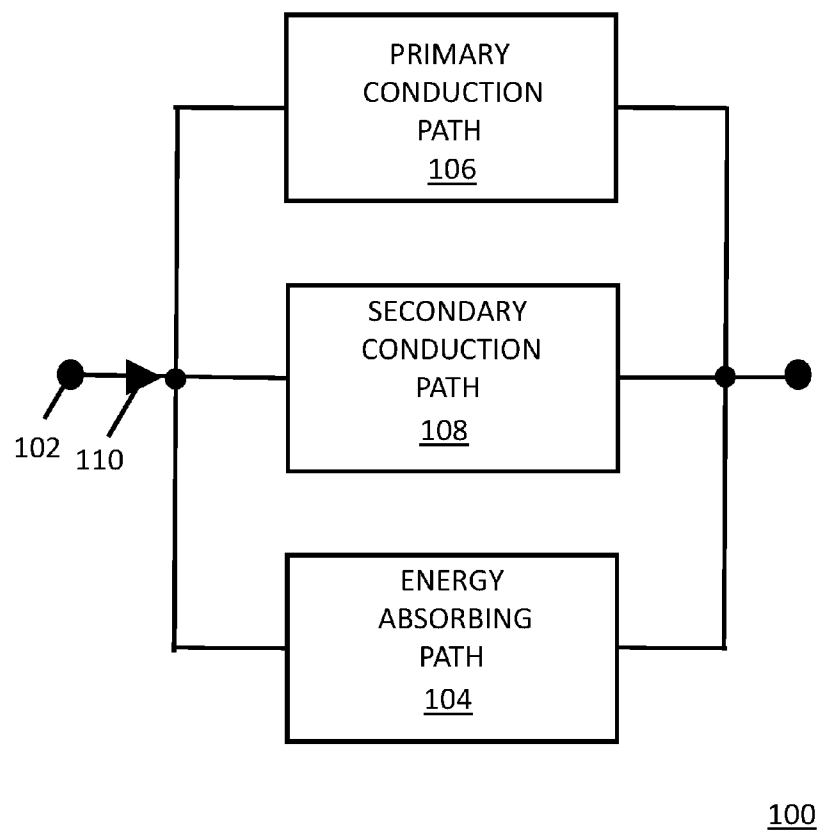


FIGURE 1

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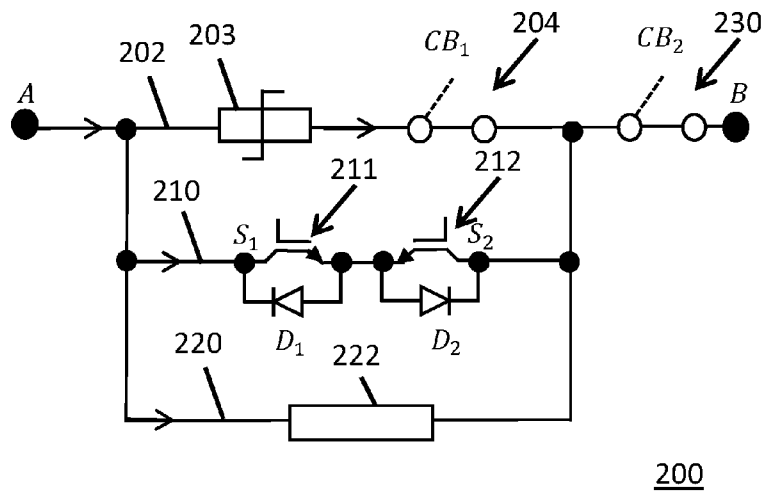


FIGURE 2

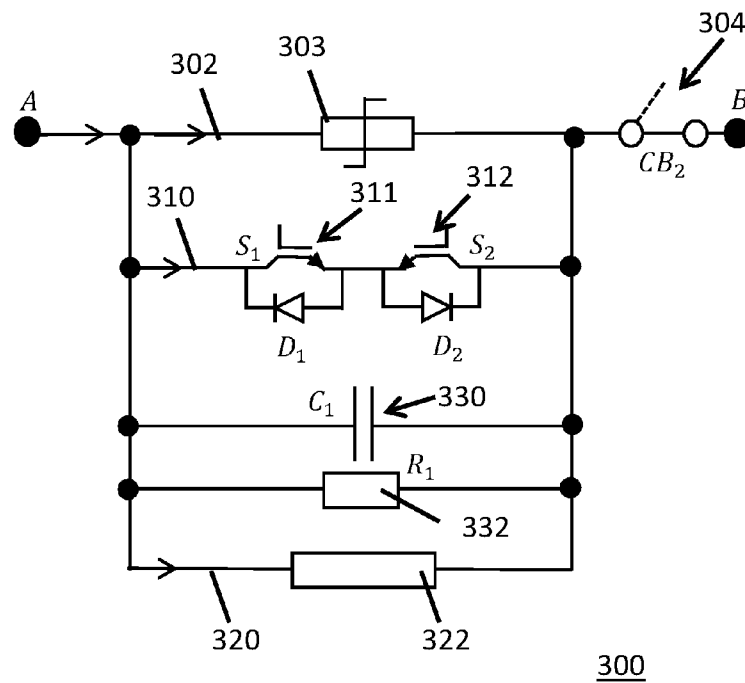


FIGURE 3

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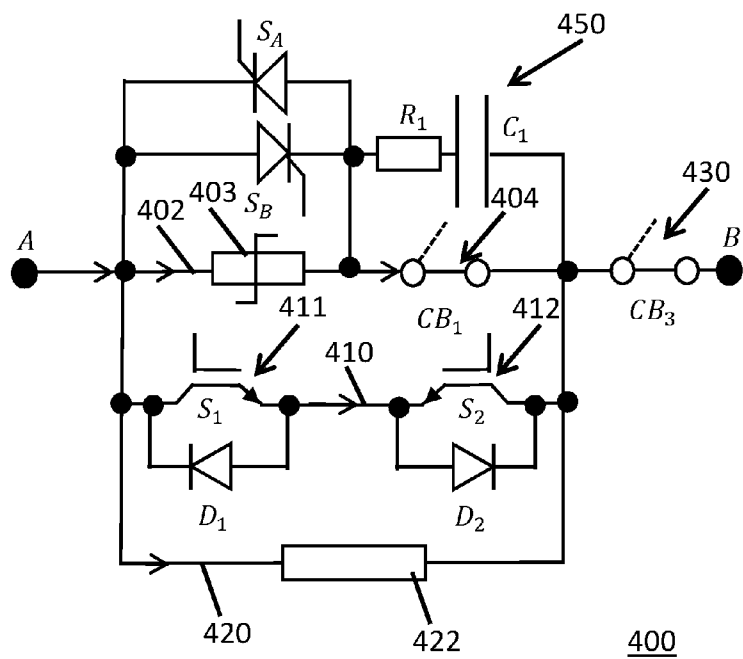


FIGURE 4

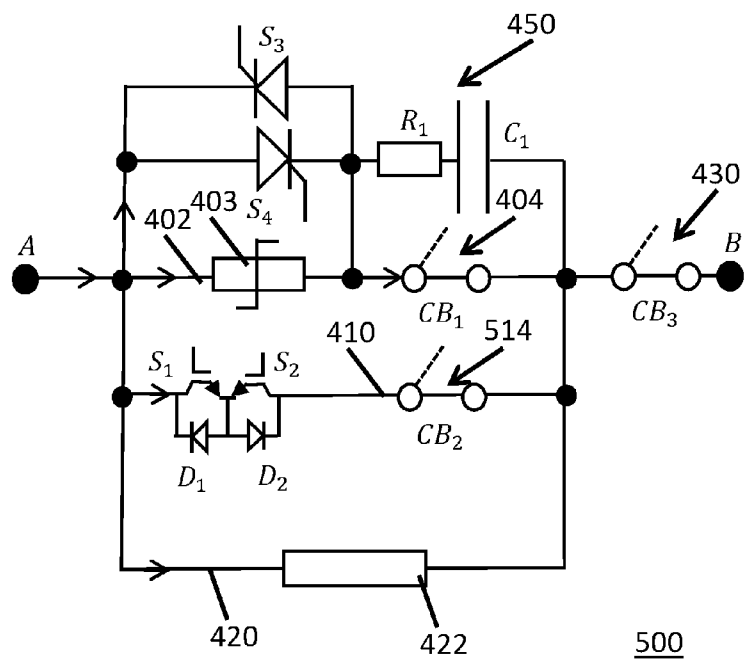


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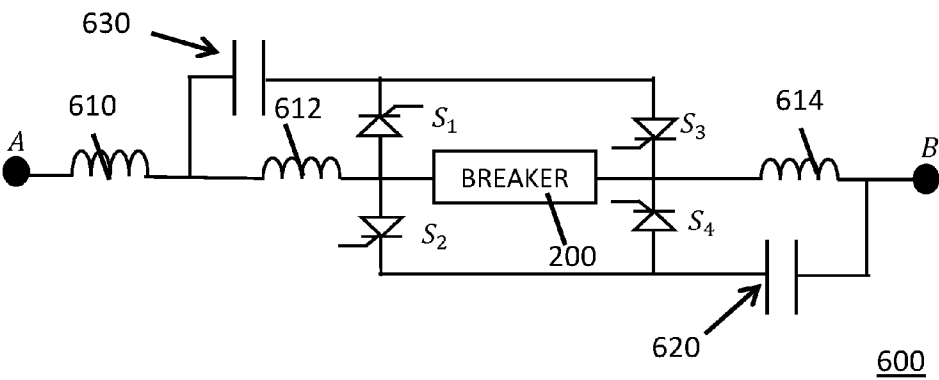


FIGURE 6

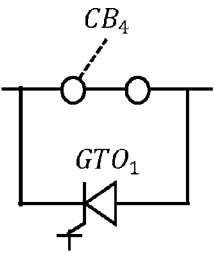


FIGURE 8A

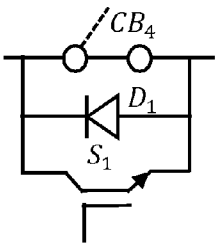


FIGURE 8B

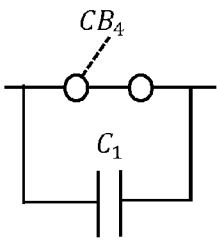


FIGURE 8C

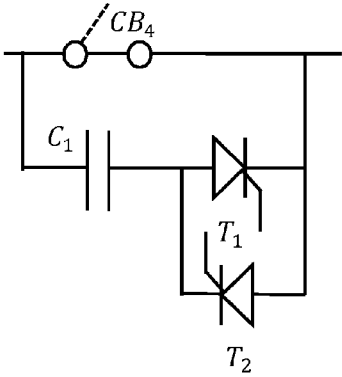


FIGURE 7A

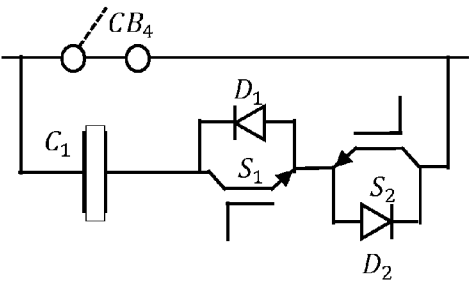


FIGURE 7B

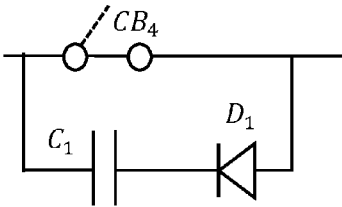


FIGURE 7C

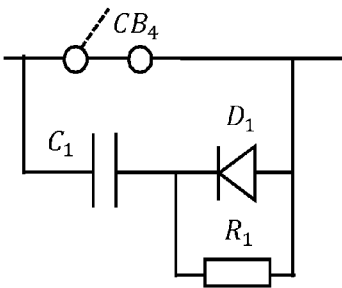


FIGURE 7D

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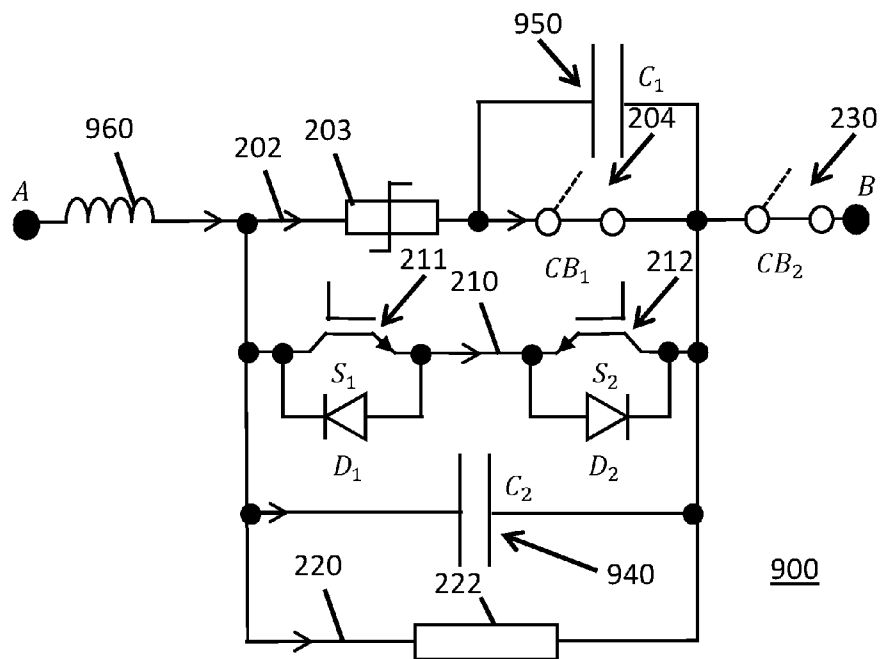


FIGURE 9

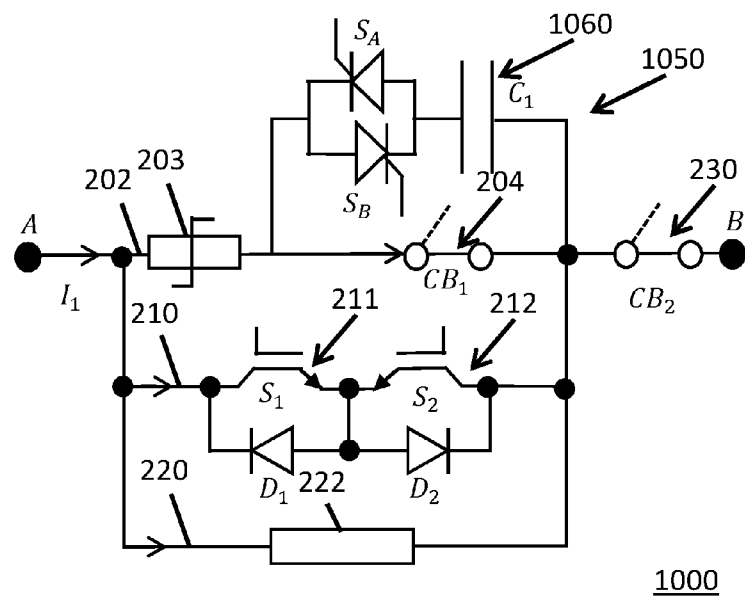


FIGURE 10

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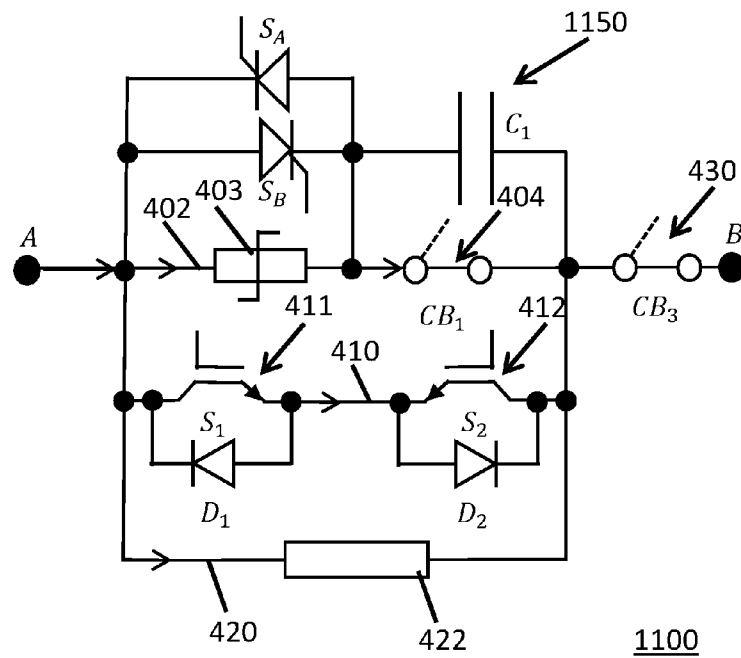


FIGURE 11

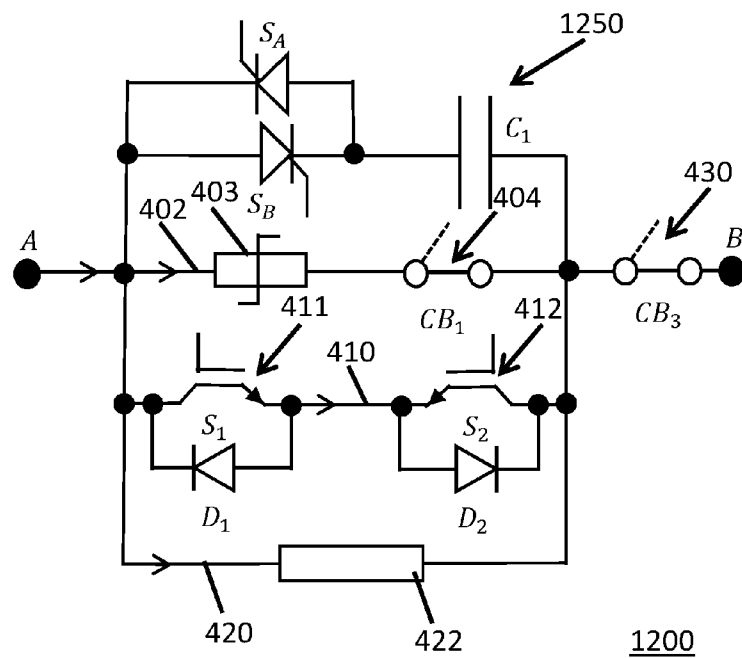


FIGURE 12

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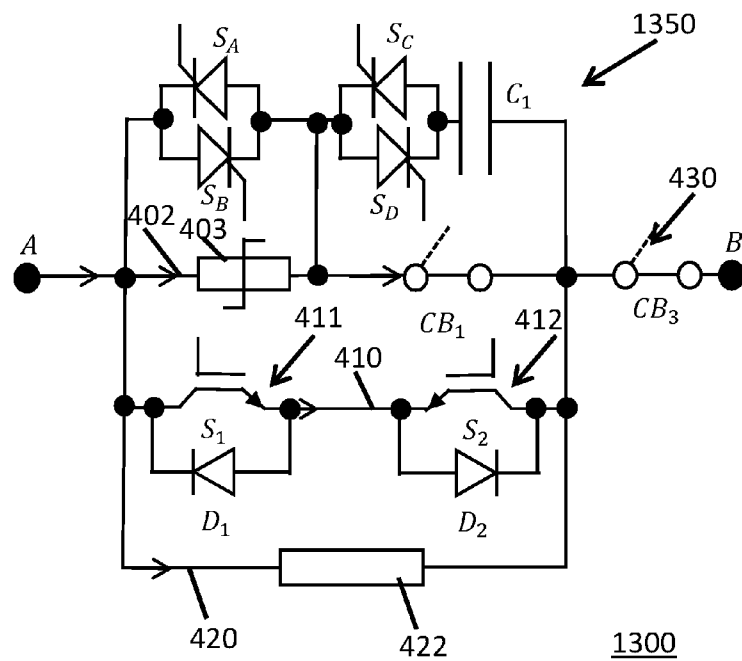


FIGURE 13

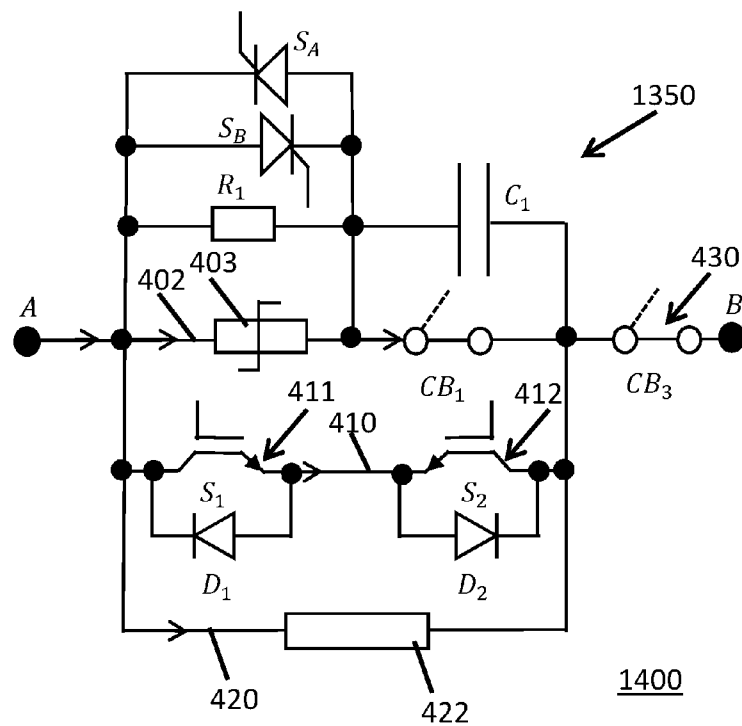
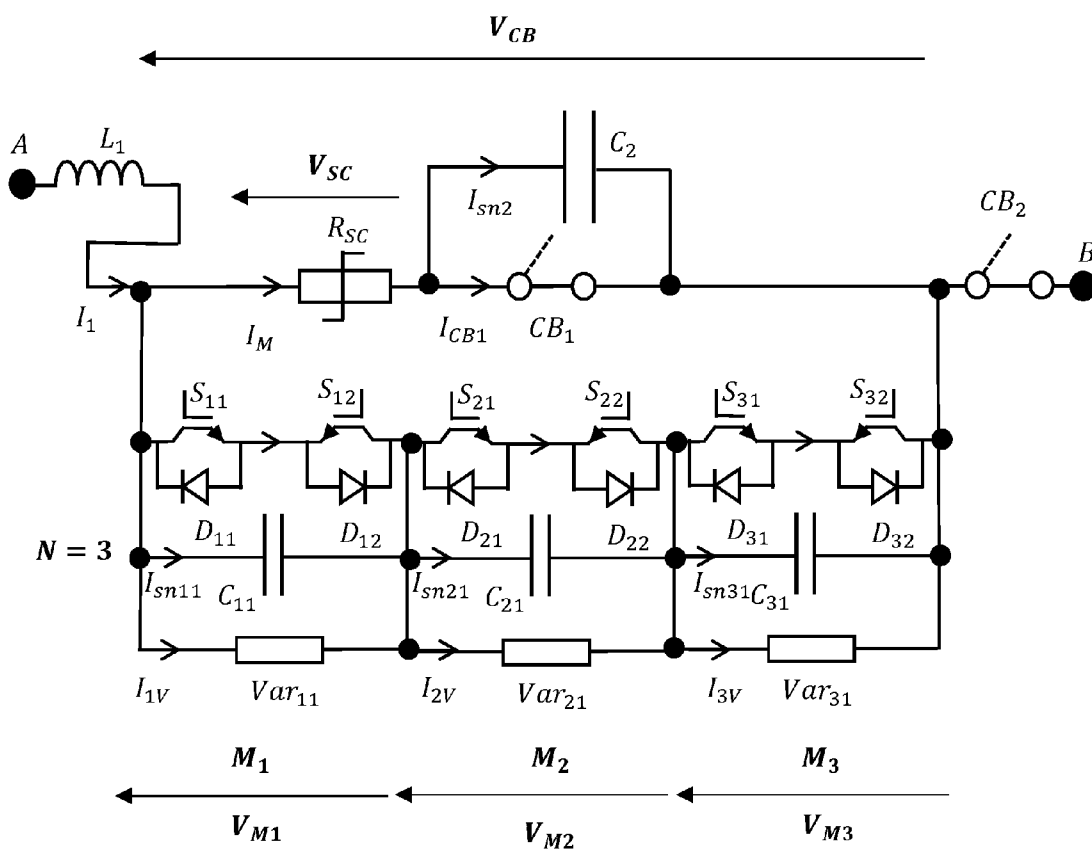


FIGURE 14

**FIGURE 15**

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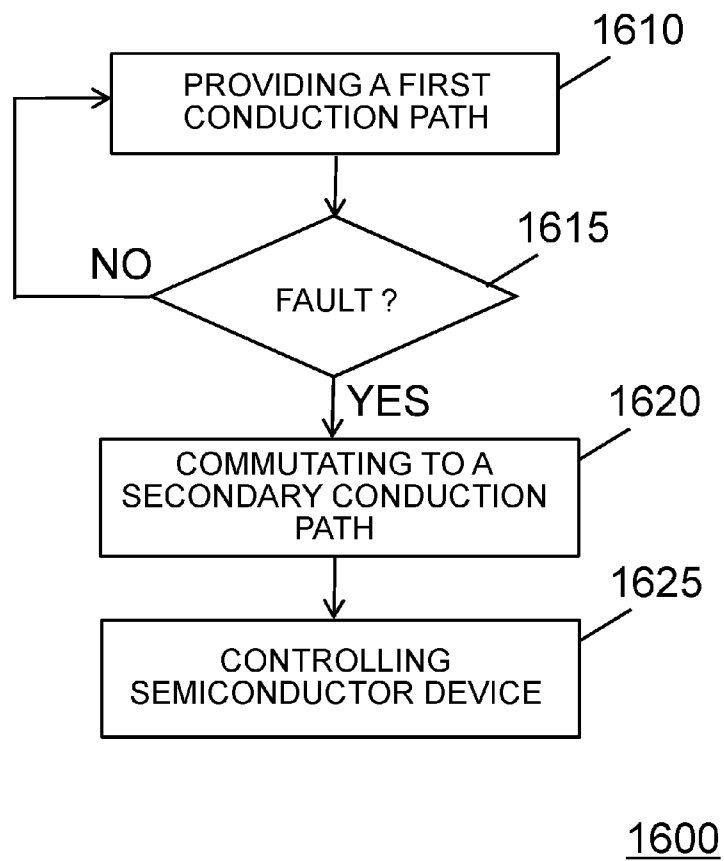


FIGURE 16