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(71) Applicant: **Alstom Technology Ltd**
5400 Baden (CH)

(72) Inventor: **Parashar, Rama Shanker**
Stafford ST17 0AL (GB)

(74) Representative: **Potter Clarkson LLP**
The Belgrave Centre
Talbot Street
Nottingham, NG1 5GG (GB)

(54) **Power switching apparatus**

(57) There is a power switching apparatus (6) for switching a DC current.

The power switching apparatus (6) comprises:
a vacuum switch assembly (8) for switching a DC current; and
a switching assembly (9) connected in parallel between a pair of terminals (7), each of the terminals (7) being connectable in use to an electrical circuit,
wherein the vacuum switch assembly (8) includes at least one vacuum switch, the or each vacuum switch including:
first and second electrically conductive rods connected at a first end to a respective one of the terminals and extending at a second end into a vacuum tight enclosure;
a first electrode being mounted at or near the second end of the first rod; and
a second electrode mounted at or near the second end of the second rod, the second electrode including at least one slot, the second ends of the rods extending into the vacuum tight enclosure such that the first and second electrodes define opposed electrodes, at least one of the rods being movable relative to the other to open or close a gap between the first and second electrodes,

wherein the switching assembly (9) includes at least one pulsed power switch that conducts and carries current only in its closed state, the switching assembly (9) being controllable to switch between open and closed states to modify, in use of the power switching apparatus (6), a current flowing through the vacuum switch assembly (8), provided that the or each pulsed power switch is not a crossed-field plasma discharge switch.

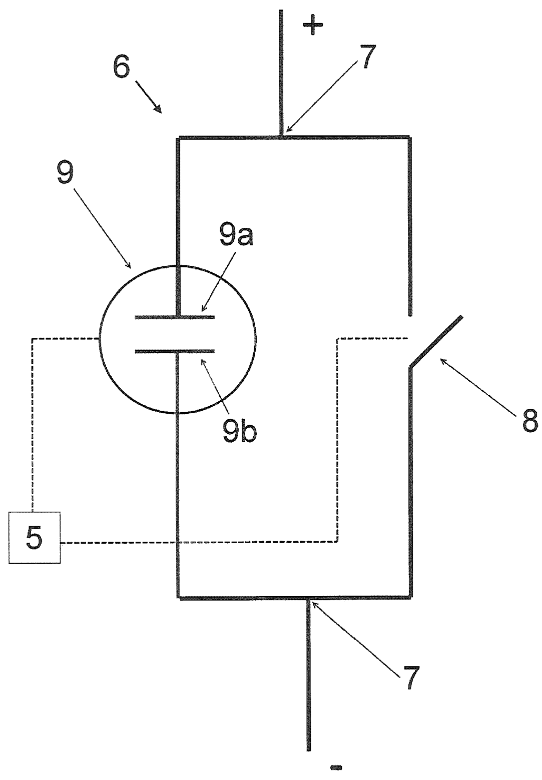

Figure 1

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Description

[0001] This invention relates to a power switching apparatus for switching a DC current.

[0002] The operation of multi-terminal high voltage direct current (HVDC) transmission and distribution networks involves load and fault/short-circuit current switching operations. The availability of switching components to perform such switching permits flexibility in the planning and design of HVDC applications such as parallel HVDC lines with a tap-off line or a closed loop circuit.

[0003] A known solution for load and fault/short-circuit current switching is the use of semiconductor-based switches, which are typically used in point-to-point high power HVDC transmission. The use of semiconductor-based switches results in faster switching and smaller values of let-through fault current. The disadvantages of using such switches however include high forward losses, sensitivity to transients and the lack of tangible isolation when the devices are in their off-state.

[0004] Another known solution for load and fault/short-circuit current switching is a vacuum interrupter. The operation of the vacuum interrupter relies on the mechanical separation of electrically conductive contacts to open the associated electrical circuit. Such a vacuum interrupter is capable of allowing high magnitude of continuous AC current with a high short-circuit current interrupting capability.

[0005] The conventional vacuum interrupter however exhibits poor performance in interrupting DC current because of the absence of current zero. Although it is feasible to use the conventional vacuum interrupter to interrupt low DC currents up to a few hundred amperes due to the instability of an arc at low currents, such a method is not only unreliable but is also incompatible with the levels of current typically found in HVDC applications.

[0006] It is possible to carry out DC current interruption using conventional vacuum interrupters by applying a forced current zero or artificially creating a current zero. This method of DC current interruption involves connecting an auxiliary circuit in parallel across the conventional vacuum interrupter, the auxiliary circuit comprising a capacitor, a combination of a capacitor and an inductor or any other oscillatory circuit. The auxiliary circuit remains isolated by a spark gap during normal operation of the vacuum interrupter.

[0007] When the contacts of the vacuum interrupter begin to separate, the spark ignition gap is switched on to introduce an oscillatory current of sufficient magnitude across the vacuum interrupter and thereby force the current across the interrupter to pass through a current zero. This allows the vacuum interrupter to successfully interrupt the DC current. Such an arrangement however becomes complex, costly and space consuming due to the need to integrate the additional components of the auxiliary circuit.

[0008] According to a first aspect of the invention, there is provided a power switching apparatus for switching a DC current, the switching apparatus comprising:

a vacuum switch assembly; and
a switching assembly connected in parallel between a pair of terminals, each of the terminals being connectable in use to an electrical circuit,
wherein the vacuum switch assembly includes at least one vacuum switch, the or each vacuum switch including:

first and second electrically conductive rods connected at a first end to a respective one of the terminals and extending at a second end into a vacuum tight enclosure;
a first electrode being mounted at or near the second end of the first rod; and
a second electrode mounted at or near the second end of the second rod, the second electrode including at least one slot, the second ends of the rods extending into the vacuum tight enclosure such that the first and second electrodes define opposed electrodes, at least one of the rods being movable relative to the other to open or close a gap between the first and second electrodes,
wherein the switching assembly includes at least one pulsed power switch that conducts and carries current only in its closed state, the switching assembly being controllable to switch between open and closed states to modify, in use of the power switching apparatus, a current flowing through the vacuum switch assembly,
provided that the or each pulsed power switch is not a crossed-field plasma discharge switch.

[0009] The parallel connection of the vacuum switch and switching assemblies in the power switching apparatus as described herein above has been found to improve current interruption carried out using the vacuum switch assembly.

[0010] The above arrangement of the first electrode and the slotted, second electrode in the vacuum switch assembly enables the generation of a self-induced magnetic field that is perpendicular to the arc current drawn between the first and second electrodes during the current interruption process. In the presence of the magnetic field, the arc voltage begins to rise while the arc current begins to drop rapidly to a residual current value until it reaches a value lower than the chopping current value of the electrode material. At this point the current drops instantly to zero, which results in full dielectric recovery and successful current interruption. The generation of the self-induced magnetic field removes the need to incorporate additional equipment into the vacuum switch assembly in order to generate the required magnetic field and thereby reduces the complexity of the layout of the vacuum switch assembly.

[0011] The switching assembly provides additional control over the current interruption process by enabling modification of the size of current flowing through the vacuum switch assembly during the current interruption process. For example, the size of current can be altered to minimise any adverse effects of high current densities on the electrodes to thereby improve the lifetime of the vacuum switch assembly.

[0012] The parallel connection of the vacuum switch and switching assemblies in the power switching apparatus also results in a simple layout of the power switching apparatus, which in turn reduces the manufacturing and installation costs of such an apparatus.

[0013] The pulsed power switch is simple in design with no moving parts, and can be designed to handle bidirectional power flow. In addition, the pulsed power switch is capable of switching off power flow after a predetermined period of conduction, and has rapid switching capability, e.g. the period taken to switch from a closed state to an open state can vary in the range of nanoseconds to a few milliseconds. The pulsed power switch can support a high voltage drop in its open state, e.g. up to a few MV, and is capable of carrying out repetitive operation. This in turn renders the pulsed power switch compatible for use in the switching assembly to aid current interruption in high voltage applications.

[0014] In embodiments of the invention, the or each pulsed power switch may be any one of:

- a pulsed power switch of the hard tube type, e.g. a triode, a tetrode;
- a pulsed power switch of the plasma tube type, e.g. a magnetically-quenched thyratron, a hollow-cathode discharge-based hollotron;
- a plasma erosion switch;
- a reflex triode switch.

[0015] Examples of pulsed power switches and their operation are described in:

- K. H. Schoenbach, A review of opening switch technology for inductive energy storage, proceedings of The IEEE, Vol. 72, No. 8, pp. 1019-1040, August 1984
- K.H. Schoenbach, M. Kristiansen, Diffuse Discharges and Opening Switches - A Review of the Tamarrow Workshops, Proceeding of 4th IEEE Pulsed Power conference, Albuquerque, New Mexico, pp. 26-32, 1983
- K. H. Schoenbach, M. Kristiansen, G. Schaefer, A review of opening switch technology for inductive energy storage, Proceedings of the IEEE, Vol. 72, No. 8, pp.1019 - 1040, August 1984

[0016] Pulsed power switches of the hard tube type are high vacuum devices with a hot-cathode filament based cathode, and require a high forward voltage to achieve conduction.

[0017] Pulsed power switches of the plasma tube type are gas-filled devices, and require a relatively lower forward voltage to achieve conduction. The nature of the filled gas may be, but is not limited to, hydrogen, nitrogen, argon, neon, xenon, or other gases and gas mixtures. Depending upon the design of the pulsed power switch, gases or gas mixtures are selected to provide the lowest forward voltage to reduce heat dissipation during normal conduction and to withstand high voltage during non-conduction. Gases such as helium, krypton or hydrogen provide enhanced switching characteristics.

[0018] The power switching apparatus may further include a control circuit to switch the switching assembly between open and closed states. The use of the control circuit enables rapid and automatic switching of the switching assembly.

[0019] In further embodiments of the invention, the switching assembly may be controllable to switch from an open state to a closed state in response to a formation of a gap between the first and second electrodes of the or each vacuum switch.

[0020] During normal operation, current only flows through the or each vacuum switch while the switching assembly remains in an open state and therefore does not conduct current. As soon as a gap between the first and second electrodes of the or each vacuum switch is formed, the switching assembly is switched to a closed state to divert part of the flow of current through the switching assembly. This not only limits the arc voltage across the or each vacuum switch, but also reduces the current density at the first and second electrodes to thereby minimise the damage to the first and second electrodes during the stage when the length of the gap is still very small and the current is flowing through molten globules of electrode material.

[0021] Thereafter, the switching assembly may be controllable to switch from a closed state to an open state at a predetermined gap between the first and second electrodes of the or each vacuum switch following the formation of a gap between the first and second electrodes of the or each vacuum switch.

[0022] The predetermined gap between the first and second electrodes may correspond to formation of a magnetic field that is substantially perpendicular to an arc current drawn between the first and second electrodes of the or each vacuum switch.

[0023] Once the gap between the first and second electrodes reaches a sufficiently large length, the flow of current in the second electrode results in formation of the magnetic field. At this stage the switching assembly is switched back to an open state so that all of the current flows through the vacuum switch. This in turn allows the magnetic field generated in the slotted, second electrode to act on all of the current flowing through the or each vacuum switch.

[0024] In still further embodiments of the invention, the switching assembly may be controllable to switch from an open state to a closed state at a predetermined level of current prior to the extinguishing of current in the or each vacuum switch and is controllable to switch from a closed state to an open state following the extinguishing of current in the or each vacuum switch. In such embodiments, the predetermined level of current may correspond to flow of residual current in the or each vacuum switch.

[0025] In the presence of the magnetic field, the arc voltage begins to rise while the arc current begins to drop rapidly to a residual current value until it reaches a value lower than the chopping current value of the electrode material. Switching the switching assembly to a closed state in the moments prior to the current being extinguished diverts the flow of any residual current through the switching assembly. The switching assembly is then switched to an open state to complete the current interruption process.

[0026] Such operation of the power switching apparatus not only allows each electrode to be made from material that are conducive to the high dielectric withstand requirements in the or each vacuum switch during open condition, but also has lower chopping current value which reduces any overvoltage generated during the current interruption process.

[0027] According to a second aspect of the invention, there is provided a power switching apparatus for switching a DC current, the power switching apparatus comprising:

a vacuum switch assembly;
a switching assembly connected in parallel between a pair of terminals, each of the terminals being connectable in use to an electrical circuit; and
a control circuit,
wherein the vacuum switch assembly includes at least one vacuum switch, the or each vacuum switch including:

first and second electrically conductive rods connected at a first end to a respective one of the terminals and extending at a second end into a vacuum tight enclosure;
a first electrode being mounted at or near the second end of the first rod; and
a second electrode mounted at or near the second end of the second rod, the second electrode including at least one slot, the second ends of the rods extending into the vacuum tight enclosure such that the first and second electrodes define opposed electrodes, at least one of the rods being movable relative to the other to open or close a gap between the first and second electrodes,
wherein the switching assembly includes at least one pulsed power switch that conducts and carries current only in its closed state, the control circuit switching the switching assembly between open and closed states to modify, in use of the power switching apparatus, a current flowing through the vacuum switch assembly, and
the control circuit switches the switching assembly from an open state to a closed state at a predetermined level of current prior to the extinguishing of current in the or each vacuum switch, the switching of the switching assembly from an open state to a closed state taking place only in response to formation of a magnetic field that is substantially perpendicular to an arc current drawn between the first and second electrodes of the or each vacuum switch; and
the control circuit switches the switching assembly from a closed state to an open state following the extinguishing of current in the or each vacuum switch.

[0028] In embodiments of the second aspect of the invention the predetermined level of current may correspond to flow of residual current in the or each vacuum switch.

[0029] The configuration of the power switching apparatus according to the second aspect of the invention provides a further mode of operation of the power switching apparatus to interrupt current.

[0030] The shape of the slotted electrode and the material of each electrode in each aspect of the invention may vary, depending on the design requirements of the vacuum switch. The slotted electrode may, for example, includes either only a single slot or a plurality of slots, while each electrode may, for example, be made from a refractory material, which may be selected from a group of chromium-chromium, copper-tungsten, copper tungsten carbide, tungsten, chromium or molybdenum.

[0031] Furthermore, in each aspect of the invention, the second electrode may be shaped in the form of either a cup or a coil, and/or the first electrode may be shaped in the form of any one of:

- a butt-type electrode;
- a multi-arm electrode;
- a cup or a slotted cup;
- a single-arm or multi-arm coil.

[0032] The number and arrangement of vacuum switches in the vacuum switch assembly may vary, depending on the design requirements of the power switching apparatus. The vacuum switch assembly may, for example, include a plurality of series-connected and/or parallel-connected vacuum switches.

[0033] Multiple vacuum switches may be connected to define different configurations of the vacuum switch assembly in order to vary its operating voltage and current characteristics to match the requirements of the associated power application.

[0034] As with the vacuum switch assembly, multiple pulsed power switches may be connected to define different configurations of the switching assembly in order to vary its operating voltage and current characteristics to match the requirements of the associated power application. The switching assembly may, for example, include a plurality of series-connected and/or parallel-connected pulsed power switches.

[0035] In embodiments in which the switching assembly includes a plurality of parallel-connected pulsed power switches, the switching assembly may be controllable to sequentially open or close the plurality of parallel-connected pulsed power switches.

[0036] Sequentially opening and closing the plurality of parallel-connected pulsed power switches allows discharge to be maintained for a longer duration and thereby increases the overall duration of current conduction in the switching assembly. This in turn renders the switching assembly compatible for use in current interruption processes in which the time taken to initially separate the opposed electrodes and the time taken to diffuse the arc is longer than the allowed duration of current conduction in a single pulsed power switch.

[0037] In embodiments of the invention the power switching apparatus may be controllable to switch an AC current.

[0038] Examples of applications that are compatible with the power switching apparatus according to the invention include, for example, AC power networks, AC high voltage circuit breakers, AC generator circuit breakers, railway traction, ships, superconducting magnetic storage devices, high energy fusion reactor experiments, stationary power applications, and high voltage direct current (HVDC) multi-terminal networks.

[0039] A preferred embodiment of the invention will now be described, by way of non-limiting examples, with reference to the accompanying drawings in which:

Figure 1 shows a power switching apparatus according to an embodiment of the invention;
Figure 2 shows a vacuum switch assembly that forms part of the power switching apparatus of Figure 1; and
Figure 3 illustrates, in graph form, the behaviour of the arc voltage across the power switching apparatus during a mode of operation of the power switching apparatus.

[0040] A power switching apparatus 6 according to an embodiment of the invention is shown in Figure 1.

[0041] The power switching apparatus 6 comprises a pair of terminals 7, a vacuum switch assembly 8, a switching assembly 9 and a control circuit 5.

[0042] The vacuum switch assembly 8 is connected in parallel with the switching assembly 9 between the terminals 7.

[0043] In use, the terminals 7 are respectively connected to positive and negative terminals of a DC electrical circuit.

[0044] The vacuum switch assembly 8 comprises a single vacuum switch 10.

[0045] The vacuum switch 10 includes a pair of cylindrical housings 12, first and second end flanges 14,16 and an annular structure 18 assembled to define a vacuum-tight enclosure. Each end flange 14,16 is brazed to a first end of a respective cylindrical housing 12 to form a hermetic joint. The two cylindrical housings 12 are joined together at their second ends via the annular structure 18. The annular structure 18 includes a central shield 20 that overlaps inner walls of the cylindrical housings 12 to protect the inner walls of the cylindrical housings 12 from metal vapour deposition arising from arc discharge, while each end flange 14,16 includes an end shield 22 to improve the electrostatic field line distribution along the length of the vacuum switch 10.

[0046] Each cylindrical housing 12 is metallised and nickel-plated at both ends. The length and diameter of the respective cylindrical housing 12 varies depending on the operating voltage rating of the vacuum switch 10, while the dimensions and shape of the first and second end flanges 14,16 and the annular structure 18 may vary to correspond to the size and shape of the cylindrical housings 12.

[0047] The vacuum switch 10 also includes a tubular bellows 24 and first and second electrically conductive rods 26,28.

[0048] The first end flange 14 includes a hollow bore dimensioned to accommodate the tubular bellows 24, while the second end flange 16 includes a hollow bore dimensioned to accommodate the second rod 28 within its hollow bore. The tubular bellows 24 also includes a hollow bore for retention of the first rod 26.

[0049] The first and second rods 26,28 are respectively retained within the hollow bores of the tubular bellows 24 and the second end flange 16 so that the second ends of the rods 26,28 are located inside the enclosure and the first ends of the rods 26,28 are located outside the enclosure. The first and second rods 26,28 may be fabricated from, for example, oxygen-free high conductivity (OFHC) copper.

[0050] The vacuum switch 10 further includes first and second electrodes 30,32. The second electrode 32 includes a multiple slotted coil 38 with a plurality of slots (not shown).

[0051] It is envisaged that, in other embodiments, the multiple slotted coil may be replaced by a slotted coil that includes only a single slot. Preferably such a single slot would extend completely around the full perimeter, e.g. the circumference of the coil.

[0052] The first electrode 30 consists of a first electrode portion 30a in the form of a rounded electrode portion that is mounted at the second end of the first rod 26, and a second electrode portion 30b in the form of an annular electrode portion that is mounted around the circumference of the first rod 26 and is adjacent to the other electrode portion 30a.

[0053] The second electrode 32 further includes an annular electrode portion 34a that is mounted on an inner surface of the multiple slotted coil 38.

[0054] The second electrode 32 further includes a support base 36. The support base 36 is mounted at the second end of the second rod 28 while the multiple slotted coil 38 is mounted on the support base 36.

[0055] The second electrode 32 further includes a central electrode portion 34b that is mounted at the centre of the support base 36. The rods 26,28 are coaxially aligned so that the first and second electrodes 30,32 define opposed electrodes. The central electrode portion 34b includes a recess 40 for receipt of the first electrode portion 30a and the shape of the recess 40 corresponds to the shape of the rounded first electrode portion 30a so as to maximise contact between the first and second electrodes 30,32.

[0056] Each electrode 30,32 is made from a refractory material, which may be selected from a group of, for example, chromium-chromium, copper-tungsten, copper tungsten carbide, tungsten, chromium or molybdenum. These refractory materials not only exhibit excellent electrical conductivity, but also display high dielectric strength subsequent to the current interruption. Moreover, these refractory materials have relatively high chopping current values, which helps to rapidly extinguish the arc once the current has dropped below the chopping current value.

[0057] Corrugated walls of the tubular bellows 24 allow the tubular bellows 24 to undergo expansion or contraction so as to increase or decrease the tubular length of the tubular bellows 24. This allows the first rod 26 to move relative to the second rod 28 between a first position where the first and second electrodes 30,32 are kept in contact through receipt of the first electrode portion 30a in the recess 40 of the central electrode portion 34b, and a second position where only part of the first electrode portion 30a remains located inside the multiple slotted coil 38. The second rod 28 is kept at a fixed position.

[0058] In use, the first ends of the first and second rods 26, 28 are respectively connected to the terminals 7 of the power switching apparatus 6 so that the first end of the first rod 26 is connected to the negative terminal 42 of the DC electrical circuit, while the first end of the second rod 28 is connected to the positive terminal 44 of the DC electrical circuit.

[0059] The switching assembly 9 includes a pulsed power switch. The pulsed power switch includes an anode 9a and a cathode 9b.

[0060] The switching assembly 9 is normally kept in an open state to not to conduct current. The switching assembly 9 can be switched to a closed state to conduct current.

[0061] The pulsed power switch is simple in design with no moving parts, and can be designed to handle bidirectional power flow, if necessary. In addition, the pulsed power switch is capable of switching off power flow after a predetermined period of conduction, and has rapid switching capability, e.g. the period taken to switch from a closed state to an open state can vary in the range of nanoseconds to a few milliseconds. The pulsed power switch can support a high voltage drop in its open state, e.g. up to a few MV, and is capable of carrying out repetitive operation. This in turn renders the pulsed power switch compatible for use in the switching assembly 9 to aid current interruption in high voltage applications.

[0062] During normal operation of the connected DC electrical circuit, the tubular bellows 24 is controlled to move the first rod 26 to the first position to bring the first and second electrodes 30,32 into contact. At the same time the pulsed power switch remains in an open state. This allows current to flow between the negative and positive terminals 42,44 of the connected DC electrical circuit via the electrically conductive rods 26,28 of the vacuum switch 10 whilst no current flows through the switching assembly 9. The low contact resistance resulting from the contact between the first and second electrodes 30,32 means that there is no flow of current through the multiple slotted coil 38.

[0063] In the event of a fault resulting in a high fault current flowing in the connected DC electrical circuit, the current must be interrupted in order to prevent the high fault current from damaging components of the DC electrical circuit. Interruption of the fault current permits isolation and subsequent repair of the fault in order to restore the DC electrical circuit to normal operating conditions.

[0064] The current interruption process is initiated by controlling the tubular bellows 24 to move the first rod 26 towards its second position so as to separate the first and second electrodes 30,32. The separation of the first and second electrodes 30,32 results in the formation of a gap between the first electrode portion 30a and the central electrode portion 34b, which leads to the formation of an arc in this gap. The arc consists of metal vapour plasma, which continues to conduct the current flowing between the first and second electrodes 30,32.

[0065] The control circuit 5 detects the formation of the gap between the first electrode portion 30a and the central electrode portion 34b, and generates a control signal that is subsequently transmitted to the switching assembly 9. Upon receipt of the control signal, the switching assembly 9 is controlled to switch from an open state to a closed state. The switching assembly 9 then begins to conduct current, which has the effect of diverting part of the current through the switching assembly 9. Thus, both the vacuum switch assembly 8 and the switching assembly 9 conduct and share the current depending upon the voltage drop across them.

[0066] The pulsed power switch can provide a forward voltage drop of 10 - 100 V and the vacuum switch 10 can develop an arc voltage of 30 - 120 volts following formation of a gap between the first electrode portion 30a and the central electrode portion 34b. It will be appreciated that the forward voltage drop across the pulsed power switch and the arc voltage across the vacuum switch 10 may vary depending upon the exact design and construction of the power switching apparatus 6.

[0067] The diversion of current flow through the switching assembly 9 not only limits the arc voltage across the vacuum switch 10, but also reduces the current density at the first electrode portion 30a and the central electrode portion 34b to thereby minimise the damage to the first and second electrodes 30,32 during the stage when the length of the gap is still very small and the current is flowing through molten globules of electrode material. This helps to minimise damage to the electrodes 30,32 during current interruption and thereby extend the lifetime of the vacuum switch 10.

[0068] As the gap between the first and second electrodes 30,32 increases and the magnitude of current increases, the multiple slotted coil 38 begins to draw current via the annular electrode portion 34a. The shape of the multiple slotted coil 38 causes the drawn current to flow in a preferential direction within the multiple slotted coil 38, which results in generation of an magnetic field in the gap between the first electrode 30 and the annular electrode portion 34b. The direction of the generated magnetic field is perpendicular to the direction of current being drawn between the first electrode 30 and the annular electrode portion 34b.

[0069] When the gap increases to the point where the multiple slotted coil 38 begins to draw current, the switching assembly 9 is controlled to switch from a closed state to an open state. The switching assembly 9 then stops conducting current, which has the effect of causing all of the current to flow through the vacuum switch 10. This allows the magnetic field generated in the multiple slotted coil 38 to act on all of the current flowing through the vacuum switch 10.

[0070] In the presence of the magnetic field, the charged metal vapour plasma is forced away from reaching the anode 32. Subsequently the arc voltage begins to rise while the magnitude of the drawn current begins to drop rapidly to a residual current value. When the magnitude of the drawn current reaches a value lower than the chopping current value of the electrode material, the arc energy becomes insufficient to sustain the current, which leads to the arc becoming highly unstable and the current dropping instantly to zero. This allows full dielectric recovery and successful current interruption to take place.

[0071] The duration of current interruption is limited by the time required to mechanically move the first rod 26 from the first position to the second position, which could vary between 1 to 10 ms and would depend upon the opening speed of the moving rod 26. Once the first rod 26 reaches the second position, the current will typically drop to zero in about 10 to 20 μs.

[0072] The arrangement of the first rod 26 and the multiple slotted coil 38 therefore allows the separation of the first and second electrodes 30,32 to result in the generation of a self-induced magnetic field which is perpendicular to the direction of the current drawn between the two electrodes 30,32 to assist in the extinguishing of the arc formed between the first and second electrodes 30,32. This removes the need to incorporate additional equipment into the vacuum switch assembly in order to generate the required magnetic field, and thereby reduces the complexity of the layout of the vacuum switch assembly.

[0073] The comparatively simpler layout of the vacuum switch assembly has the effect of reducing the amount of space required for the assembly and the associated installation costs, while the reduced number of components in the vacuum switch assembly improves the reliability of the current interruption process.

[0074] Optionally, prior to the extinguishing of current in the vacuum switch 10, the switching assembly 9 may be further controlled to switch from an open state to a closed state at a predetermined level of current. Switching the switching assembly 9 to a closed state in the moments prior to the current being extinguished diverts the flow of any residual current through the switching assembly 9. This allows the current in the vacuum switch 10 to drop to zero and allows the vacuum switch 10 to recover dielectrically. This is followed by the switching assembly 9 being controlled to switch back to an open state to complete the current interruption process.

[0075] Such operation of the power switching apparatus 6 not only allows each electrode 30,32 to be made from material that are conducive to the high dielectric withstand requirements in the vacuum switch 10 during open condition, but also has been found to reduce any overvoltage generated during the current interruption process.

[0076] Figure 3 illustrates, in graph form, the behaviour of the arc voltage across the power switching apparatus 6 during an optional, further mode of operation of the power switching apparatus 6.

[0077] In the optional, further mode of operation of the power switching apparatus 6, following initiation of the current interruption process, the switching assembly 9 is not switched from an open state to a closed state in response to formation of the gap between the first electrode portion 30a and the central electrode portion 34b. Instead the control circuit 5 switches 46 the switching assembly 9 from an open state to a closed state only in response to the build-up of the arc voltage caused by the formation of the magnetic field and prior to the extinguishing of current in the vacuum switch 10. In the period 48 prior to the switching 46 of the switching assembly 9 to switch from an open state to a closed state, the arc current only flows through the vacuum switch assembly 8.

[0078] In this manner the switching assembly 9 is switched 46 to a closed state when the arc voltage begins to rise, i.e. when the magnitude of the drawn current begins to drop rapidly to its residual current value. This diverts the arc current through the switching assembly 9 and thereby allows the current in the vacuum switch 10 to drop to zero and also allows the vacuum switch 10 to recover dielectrically. This is followed by the switching assembly 9 being controlled to switch back to an open state to complete the current interruption process. The duration of the conduction of the pulsed power switch has to be longer than the time needed for the vacuum switch 10 to achieve full dielectric recovery, which is typically in the range of 10 μs.

[0079] The parallel connection of the vacuum switch and switching assemblies 8,9 in the power switching apparatus 6 has therefore been found to improve current interruption carried out using the vacuum switch 10.

[0080] The switching assembly 9 provides additional control over the current interruption process by enabling modification of the size of current flowing through the vacuum switch 10 during the current interruption process.

[0081] The parallel connection of the vacuum switch and switching assemblies 8,9 in the power switching apparatus 6 also results in a simple layout of the power switching apparatus 6, which in turn reduces the manufacturing and installation costs of such an apparatus 6.

[0082] It is envisaged that, in other embodiments of the invention, the vacuum switch assembly may include a plurality of series-connected and/or parallel-connected vacuum switches.

[0083] Multiple vacuum switches may be connected to define different configurations of the vacuum switch assembly in order to vary its operating voltage and current characteristics to match the power requirements of the associated power application. For example, connecting multiple vacuum switches in series increases the dielectric strength of the vacuum switch assembly and thereby permits the use of the vacuum switch assembly at higher operating voltages, while connecting multiple vacuum switches in parallel permits the vacuum switch assembly to interrupt higher levels of current.

[0084] It is also envisaged that, in other embodiments of the invention, the switching assembly may include a plurality of series-connected and/or parallel-connected pulsed power switches.

[0085] As with the vacuum switch assembly, multiple pulsed power switches may be connected to define different configurations of the switching assembly in order to vary its operating voltage and current characteristics to match the power requirements of the associated power application.

[0086] For example, multiple vacuum switches and pulsed power switches can be connected in series and parallel to interrupt continuous current ≥ 6 kA and short-circuit current ≥ 100kA at an operating voltage of ≥ 400kV of a HVDC multi-terminal network.

[0087] Depending on the opening speed of the rods 26,28 and the time taken to diffuse the arc, the maximum duration of conduction of the pulsed power switch may be up to 1 to 3 ms.

[0088] The use of parallel-connected pulsed power switches in a switching assembly allows the plurality of parallel-connected pulsed power switches to be sequentially closed/opened. This in turn allows discharge to be maintained for a longer duration and thereby increases the overall duration of current conduction in the switching assembly. This in turn renders the switching assembly compatible for use in current interruption processes in which the time taken to initially separate the opposed contact surfaces and the time taken to diffuse the arc is longer than the duration of current conduction in a single pulsed power switch.

[0089] It is envisaged that, in further embodiments of the invention, the shape of each electrode may vary depending on the magnitude of current to be interrupted. For example, the second electrode may be shaped in the form of a coil only, and/or the first electrode may be shaped in the form of any one of:

- a butt electrode;
- a multi-arm electrode;
- a cup or a slotted cup;
- a single-arm or multi-arm coil.

[0090] In such embodiments, the surface area and diameter of the second electrode is preferably larger than the surface area and diameter of the first electrode.

[0091] The power switching apparatus of Figure 1 is compatible for use, but is not limited to, applications such as AC power networks, AC high voltage circuit breakers, AC generator circuit breakers, railway traction, ships, superconducting magnetic storage devices, high energy fusion reactor experiments, stationary power applications, and high voltage direct current (HVDC) multi-terminal networks.

Claims

1. A power switching apparatus for switching a DC current, the power switching apparatus comprising:

a vacuum switch assembly; and
a switching assembly connected in parallel between a pair of terminals, each of the terminals being connectable in use to an electrical circuit, wherein the vacuum switch assembly includes at least one vacuum switch, the or each vacuum switch including:

first and second electrically conductive rods connected at a first end to a respective one of the terminals and extending at a second end into a vacuum tight enclosure;
a first electrode being mounted at or near the second end of the first rod;

and
a second electrode mounted at or near the second end of the second rod, the second electrode including at least one slot, the second ends of the rods extending into the vacuum tight enclosure such that the first and second electrodes define opposed electrodes, at least one of the rods being movable relative to the other to open or close a gap between the first and second electrodes,
wherein the switching assembly includes at least one pulsed power switch that conducts and

carries current only in its closed state, the switching assembly being controllable to switch between open and closed states to modify, in use of the power switching apparatus, a current flowing through the vacuum switch assembly, provided that the or each pulsed power switch is not a crossed-field plasma discharge switch.

2. A power switching apparatus according to Claim 1 wherein the or each pulsed power switch is any one of:

- a pulsed power switch of the hard tube type;
- a pulsed power switch of the plasma tube type;
- a plasma erosion switch;
- a reflex triode switch.

3. A power switching apparatus according to any preceding claim further including a control circuit to switch the switching assembly between open and closed states.

4. A power switching apparatus according to any preceding claim wherein the switching assembly is controllable to switch from an open state to a closed state in response to a formation of a gap between the first and second electrodes of the or each vacuum switch.

5. A power switching apparatus according to Claim 4 wherein the switching assembly is controllable to switch from a closed state to an open state at a predetermined gap between the first and second electrodes of the or each vacuum switch following the formation of a gap between the first and second electrodes of the or each vacuum switch.

6. A power switching apparatus according to Claim 5 wherein the predetermined gap between the first and second electrodes corresponds to formation of a magnetic field that is substantially perpendicular to an arc current drawn between the first and second electrodes of the or each vacuum switch.

7. A power switching apparatus according to any preceding claim wherein the switching assembly is controllable to switch from an open state to a closed state at a predetermined level of current prior to the extinguishing of current in the or each vacuum switch and is controllable to switch from a closed state to an open state following the extinguishing of current in the or each vacuum switch.

8. A power switching apparatus according to Claim 7 wherein the predetermined level of current corresponds to flow of residual current in the or each vacuum switch.

9. A power switching apparatus for switching a DC current, the power switching apparatus comprising:

a vacuum switch assembly;
a switching assembly connected in parallel between a pair of terminals, each of the terminals being connectable in use to an electrical circuit; and
a control circuit,
wherein the vacuum switch assembly includes at least one vacuum switch, the or each vacuum switch including:

first and second electrically conductive rods connected at a first end to a respective one of the terminals and extending at a second end into a vacuum tight enclosure;
a first electrode being mounted at or near the second end of the first rod;

and
a second electrode mounted at or near the second end of the second rod, the second electrode including at least one slot, the second ends of the rods extending into the vacuum tight enclosure such that the first and second electrodes define opposed electrodes, at least one of the rods being movable relative to the other to open or close a gap between the first and second electrodes,
wherein the switching assembly includes at least one pulsed power switch that conducts and carries current only in its closed state, the control circuit switching the switching assembly between open and closed states to modify, in use of the power switching apparatus, a current flowing through the vacuum switch assembly, and
the control circuit switches the switching assembly from an open state to a closed state at a predetermined level of current prior to the extinguishing of current in the or each vacuum switch, the switching of the switching assembly from an open state to a closed state taking place only in response to formation of a magnetic field that is substantially perpendicular to an arc current drawn between the first and second electrodes of the or each vacuum switch; and
the control circuit switches the switching assembly from a closed state to an open state following the extinguishing of current in the or each vacuum switch.

10. A power switching apparatus according to Claim 9 wherein the predetermined level of current corresponds to flow of residual current in the or each vacuum switch.

11. A power switching apparatus according to any preceding claim wherein the second electrode is shaped in the form of either a cup or a coil.

12. A power switching apparatus according to any preceding claim wherein the first electrode is shaped in the form of any one of:

- a butt-type electrode;
- a multi-arm electrode;
- a cup or a slotted cup;
- a single-arm or multi-arm coil.

13. A power switching apparatus according to any preceding claim wherein the vacuum switch assembly includes a plurality of series-connected and/or parallel-connected vacuum switches.

14. A power switching apparatus according to any preceding claim wherein the switching assembly includes a plurality of series-connected and/or parallel-connected pulsed power switches.

15. A power switching apparatus according to Claim 14 wherein the switching assembly includes a plurality of parallel-connected pulsed power switches, and the switching assembly being controllable to sequentially open or close the plurality of parallel-connected pulsed power switches.

16. A power switching apparatus according to any preceding claim wherein the power switching apparatus is controllable to switch an AC current.

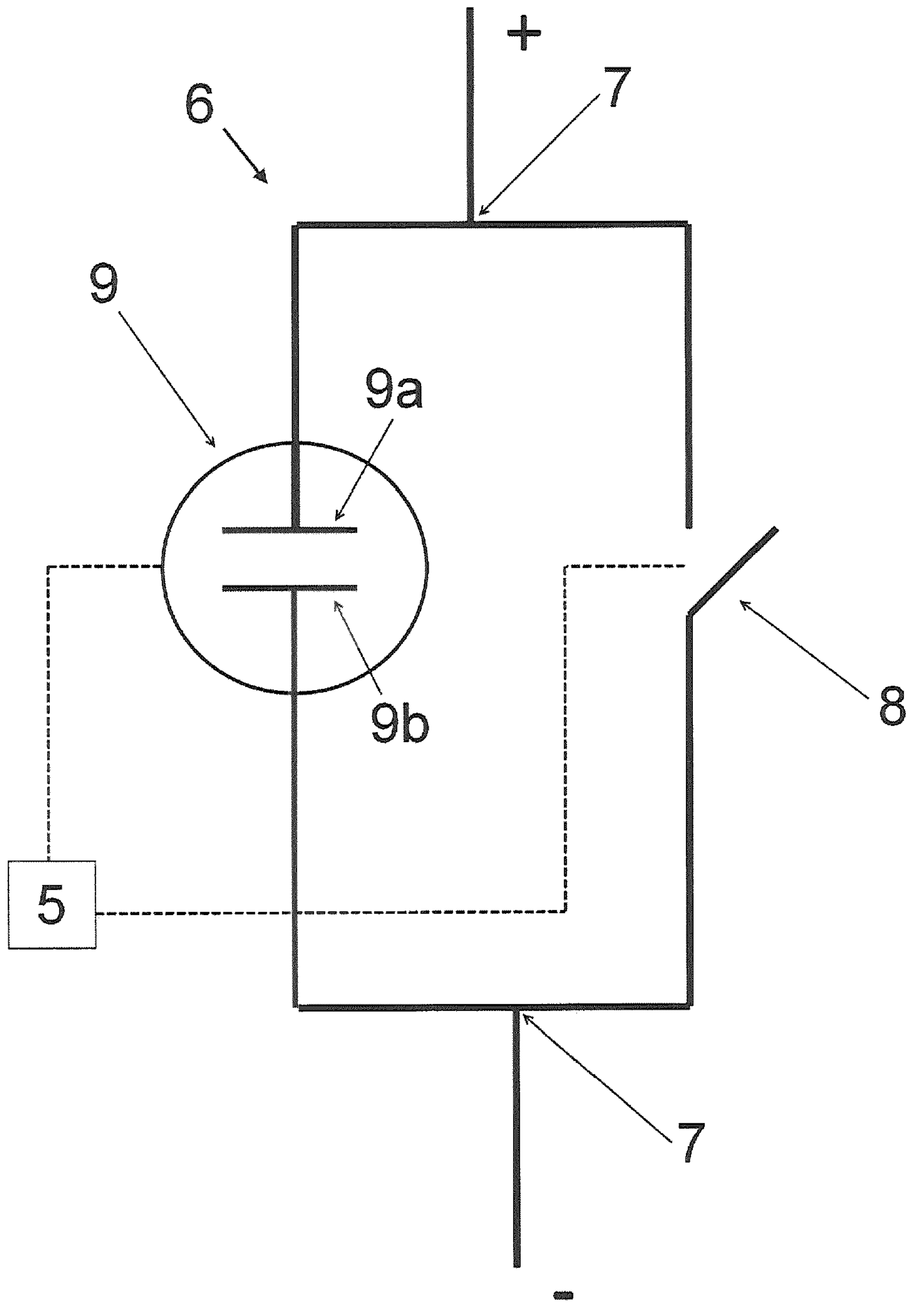

Figure 1

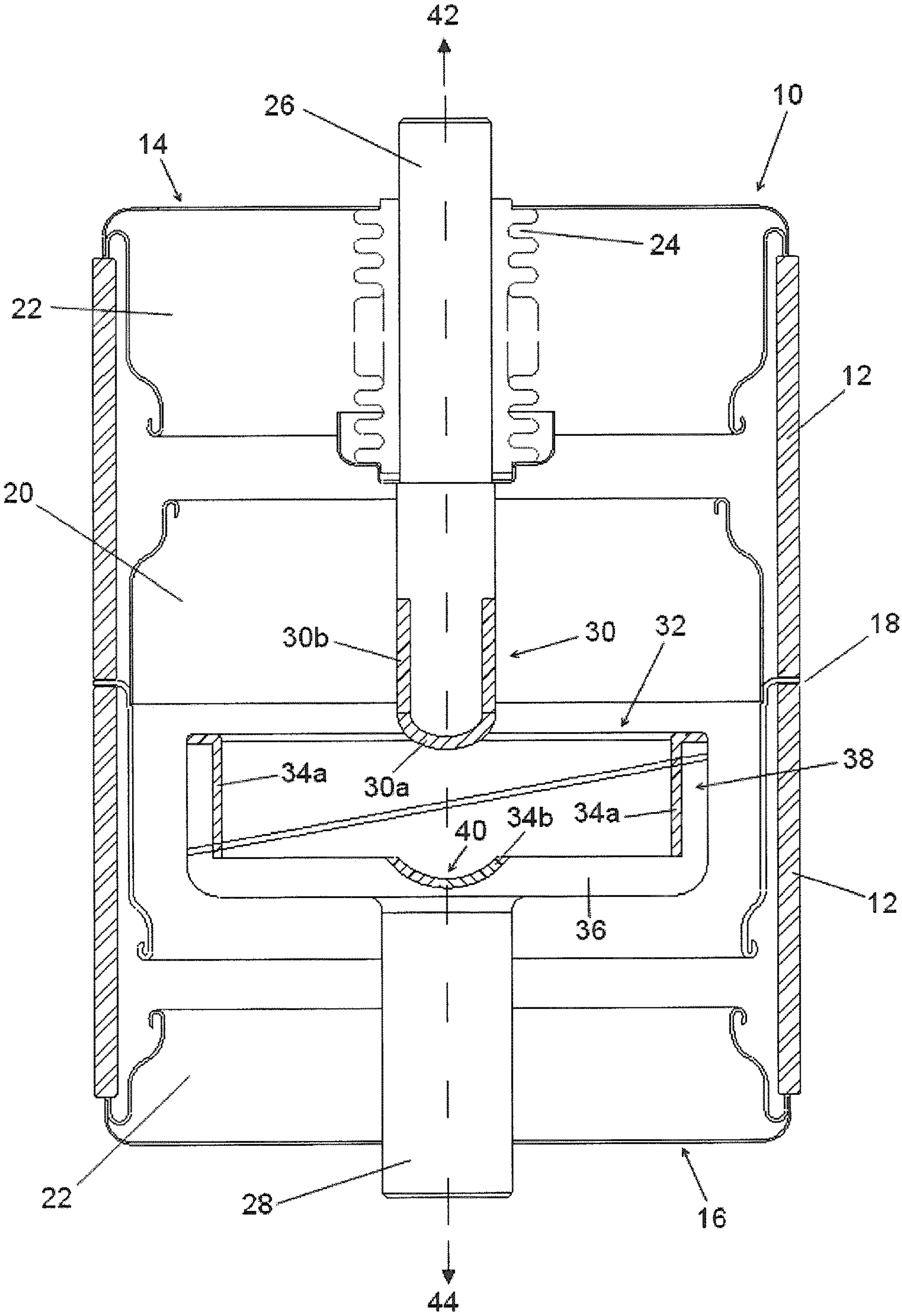
42
26
10
14
24
22
12
20
30b
30
32
18
34a
30a
38
40
34b
34a
12
36
22
28
16
44

Figure 2

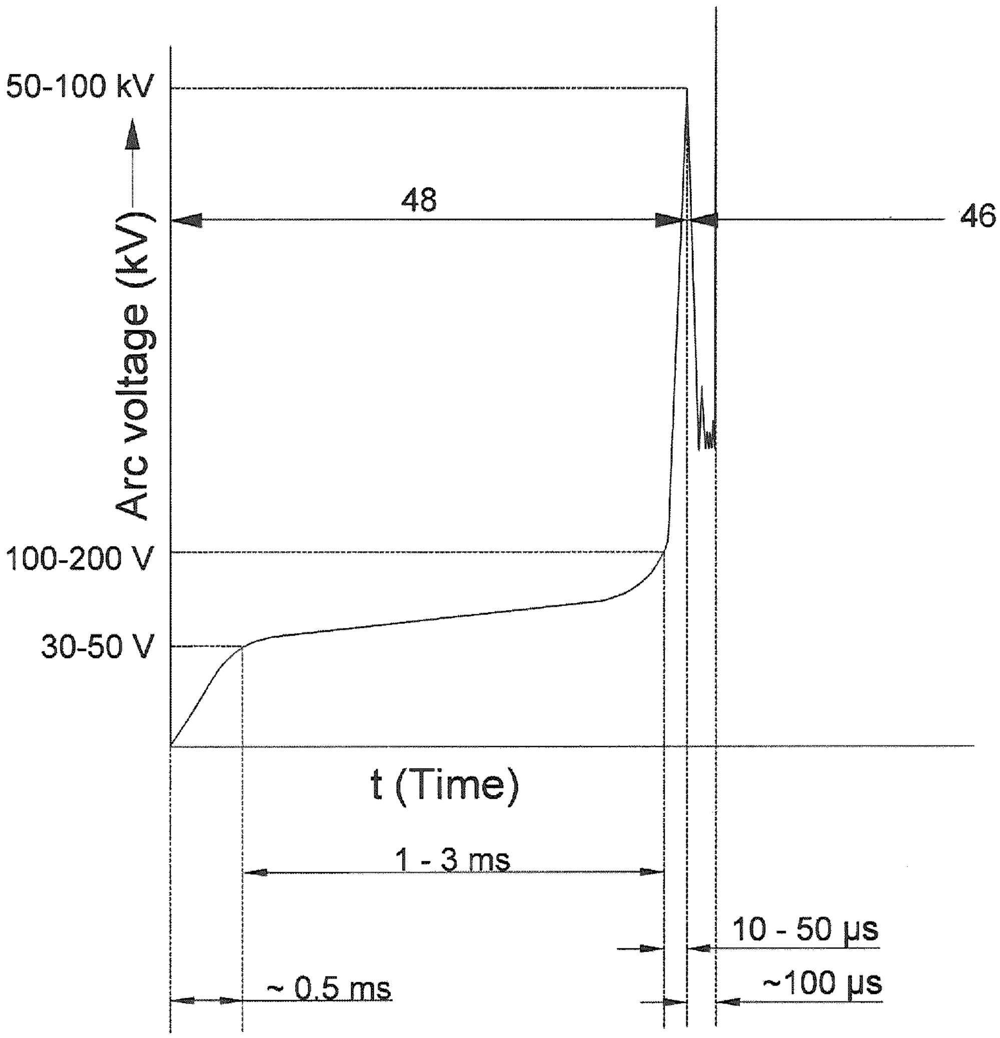
50-100 kV
48
46
Arc voltage (kV)
100-200 V
30-50 V
t (Time)
1 - 3 ms
10 - 50 µs
~ 0.5 ms
~100 µs

Figure 3

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EUROPEAN SEARCH REPORT

Application Number
EP 12 27 5182

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
Y	US 3 252 050 A (LEE THOMAS H) 17 May 1966 (1966-05-17) * column 2, line 38 - column 3, line 44 * * column 6, line 63 - column 7, line 14 * * column 7, line 25 - column 8, line 18 * * figure 3 * -----	1-5, 11-16	INV. H01H33/59 H01H33/664
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Y	US 3 210 505 A (PORTER JOSEPH W) 5 October 1965 (1965-10-05) * the whole document * -----	1-5,7,8, 11-16	

TECHNICAL FIELDS SEARCHED (IPC)

H01H

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	7 June 2013	Ledoux, Serge

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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- **K.H. SCHOENBACH ; M. KRISTIANSEN.** Diffuse Discharges and Opening Switches - A Review of the Tamarrow Workshops. *Proceeding of 4th IEEE Pulsed Power conference,* 1983, 26-32 **[0015]**
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