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(54) Vacuum interrupter assembly

(57) A vacuum switch assembly is for switching a DC current.

The vacuum switch assembly comprises at least one vacuum switch (10), the or each vacuum switch (10) including:

first and second electrically conductive rods (26,28), each rod (26,28) being connectable at a first end to an electrical network (42,44) and extending at the second end into a vacuum tight enclosure;

a first electrode (30) being mounted at the second end of the first rod (26), the first electrode (30) including at least one slot and defining a cathode; and

a second electrode (32) being mounted at a second end of the second rod (28), the second electrode (32) including at least one slot and defining an anode, the second ends of the rods (26,28) extending into the vacuum tight enclosure such that the first and second electrodes (30,32) define opposed electrodes, at least one of the rods (26) being movable relative to the other rod (28) to open or close a gap between the first and second electrodes (30,32),

wherein the diameter of the second electrode (32) is larger than the diameter of the first electrode (30), and

the direction of the or each slot in each electrode (30,32) is arranged to allow magnetic fields respectively generated, in use, by the first and second electrodes (30,32) to interact and form a resultant magnetic field that is substantially perpendicular to an arc current drawn between the first and second electrodes (30,32) at a predetermined separation of the first and second electrodes (30,32).

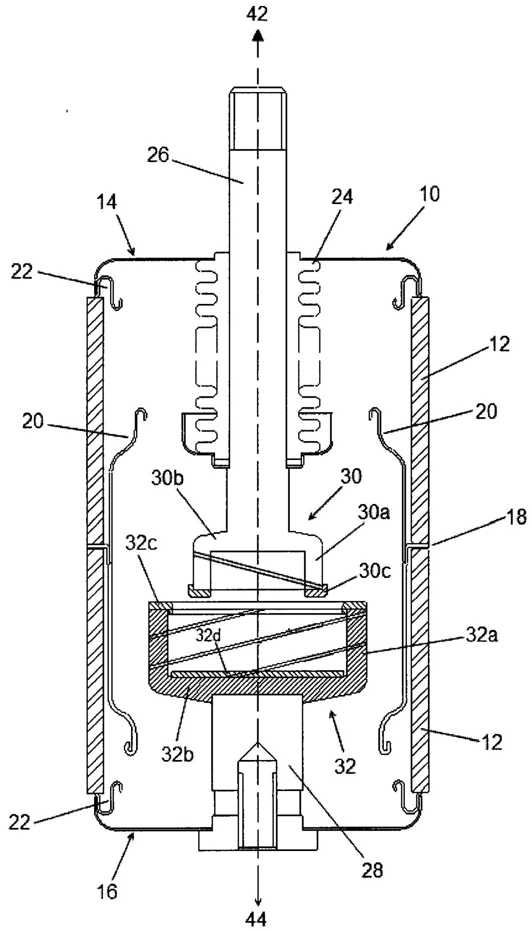

Figure 1

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Description

[0001] This invention relates to a vacuum interrupter assembly 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 vacuum switch assembly for switching a DC current, the vacuum switch assembly comprising at least one vacuum switch, the or each vacuum switch including:

first and second electrically conductive rods, each rod being connectable at a first end to an electrical network and extending at a second end into a vacuum tight enclosure;

a first electrode being mounted at the second end of the first rod, the first electrode including at least one slot and defining a cathode; and

a second electrode being mounted at the second end of the second rod, the second electrode including at least one slot and defining an anode, 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 rod to open or close a gap between the first and second electrodes, wherein the diameter of the second electrode is larger than the diameter of the first electrode, and

the direction of the or each slot in each electrode is arranged to cause magnetic fields respectively generated, in use, by the first and second electrodes to interact and form a resultant magnetic field that is substantially perpendicular to an arc current drawn between the first and second electrodes at a predetermined separation of the first and second electrodes.

[0009] The above configuration of the slotted, first and second electrodes 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 resultant 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 ability to create a current zero in this manner therefore renders the vacuum switch assembly compatible for use as a load break switch or a circuit breaker in a DC network. In addition the use of two slotted electrodes, each capable of generating a respective magnetic field in use, maintains the arc formed between the two electrodes in a diffused mode even at high levels of current, e.g. $\geq$ 6 kA, and thereby permits interruption of high levels of current.

[0010] 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 resultant magnetic field and thereby reduces the complexity of the layout of the vacuum switch assembly. As such, 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.

[0011] Moreover configuration of the or each vacuum switch to set the diameter of the second electrode (anode) to be much larger than the diameter of the first electrode (cathode) results in a more efficient design of the or each vacuum switch for the following reason. The difference in diameter between the two electrodes means that the first electrode is in contact with only a portion of the second electrode when the gap between the first and second electrodes are closed. This allows each slotted portion(s) of the first electrode to be located in the remaining portion of the second electrode so that, in use, current is inhibited from flowing through the slotted portion(s) of the second electrode when the first and second electrodes are in contact. As such the second electrode does not generate a magnetic field when the first and second electrodes are in contact, thus minimising energy losses. Once the arc between the first and second electrodes is formed, expansion of the arc in the diffused mode causes the slotted portion(s) of the second electrode to draw current and thereby generate a magnetic field.

[0012] Furthermore configuration of the or each vacuum switch to set the diameter of the second electrode to be much larger than the diameter of the first electrode causes current to flow, in use, through each slotted portion(s) of the first electrode when the gap between the first and second electrodes is closed, thus allowing the first electrode to generate a magnetic field when the first and second electrodes are in contact. As such the presence of a magnetic field prior to formation of an arc between the first and second electrodes aids the maintenance of the arc in the diffused mode once the arc between the first and second electrodes is formed.

[0013] In embodiments of the invention, the predetermined separation of the first and second electrodes may correspond to a maximum separation of the first and second electrodes.

[0014] The current interruption capability of the or each vacuum switch is dependent on the maximum separation between the first and second electrodes. Thus, ensuring that formation of the resultant magnetic field coincides with the maximum separation between the first and second electrodes utilises the full current interruption capability, and thereby improves the efficiency, of the or each vacuum switch.

[0015] Each electrode may have any geometry that allows it to generate its respective magnetic field so as to enable formation of the required resultant magnetic field, as follows.

[0016] For example, the second electrode may include an annular portion and the first electrode is shaped to be receivable inside the annular portion. Furthermore the first electrode may be sized to maintain a gap between the first electrode and the annular portion when the first electrode is received inside the annular portion.

[0017] In embodiments employing the use of a second electrode with an annular portion, the second electrode may further include a base, the annular portion being mounted on the base, and at least one of the rods may be movable relative to the other rod to open or close a gap between the first electrode and the base when the first electrode is received inside the annular portion.

[0018] At least one of the first and second electrodes may be shaped in the form of either

- a single-slotted or multi-slotted cup
- a single-arm or multi-arm coil.

[0019] In further embodiments employing the use of a second electrode with an annular portion, the resultant magnetic field may be formed to be substantially perpendicular to an arc current drawn in a gap between the annular portion and an outer radial portion of the first electrode. The respective diameters of the first and second electrodes may be selected to ensure that, in use, the resultant magnetic field is substantially perpendicular to an arc current drawn in a gap between the annular portion and an outer radial portion of the first electrode.

[0020] The magnitude of current that can be interrupted by the or each vacuum switch is directly proportional to the diameter of the first electrode and the surface area of the second electrode. Preferably the surface area of the anode is larger than the surface area of the cathode.

[0021] The number of slots and material of each electrode may vary, depending on the design requirements of the vacuum switch. Each electrode may, for example, include either only a single slot or a plurality of slots, and each electrode may, for example, be made from a refractory material, which may be selected from a group of copper-chromium, copper-tungsten, copper tungsten carbide, tungsten, chromium or molybdenum. At least part of the first and/or second electrodes may be made from a material with a chopping current value in the range of 0.5 A to 100 A.

[0022] Optionally the or each vacuum switch may further include a magnetic field generator located outside the vacuum tight enclosure, the magnetic field generator being controllable to provide a pulsed magnetic field inside the vacuum tight enclosure.

[0023] Once the arc current drops to a sufficiently low value, the magnetic field generator may be controlled to generate the pulsed magnetic field to boost the resultant magnetic field and thereby help speed up the extinguishing of any residual arc. In addition, the ability to manipulate the timing of the generation of the pulsed magnetic field and the magnitude of the pulsed magnetic field provides precise control over the current interruption process. The provision of the magnetic field generator also allows each electrode to be made from material that has low chopping current value and high electrical conductivity but are conducive to the high dielectric withstand requirements in a vacuum switch when the first and second electrodes are separated.

[0024] 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.

[0025] 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.

[0026] According to a second aspect of the invention, there is provided a power switching apparatus for switching a DC current, the power switching apparatus including:

a vacuum switch assembly according to any preceding claim; and

a switching assembly connected in parallel with the vacuum switch assembly between a pair of terminals, each of the terminals being connectable in use to an electrical circuit,

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.

[0027] The switching assembly provides additional control over the current interruption process by enabling modification of the magnitude of current flowing through the vacuum switch assembly during the current interruption process. For example, the magnitude 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.

[0028] 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.

[0029] 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.

[0030] 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 crossed-field plasma discharge switch or a crossatron, a hollow-cathode discharge based hollotron;
- a plasma erosion switch;
- a reflex triode switch.

[0031] 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

[0032] 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.

[0033] 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.

[0034] 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.

[0035] In further embodiments of the power switching apparatus according to 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.

[0036] 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.

[0037] 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.

[0038] The predetermined gap between the first and second electrodes may correspond to formation of the resultant magnetic field.

[0039] Once the gap between the first and second electrodes reaches a sufficiently large length, the resultant magnetic field is formed in the gap between the first and second electrodes through interaction of the respective magnetic fields generated by the first and second electrodes. 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 resultant magnetic field to act on all of the current flowing through the or each vacuum switch.

[0040] In still further embodiments of the power switching apparatus according to 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.

[0041] In the presence of the resultant 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.

[0042] 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. In other 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, the switching of the switching assembly from an open state to a closed state taking place only in response to formation of the resultant magnetic field, and the switching assembly may be 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.

[0043] The configuration of the power switching apparatus in this manner provides a further mode of operation of the power switching apparatus to interrupt current.

[0044] 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.

[0045] In embodiments where 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.

[0046] Sequentially opening and closing the plurality of parallel-connected pulsed power switches allows discharge to be maintained in at least one pulsed power switch 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.

[0047] The vacuum switch assembly may be controllable to switch an AC current.

[0048] The power switching apparatus is controllable to switch an AC current.

[0049] Examples of applications that are compatible with the vacuum switch assembly and 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.

[0050] Preferred embodiments of the invention will now be described, by way of non-limiting examples, with reference to the accompanying drawings in which:

Figure 1 shows, in schematic form, a vacuum switch assembly according to a first embodiment of the invention;

Figure 2 shows, in schematic form, the configuration of the vacuum switch assembly of Figure 1 when the first and second electrodes are in contact with each other;

Figure 3 illustrates the magnetic field distribution in the vacuum switch assembly of Figure 1 during formation of the resultant magnetic field;

Figure 4 shows, in schematic form, a vacuum switch assembly according to a second embodiment of the invention;

Figure 5 show, in schematic form, a power switching apparatus according to a third embodiment of the invention; and

Figure 6 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.

[0051] A first vacuum switch assembly according to a first embodiment of the invention is shown in Figure 1.

[0052] The first vacuum switch assembly comprises a single vacuum switch 10.

[0053] 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.

[0054] 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.

[0055] The vacuum switch 10 also includes a tubular bellows 24 and first and second electrically conductive rods 26,28.

[0056] 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.

[0057] 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.

[0058] The vacuum switch 10 further includes first and second electrodes 30,32.

[0059] The first electrode 30 is shaped in the form of a cup in that the first electrode 30 includes a first annular portion 30a and a first base 30b. The first annular portion 30a includes a plurality of slots.

[0060] The first annular portion 30a further includes: first and second faces bridging the inner and outer circumferences of the first annular portion 30a; and a first annular sub-portion 30c mounted on the first face. The first face of the first annular portion 30a is located at a first end of the first annular portion 30a, while the second face of the first annular portion 30a is located at an opposite, second end of the first annular portion 30a and is directly mounted on the first base 30b, which itself is mounted at the second end of the first rod 26.

[0061] The second electrode 32 is also shaped in the form of a cup in that the second electrode 30 includes a second annular portion 32a and a second base 32b. The second annular portion 30a includes a plurality of slots.

[0062] The second annular portion 32a further includes: first and second faces bridging the inner and outer circumferences of the second annular portion 32a; and a second annular sub-portion 32c mounted on the first face. The first face of the second annular portion 32a is located at a first end of the second annular portion 32a, while the second face of the second annular portion 32a is located at an opposite, second end of the second annular portion 32a and is directly mounted on the second base 32b, which itself is mounted at the second end of the second rod 28.

[0063] The second electrode 32 further includes a central electrode portion 32d that is mounted at the centre of the second base 32b.

[0064] The diameter and surface area of the second electrode is much larger than the diameter and surface area of the first electrode. The first electrode 30 is shaped so that it is receivable inside the second annular portion 32a. Furthermore the first electrode 30 is sized to maintain a gap between the first and second annular portions 30a,32a when the first electrode 30 is received inside the second annular portion 32a.

[0065] It is envisaged that, in other embodiments, each annular portion 30a,32a may be replaced by an annular portion that includes only a single slot. Preferably such a single slot would extend completely around the full perimeter, e.g. the circumference of the annular portion.

[0066] The rods 26,28 are coaxially aligned so that the first and second electrodes 30,32 define opposed electrodes.

[0067] Each electrode 30c,32c,32d is made from copper-chromium. In other embodiments, it is envisaged that each electrode may be made from another refractory material, which may be selected from a group of, for example, 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.

[0068] 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 contact between the first annular sub-portion 30c and the central electrode portion 32d, as shown in Figure 2, and a second position where the first electrode 30 is located outside the second electrode 32 and just above the second annular sub-portion 32c, as shown in Figure 1. The second rod 28 is kept at a fixed position.

[0069] When the first rod 26 is at its second position, the flow of current through the first and second annular portions 30a,32a results in generation of respective magnetic fields by the first and second electrodes 30,32. In the gap between the first and second electrodes 30,32, the respective magnetic fields oppose each other. The direction of the plurality of slots in each electrode 30,32 is arranged to cause the magnetic fields respectively generated, in use, by the first and second electrodes 30,32 to interact and form a resultant magnetic field that is substantially perpendicular to any arc current drawn between the first and second annular sub-portions 30c,32c when the first rod 26 is at its second position.

[0070] In addition, when the first rod 26 is at its second position, the separation of the first and second electrodes 30,32 corresponds to a maximum separation of the first and second electrodes 30,32. This is because the current interruption capability of the vacuum switch 10 is dependent on the maximum separation between the first and second electrodes 30,32, and so ensuring that formation of the resultant magnetic field coincides with the maximum separation between the first and second electrodes 30,32 utilises the full current interruption capability, thus improving the efficiency, of the vacuum switch 10.

[0071] In use, the first end of the first rod 26 is connected to a negative terminal 42 of a DC network, while the first end of the second rod 28 is connected to a positive terminal 44 of the DC network. In other words, the first electrode 30 defines a cathode while the second electrode 32 defines an anode.

[0072] 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. 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.

[0073] The low contact resistance resulting from the contact between the first and second electrodes 30,32 and the difference in diameter between the first and second electrode 30,32 means that there is no flow of current through the second annular portion 32a. As such the second electrode 32 does not generate a magnetic field when the first and second electrodes 30,32 are in contact, thus minimising energy losses and thereby improving the efficiency of the vacuum switch 10.

[0074] On the other hand, the structure of the first electrode 30 and the difference in diameter between the first and second electrode 30,32 means that current flows through the first annular portion 30a. As such the first electrode 30 generates a magnetic field when the first and second electrodes 30,32 are in contact. This magnetic field does not affect the conduction of current through the first and second electrodes 30,32 during normal operation of the connected DC electrical circuit.

[0075] 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.

[0076] 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 annular sub-portion 30c and the central electrode portion 32d, which leads to the formation of an arc in this gap.

[0077] The arc consists of metal vapour plasma, which continues to conduct the current flowing between the first and second electrodes 30,32. This is because the metal vapour plasma remains electrically charged under an electric field generated between the two electrodes 30,32. Electrons and negatively charged plasma ions travel from the first electrode 30 to the second electrode 32, and so the flow of current remains established between the two electrodes 30,32. Similarly, positively charged plasma ions travel from the second electrode 32 to the first electrode 30.

[0078] The presence of the magnetic field generated by the first electrode 30 prior to formation of an arc between the first and second electrodes 30,32 aids the maintenance of the arc in a diffused mode once the arc between the first and second electrodes 30,32 is formed. As the gap between the first and second electrodes 30,32 increases and the magnitude of current increases, the metal vapour plasma begins to expand in a diffused mode. This causes the second annular portion 32a to begin drawing current. The shape of the second annular portion 32a causes the drawn current to flow in a preferential direction within the second annular portion 32a, which results in generation of a magnetic field. As described earlier, this magnetic field interacts with the magnetic field generated by the first electrode 30 to form a resultant magnetic field. As described earlier, the direction of the resultant magnetic field is substantially perpendicular to the direction of current being drawn between the first and second annular sub-portions 30c,32c when the first rod 26 is at its second position, as shown in Figure 3 which illustrates the magnetic field distribution of the resultant magnetic field at the maximum separation between the first and second electrodes 30,32.

[0079] In the presence of the combined electric and resultant magnetic fields present between the two electrodes 30,32, the electrons and the negatively-charged plasma ions are forced to deviate from their path and not reach the second electrode 32, i.e. the negatively-charged metal vapour plasma is forced away from reaching the anode 32. This creates a sheath region around the second electrode 32 that creates a sufficiently high arc voltage, which causes the magnitude of the drawn current drops 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.

[0080] 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 first rod 26. Once the first rod 26 reaches the second position, the current will typically drop to zero in about 10 to 20 μs.

[0081] The configuration of the slotted, first and second electrodes 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 resultant magnetic field, and thereby reduces the complexity of the layout of the vacuum switch assembly.

[0082] 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.

[0083] In addition the use of two slotted electrodes 30,32, each capable of generating a magnetic field in use, maintains the arc formed between the two electrodes 30,32 in a diffused mode even at high levels of current, e.g. $\geq$ 6 kA, and thereby permits interruption of high levels of current.

[0084] The magnitude of current that can be interrupted by the vacuum switch 10 is directly proportional to the diameter of the first electrode 30, the separation between the first and second electrodes 30,32, and the surface area of the second electrode 32.

[0085] In other embodiments, it is envisaged that the vacuum switch assembly may include a plurality of series-connected and/or parallel-connected vacuum switches.

[0086] Multiple vacuum switches may be connected to define different configurations of the vacuum switch assembly in order to improve its operating voltage and current characteristics. 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.

[0087] A second vacuum switch assembly according to a second embodiment of the invention is shown in Figure 4. The structure and operation of the second vacuum switch assembly of Figure 4 is similar to that of the first vacuum switch assembly of Figure 1, except that the second embodiment includes a magnetic field generator 46 in the form of a solenoid, which is located outside the vacuum tight enclosure of the vacuum switch 10 and above the end flange 14.

[0088] The magnetic field generator 46 is associated with a DC current source 48. In use, the DC current source 48 is controlled to supply a pulsed DC current to the magnetic field generator 46 so that the magnetic field generator 46 generates a pulsed magnetic field inside the vacuum tight enclosure.

[0089] During the fall in current following the generation of the resultant magnetic field, the magnetic field generator 46 is controlled to generate the pulsed magnetic field once the current reaches a low residual current value. This results in the pulsed magnetic field being superimposed on the resultant magnetic field, and thereby boosts the strength of the resultant magnetic field. This helps to reduce the time required to extinguish the residual arc.

[0090] The provision of the magnetic field generator 46 in the vacuum switch assembly allows each electrode 30,32 to be made from material that has low chopping current value and high electrical conductivity but are conducive to the high dielectric withstand requirements in the vacuum switch 10 during open condition.

[0091] The provision of the magnetic field generator 46 in the vacuum switch assembly also permits precise control over the timing of injection of the pulsed DC current into the magnetic field generator 46 and the magnitude and duration of the injected pulsed DC current and thereby improves the performance of the current interruption process.

[0092] A power switching apparatus 50 according to a third embodiment of the invention is shown in Figure 5.

[0093] The power switching apparatus 50 comprises a pair of terminals 52, a vacuum switch assembly 54, a switching assembly 56 and a control circuit 58.

[0094] The structure of the vacuum switch assembly shown in Figure 5 is identical to that of either of the first and second vacuum switch assemblies shown in Figures 1 and 4. The vacuum switch assembly 54 is connected in parallel with the switching assembly 56 between the terminals 52.

[0095] In use, the terminals 52 are respectively connected to positive and negative terminals of a DC electrical circuit.

[0096] The switching assembly 56 includes a pulsed power switch. The pulsed power switch includes an anode 56a and a cathode 56b.

[0097] The switching assembly 56 is normally kept in an open state to not to conduct current. The switching assembly 56 can be switched to a closed state to conduct current to allow the pulsed power switch to achieve conduction.

[0098] 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 56 to aid current interruption in high voltage applications.

[0099] In use, the first ends of the first and second rods 26, 28 are respectively connected to the terminals 52 of the power switching apparatus 50 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.

[0100] Operation of the power switching apparatus 50 is described as follows, whereby the operation of the vacuum switch assembly is identical to the operation of either of the first and second vacuum switch assemblies shown in Figures 1 and 4.

[0101] 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 56.

[0102] When the tubular bellows 24 is controlled to initiate the current interruption process, the control circuit 58 detects the formation of the gap between the first and second electrodes 30,32, and generates a control signal that is subsequently transmitted to the switching assembly 56. Upon receipt of the control signal, the switching assembly 56 is controlled to switch from an open state to a closed state. The switching assembly 56 then begins to conduct current, which has the effect of diverting part of the current through the switching assembly 56. Thus, both the vacuum switch assembly 54 and the switching assembly 56 conduct and share the current depending upon the voltage drop across them.

[0103] 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 annular sub-portion 30c and the central electrode portion 32d. 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 components of the power switching apparatus 50.

[0104] The diversion of current flow through the switching assembly 56 not only limits the arc voltage across the vacuum switch 10, but also reduces the current density at the first annular sub-portion 30c and the central electrode portion 32d 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.

[0105] Upon formation of the resultant magnetic field, the switching assembly 56 is controlled to switch from a closed state to an open state. The switching assembly 56 then stops conducting current, which has the effect of causing all of the current to flow through the vacuum switch 10. This allows the resultant magnetic field to act on all of the current flowing through the vacuum switch 10 and thereby allow full dielectric recovery and successful current interruption to take place.

[0106] Optionally, prior to the extinguishing of current in the vacuum switch 10, the switching assembly 56 may be further controlled to switch from an open state to a closed state at a predetermined level of current. Switching the switching assembly 56 to a closed state in the moments prior to the current being extinguished diverts the flow of any residual current through the switching assembly 56. 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 56 being controlled to switch back to an open state to complete the current interruption process.

[0107] Such operation of the power switching apparatus 50 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.

[0108] Figure 6 illustrates, in graph form, the behaviour of the arc voltage across the power switching apparatus 50 during an optional, further mode of operation of the power switching apparatus 50.

[0109] In the optional, further mode of operation of the power switching apparatus 50, following initiation of the current interruption process, the switching assembly 56 is not switched from an open state to a closed state in response to formation of the gap between the first annular sub-portion 30c and the central electrode portion 32d. Instead the control circuit 58 switches 60 of the switching assembly 56 from an open state to a closed state only in response to build-up of the arc voltage caused by the formation of the resultant magnetic field and prior to the extinguishing of current in the vacuum switch 10. In the period 62 prior to the switching 60 of the switching assembly 56 to switch from an open state to a closed state, the arc current only flows through the vacuum switch assembly 54.

[0110] As such the switching assembly 56 is switched 60 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 56 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 56 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.

[0111] The parallel connection of the vacuum switch and switching assemblies 54,56 in the power switching apparatus 50 has therefore been found to improve current interruption carried out using the vacuum switch 10.

[0112] The switching assembly 56 provides additional control over the current interruption process by enabling modification of the magnitude of current flowing through the vacuum switch 10 during the current interruption process.

[0113] The parallel connection of the vacuum switch and switching assemblies 54,56 in the power switching apparatus 50 also results in a simple layout of the power switching apparatus 50, which in turn reduces the manufacturing and installation costs of such an apparatus 50.

[0114] It is 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.

[0115] 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.

[0116] For example, multiple vacuum switches and pulsed power switches can be connected in series and parallel to interrupt continuous current $\geq$ 6 kA and short-circuit current $\geq$ 100kA at an operating voltage of $\geq$ 400kV of a HVDC multi-terminal network.

[0117] 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.

[0118] 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 in at least one pulsed power switch 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.

[0119] 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 slotted cup;
- a single-arm or multi-arm coil.

[0120] The vacuum switch assemblies of Figures 1 and 2, and the power switching apparatus of Figure 5 are compatible for use, but are not limited to, applications such as 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 vacuum switch assembly for switching a DC current, the vacuum switch assembly comprising at least one vacuum switch, the or each vacuum switch including:

first and second electrically conductive rods, each rod being connectable at a first end to an electrical network and extending at a second end into a vacuum tight enclosure;

a first electrode being mounted at the second end of the first rod, the first electrode including at least one slot and defining a cathode; and

a second electrode being mounted at the second end of the second rod, the second electrode including at least one slot and defining an anode, 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 rod to open or close a gap between the first and second electrodes,
wherein the diameter of the second electrode is larger than the diameter of the first electrode, and
the direction of the or each slot in each electrode is arranged to cause magnetic fields respectively generated, in use, by the first and second electrodes to interact and form a resultant magnetic field that is substantially perpendicular to an arc current drawn between the first and second electrodes at a predetermined separation of the first and second electrodes.

2. A vacuum switch assembly according to any preceding claim wherein the predetermined separation of the first and second electrodes corresponds to a maximum separation of the first and second electrodes.

3. A vacuum switch assembly according to any preceding claim wherein the second electrode includes an annular portion and the first electrode is shaped to be receivable inside the annular portion.

4. A vacuum switch assembly according to Claim 3 wherein the first electrode is sized to maintain a gap between the first electrode and the annular portion when the first electrode is received inside the annular portion.

5. A vacuum switch assembly according to Claim 3 or Claim 4 wherein the second electrode further includes a base, the annular portion being mounted on the base, and at least one of the rods is movable relative to the other rod to open or close a gap between the first electrode and the base when the first electrode is received inside the annular portion.

6. A vacuum switch assembly according to any preceding claim wherein at least one of the first and second electrodes is shaped in the form of either:

- a single-slotted or multiple-slotted cup;
- a single-arm or multi-arm coil.

7. A vacuum switch assembly according to any of Claims 3 to 6 wherein the resultant magnetic field is formed to be substantially perpendicular to an arc current drawn in a gap between the annular portion and an outer radial portion of the first electrode.

8. A vacuum switch assembly according to any preceding claim wherein the surface area of the anode is larger than the surface area of the cathode.

9. A vacuum switch assembly according to any preceding claim wherein at least part of the first and/or second electrodes is made from a material with a chopping current value in the range of 0.5 A to 100 A.

10. A vacuum switch assembly according to any preceding claim wherein the or each vacuum switch further includes a magnetic field generator located outside the vacuum tight enclosure, the magnetic field generator being controllable to provide a pulsed magnetic field inside the vacuum tight enclosure.

11. A vacuum switch assembly according to any preceding claim including a plurality of series-connected and/or parallel-connected vacuum switches.

12. A power switching apparatus for switching a DC current, the power switching apparatus including:

a vacuum switch assembly according to any preceding claim; and
a switching assembly connected in parallel with the vacuum switch assembly between a pair of terminals, each of the terminals being connectable in use to an electrical circuit,
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.

13. A power switching apparatus according to Claim 12 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.

14. A power switching apparatus according to Claim 12 or Claim 13 further including a control circuit to switch the switching assembly between open and closed states.

15. A power switching apparatus according to any of Claims 12 to 14 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.

16. A power switching apparatus according to Claim 15 wherein the switching assembly is controllable to switch from a closed state to an open state at a predetermined separation of 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.

17. A power switching apparatus according to Claim 16 wherein the predetermined separation of the first and second electrodes of the or each vacuum switch corresponds to formation of the resultant magnetic field.

18. A power switching apparatus according to any of Claims 12 to 17 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.

19. A power switching apparatus according to Claim 18 wherein the predetermined level of current corresponds to flow of residual current in the or each vacuum switch.

20. A power switching apparatus according to any of Claims 12 to 14 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, the switching of the switching assembly from an open state to a closed state taking place only in response to formation of the resultant magnetic field, and the switching assembly is controllable to switch from a closed state to an open state following the extinguishing of current in the or each vacuum switch.

21. A power switching apparatus according to Claim 20 wherein the predetermined level of current corresponds to flow of residual current in the or each vacuum switch.

22. 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.

23. A power switching apparatus according to Claim 23 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.

24. A vacuum switch assembly according to any of Claims 1 to 11 wherein the vacuum switch assembly is controllable to switch AC current.

25. A power switching apparatus according to any of Claims 12 to 23 wherein the power switching apparatus is controllable to switch AC current.

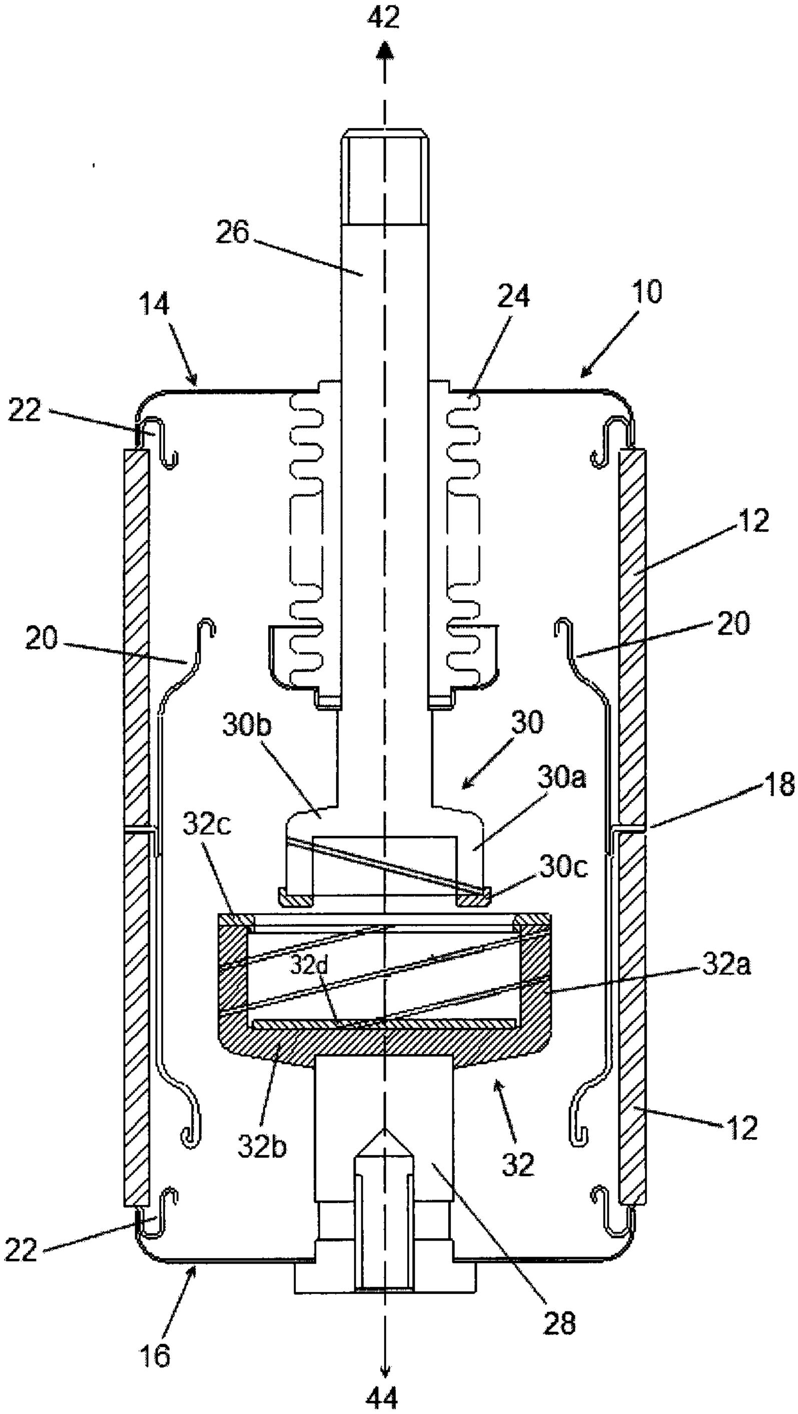
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Figure 1

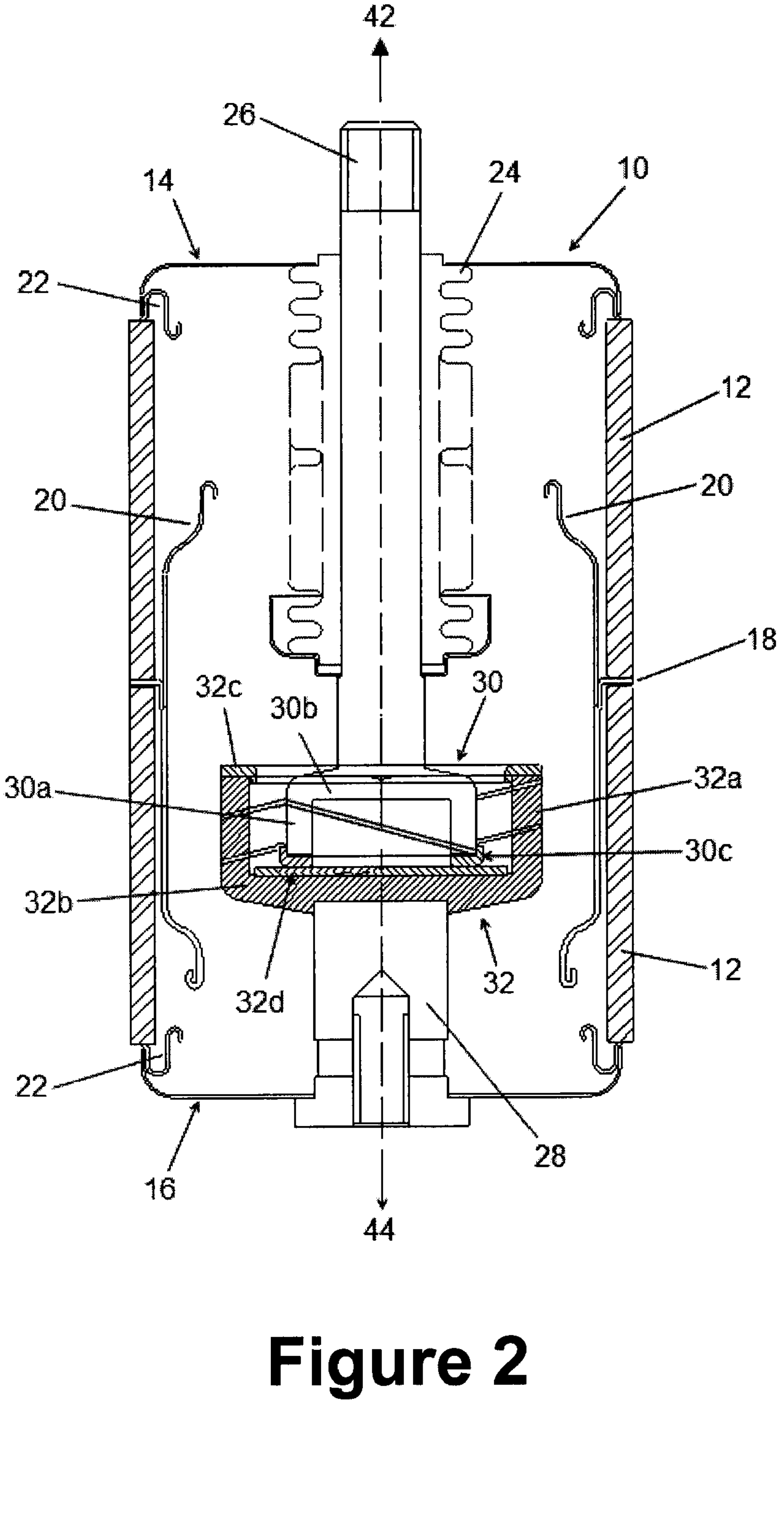
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Figure 2

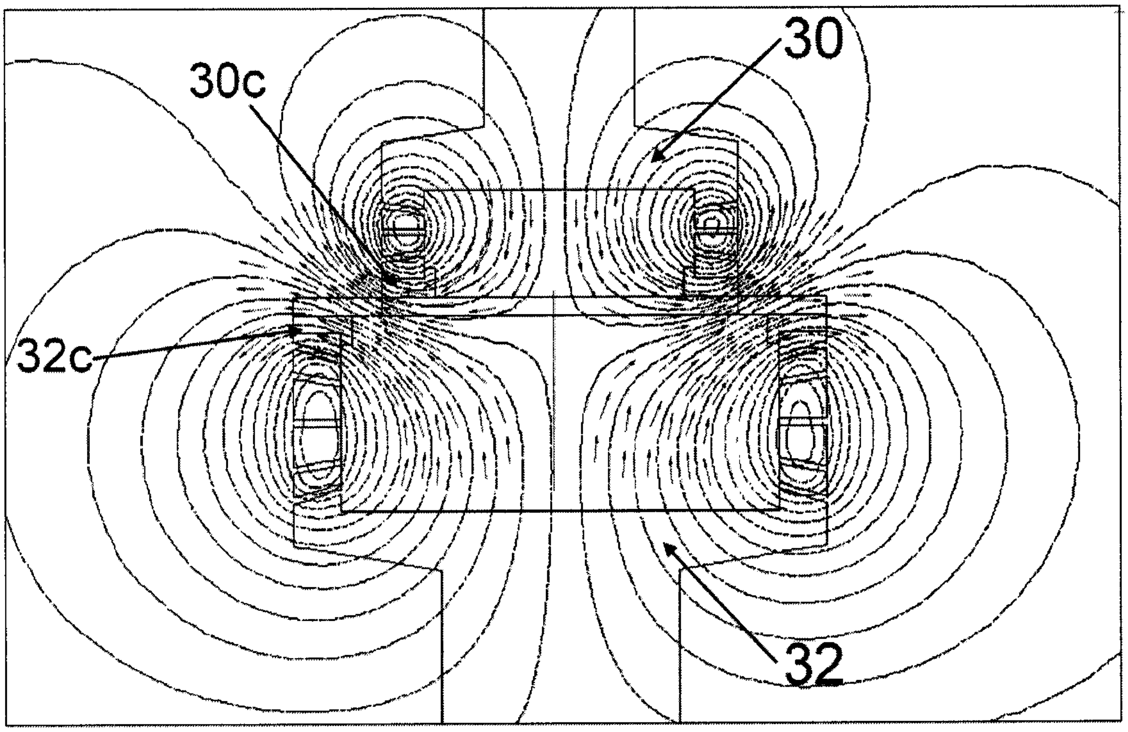

Figure 3

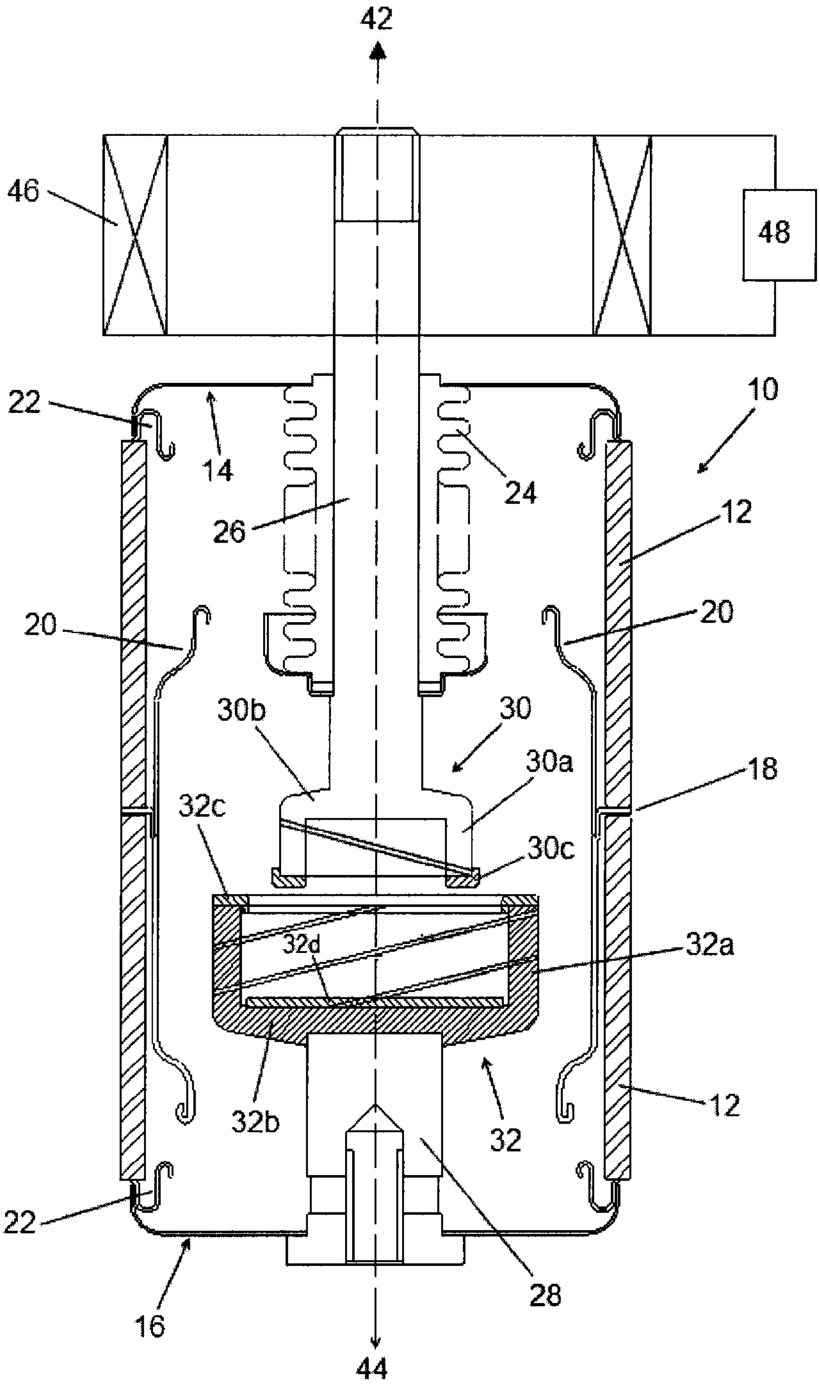
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Figure 4

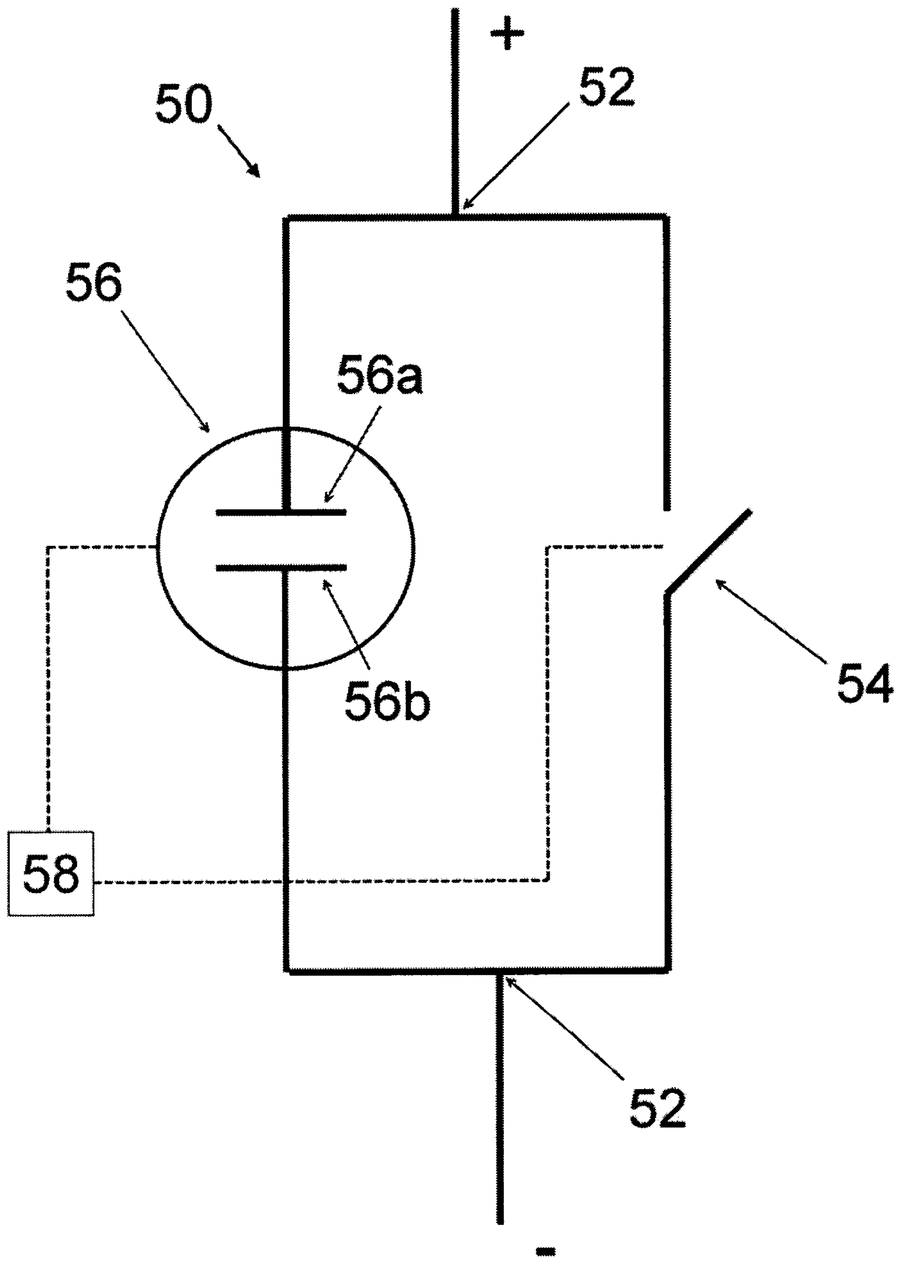

Figure 5

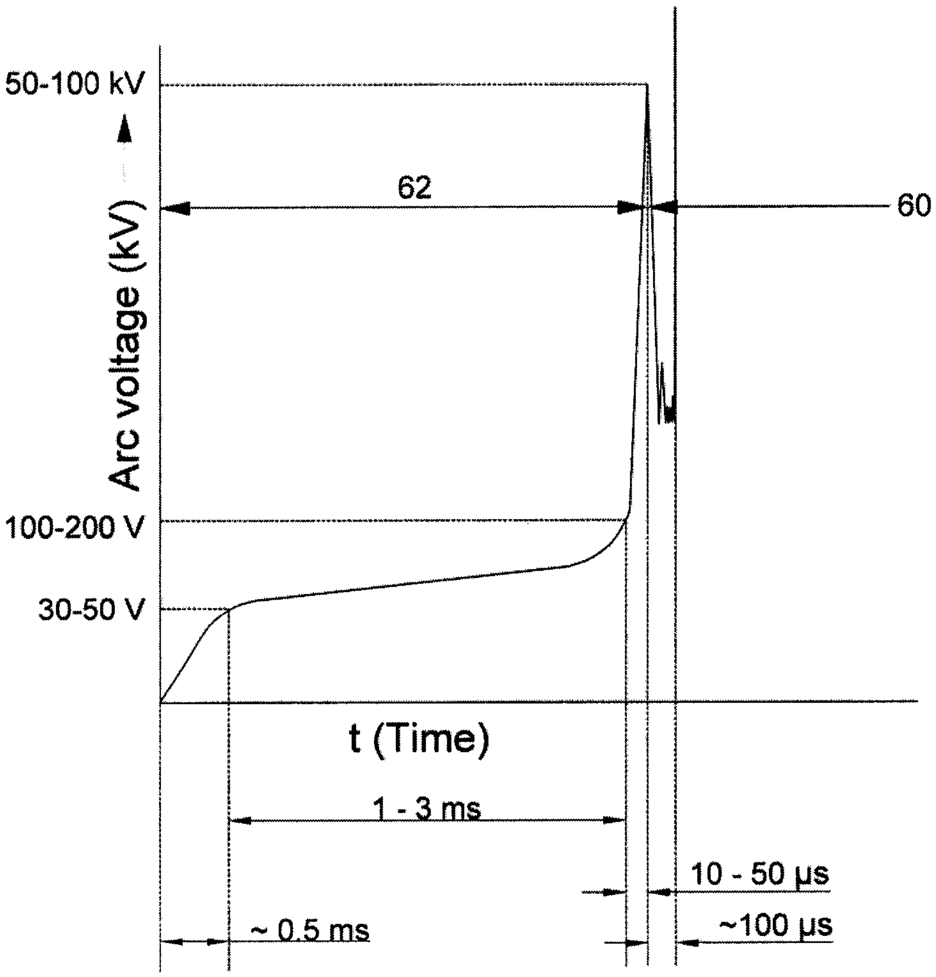
50-100 kV
Arc voltage (kV)
62
60
100-200 V
30-50 V
t (Time)
1 - 3 ms
10 - 50 μs
~100 μs
~ 0.5 ms

Figure 6

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EUROPEAN SEARCH REPORT

Application Number
EP 12 27 5184

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X Y	US 3 366 762 A (SMITH JR SIDNEY R) 30 January 1968 (1968-01-30) * column 2, lines 25-47 * * column 3, line 67 - column 4, line 41 * * figures 1,2,4,5 * -----	1-11,24 12-16, 18,19, 22,23,25	INV. H01H33/59 H01H33/664
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 * -----	12-16, 22,23,25	
Y	US 3 475 620 A (MURRAY JOHN G ET AL) 28 October 1969 (1969-10-28) * column 1, lines 14-21 * * column 2, lines 39-63 * * column 3, lines 35-47 * * column 4, lines 30-33 * * column 5, lines 9-53 * * figures 2,3,4,6 * -----	18,19	TECHNICAL FIELDS SEARCHED (IPC)
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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

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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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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