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(54) **Power switching apparatus**

(57) A power switching apparatus is for switching an AC or DC current.

The power switching apparatus comprises first and second switching assemblies (12,14) connected in parallel, wherein the first switching assembly (12) includes at least one switching element (20), the first switching assembly (12) conducting and carrying current only in its closed state, the first switching assembly (12) being controllable to switch to its closed state only when a voltage drop across the first switching assembly (12) matches or exceeds its forward voltage drop, wherein the or each switching element (20) is controllable to modify, in use of the power switching apparatus, a current flowing through the second switching assembly (14), and

the second switching assembly (14) includes:

a vacuum interrupter assembly (25) including at least one vacuum interrupter (26);
an electrical device (28) coupled with the vacuum interrupter assembly; and
a control unit (16);

wherein, in use of the vacuum interrupter assembly (25) to interrupt current, the control unit (16) controls the electrical device (28) to create a voltage or magnetic field which increases the voltage drop across the second switching assembly (14) so that the voltage drop across the second switching assembly (14) matches or exceeds the forward voltage drop of the first switching assembly (12).

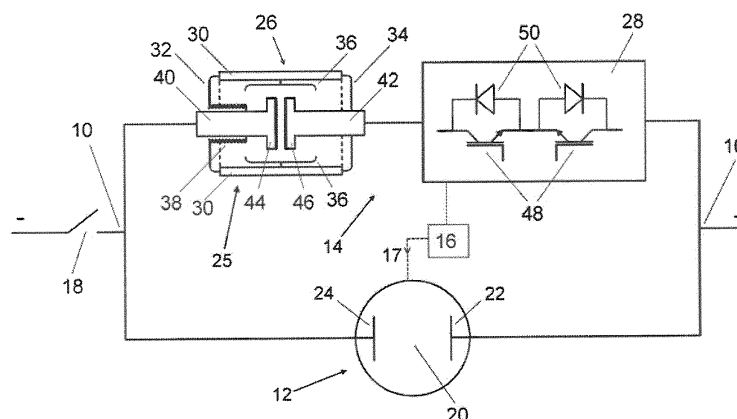


Figure 1

Description

[0001] This invention relates to a power switching apparatus for switching an AC or 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 an aspect of the invention, there is provided a power switching apparatus for switching an

AC or DC current, the power switching apparatus comprising first and second switching assemblies connected in parallel, wherein

the first switching assembly includes at least one switching element, the first switching assembly conducting and carrying current only in its closed state, the first switching assembly being controllable to switch to its closed state only when a voltage drop across the first switching assembly matches or exceeds its forward voltage drop, wherein the or each switching element is controllable to modify, in use of the power switching apparatus, a current flowing through the second switching assembly, and the second switching assembly includes:

a vacuum interrupter assembly including at least one vacuum interrupter;
an electrical device coupled with the vacuum interrupter assembly; and a control unit;

wherein, in use of the vacuum interrupter assembly to interrupt current, the control unit controls the electrical device to create a voltage or magnetic field which increases the voltage drop across the second switching assembly so that the voltage drop across the second switching assembly matches or exceeds the forward voltage drop of the first switching assembly.

[0009] The or each vacuum interrupter may include a pair of contact electrodes, the contact electrodes being connectable to an electrical network. At least one contact electrode may be movable relative to the other contact electrode to open or close a gap between the contact electrodes.

[0010] In embodiments in which at least one contact electrode is movable relative to the other contact electrode to open or close a gap between the contact electrodes, the control unit may control the electrical device to create the voltage or magnetic field on or after formation of a gap between the contact electrodes of the or each vacuum interrupter in order to increase the voltage drop across the second switching assembly so that the voltage drop across the second switching assembly matches or exceeds the forward voltage drop of the first switching assembly.

[0011] During normal operation, current only flows through the second switching assembly, i.e. through the closed electrodes of the or each vacuum interrupter, while the first switching assembly remains in an open state and therefore does not conduct current. In the event of a need to interrupt the current flowing through the power switching apparatus, the contact electrodes of the or each vacuum interrupter are opened to form a gap therebetween. This leads to the formation of an arc in the gap between the contact electrodes of the or each vacuum interrupter.

[0012] An increase in the gap between the contact electrodes of the or each vacuum interrupter causes a rise in arc voltage between the contact electrodes of the or each vacuum interrupter. Accordingly the magnitude

of the arc current drops until it reaches a lower limit which is proportional to the arc voltage generated. At this stage the first switching assembly can be switched to transfer the residual current from the second switching assembly to the first switching assembly. This allows the current in the or each vacuum interrupter to drop instantly to zero, and thereby allow full dielectric recovery of the or each vacuum interrupter. This is followed by the first switching assembly being controlled to switch back to an open state to complete the current interruption process.

[0013] The first switching assembly therefore provides additional control over the current interruption process by enabling modification of the magnitude of current flowing through the vacuum interrupter assembly during the current interruption process. Furthermore the first switching assembly can be switched to modify the magnitude of current flowing in the or each vacuum interrupter during the current interruption process to minimise any adverse effects of high current densities on the contact electrodes to thereby improve the lifetime of the vacuum interrupter assembly.

[0014] The parallel connection of the first and second switching assemblies in the power switching apparatus therefore improves the current interruption process. In addition the parallel connection of the first and second switching assemblies in the power switching apparatus results in a simple layout of the power switching apparatus, which in turn reduces the manufacturing and installation costs of such an apparatus.

[0015] However some types of first switching assemblies may have a relatively high forward voltage drop. Therefore, the maximum arc voltage that can be formed in the or each vacuum interrupter by itself may be insufficient to cause a total voltage drop across the second switching assembly to be high enough so that the voltage drop across the second switching assembly matches or exceeds the forward voltage drop of the first switching assembly. This would thereby inhibit transfer of current from the second switching assembly to the first switching assembly and thereby prevent the first switching assembly from modifying the magnitude of current flowing through the vacuum interrupter assembly during the current interruption process.

[0016] On the other hand the inclusion of the electrical device in the power switching apparatus according to the invention enables the creation of a voltage for combination with the arc voltage between the contact electrodes of the or each vacuum interrupter, or a magnetic field to interact with the electric field present between the contact electrodes so as to increase the arc voltage in the or each vacuum interrupter, thus increasing the total voltage drop across the second switching assembly so that it matches or exceeds the forward voltage drop of the first switching assembly.

[0017] The electrical device is rated so that its operation during the current interruption process causes the total voltage drop across the second switching assembly to be high enough so that the voltage drop across the

second switching assembly matches or exceeds the forward voltage drop of the first switching assembly. This enables the first switching assembly to conduct and carry current, and thereby permits transfer of current from the second switching assembly to the first switching assembly. In this manner the electrical device enables modification of the magnitude of current flowing through the vacuum interrupter assembly during the current interruption process even when the maximum arc voltage that can be formed in the or each vacuum interrupter by itself is insufficient to cause a voltage drop across the second switching assembly to be high enough so that the voltage drop across the second switching assembly matches or exceeds forward voltage drop of the first switching assembly.

[0018] The inclusion of the electrical device in the power switching apparatus according to the invention therefore enables use of the vacuum interrupter assembly with a wider range of first switching assemblies to generate high voltage drop. This in turn provides additional flexibility when it comes to design and construction of the components of the power switching apparatus.

[0019] In embodiments of the invention, the control unit may control the electrical device to create the voltage or magnetic field on or after formation of a predetermined arc voltage in the or each vacuum interrupter in order to increase the voltage drop across the second switching assembly so that the voltage drop across the second switching assembly matches or exceeds the forward voltage drop of the first switching assembly. Preferably the predetermined arc voltage corresponds to the maximum arc voltage that can be formed in the or each vacuum interrupter.

[0020] In further embodiments of the invention, the or each switching element may be a pulsed power switch.

[0021] 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 first switching assembly to aid current interruption in high voltage applications.

[0022] The or each pulsed power switch may be, for example, 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 thyatron, a crossed-field plasma discharge switch or a crossatron, a hollow-cathode discharge-based hollotron;
- a plasma erosion switch;

- a reflex triode switch.

[0023] 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 Tamarow 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

[0024] 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.

[0025] 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.

[0026] In still further embodiments of the invention, the electrical device may be any one of:

- a voltage generator;
- a gas filled switch;
- a magnetic field generator, e.g. a solenoid.

[0027] The voltage generator may include at least one semiconductor switching device. This allows the electrical device to present a low impedance based on closed semiconductor switching devices during normal operation when current only flows through the second switching assembly.

[0028] The electrical device may be connected in series with the vacuum interrupter assembly when the electrical device is controllable to create a voltage. This allows a voltage created by the electrical device to be combined in series with the total arc voltage across the vacuum interrupter assembly so as to increase the total voltage across the second switching assembly.

[0029] The electrical device may be located outside the vacuum interrupter when the electrical device may be controllable to create a magnetic field. This allows the electrical device to be coupled with any vacuum inter-

rupter without requiring significant change in design and construction of the vacuum interrupter.

[0030] In embodiments in which the electrical device is controllable to create a magnetic field, the electrical device may be arranged with respect to the or each vacuum interrupter to enable the electrical device to create a magnetic field that is substantially perpendicular to the direction of an arc current formed in the or each vacuum interrupter when the electrical device is controllable to create a magnetic field.

[0031] The creation of a magnetic field that is perpendicular to the arc current formed in the or each vacuum interrupter assists the rise in arc voltage during, and thereby improves the reliability of, the current interruption process.

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

[0033] Multiple vacuum interrupters may be connected to define different configurations of the vacuum interrupter 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 interrupter assembly, multiple switching elements may be connected to define different configurations of the first switching assembly in order to vary its operating voltage and current characteristics to match the requirements of the associated power application. The first switching assembly may, for example, include a plurality of series-connected and/or parallel-connected pulsed power switches.

[0035] In embodiments where the first switching assembly includes a plurality of parallel-connected pulsed power switches, the first switching assembly may include a plurality of parallel-connected switching elements, the first switching assembly being controllable to sequentially open or close the plurality of parallel-connected switching elements.

[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 first switching assembly. This in turn renders the first switching assembly compatible for use in current interruption processes in which the time taken to initially separate the contact 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] Examples of applications that are compatible with the power switching apparatus according to the invention include, for example, AC power networks, AC and DC high voltage circuit breakers, AC generator circuit breakers, transmission lines, railway traction, ships, superconducting magnetic storage devices, high energy fusion reactor experiments, stationary power applications,

renewable energy resources such as fuel cells and photovoltaic cells and high voltage direct current (HVDC) multi-terminal networks.

[0038] 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 power switching apparatus according to a first embodiment of the invention;

Figure 2 illustrates, in graph form, the behaviour of the arc voltage across the terminals of the power switching apparatus of Figure 1 during its operation; Figure 3 shows, in schematic form, a power switching apparatus according to a first embodiment of the invention; and

Figure 4 shows, in schematic form, a power switching apparatus according to a first embodiment of the invention.

[0039] A first power switching apparatus according to a first embodiment of the invention is shown in Figure 1.

[0040] The first power switching apparatus comprises a pair of terminals 10, a first switching assembly 12, a second switching assembly 14 and a control unit 16. The first and second switching assemblies 12, 14 are connected in parallel between the terminals 10.

[0041] In use, one of the terminals 10 is connected via an isolator 18 to the negative terminal of a DC electrical circuit, and the other of the terminals 10 is connected to a positive terminal of the DC electrical circuit.

[0042] The first switching assembly 12 includes a pulsed power switch 20. The pulsed power switch 20 includes an anode 22 and a cathode 24.

[0043] The first switching assembly 12 is normally kept in an open state to not to conduct current. The first switching assembly 12 can be switched to a closed state to conduct current only if the voltage drop across the pulsed power switch 20 is high enough to allow the pulsed power switch 20 to achieve conduction, i.e the voltage drop developed across the pulsed power switch 20 matches or exceeds its forward voltage drop.

[0044] The pulsed power switch 20 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 20 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 20 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 20 compatible for use in the first switching assembly 12 to aid current interruption in high voltage applications.

[0045] The second switching assembly 14 includes a vacuum interrupter assembly 25 and a voltage generator

28.

[0046] The vacuum interrupter assembly 25 includes a single vacuum interrupter 26. In other embodiments of the invention, the vacuum interrupter assembly may include a plurality of vacuum interrupters.

[0047] The vacuum interrupter 26 includes a cylindrical housing 30, a first end flange 32 and a second end flange 34 assembled to define a vacuum tight enclosure. Each end flange 32, 34 is brazed to the cylindrical housing 30 to form a hermetic joint. The vacuum interrupter 26 further includes a central shield 36 that overlaps inner walls of the cylindrical housing 30 to protect the inner walls of the cylindrical housing 30 from metal vapour deposition arising from arc discharge.

[0048] Each cylindrical housing 30 is metallised and nickel-plated at both ends. The length and diameter of the respective cylindrical housing 30 varies depending on the operating voltage rating of the vacuum interrupter 26, while the dimensions and shape of the first and second end flanges 32, 34 may vary to correspond to the size and shape of the cylindrical housing 30.

[0049] The vacuum interrupter 26 also includes a tubular bellows 38 and first and second electrically conductive rods 40, 42.

[0050] The first end flange 32 includes a hollow bore dimensioned to accommodate the tubular bellows 38, while the second end flange 34 includes a hollow bore dimensioned to accommodate the second rod 42 within its hollow bore. The tubular bellows 38 also includes a hollow bore for retention of the first rod 40.

[0051] The first and second rods 40, 42 are respectively retained within the hollow bores of the tubular bellows 38 and the second end flange 34 so that the second ends of the rods 40, 42 are located inside the enclosure and the first ends of the rods 40, 42 are located outside the enclosure. The first and second rods 40, 42 may be fabricated from, for example, oxygen-free high conductivity (OFHC) copper.

[0052] The vacuum interrupter 26 further includes first and second contact electrodes 44, 46.

[0053] The first contact electrode 44 is mounted at the second end of the first rod 40, while the second contact electrode 46 is mounted at the second end of the second rod 42. The rods 40, 42 are coaxially aligned so that the first and second contact electrodes 44, 46 define opposed electrodes.

[0054] Each contact electrode 44, 46 is made from a refractory material, which may be selected from a group of, for example, copper-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.

[0055] Corrugated walls of the tubular bellows 38 allow

the tubular bellows 38 to undergo expansion or contraction so as to increase or decrease the tubular length of the tubular bellows 38. This allows the first rod 40 to move relative to the second rod 42 between a first position where the first and second contact electrodes 44,46 are kept in contact, and a second position where the first and second contact electrodes 44,46 are kept at a maximum separation therebetween. The second rod 42 is kept at a fixed position.

[0056] The voltage generator 28 further includes a plurality of series-connected semiconductor switching devices. Each semiconductor switching device constitutes an insulated gate bipolar transistor 48 connected in parallel with an anti-parallel diode 50. It is envisaged that, in other embodiments of the invention, each insulated gate bipolar transistor 48 may be replaced by a different type of semiconductor switching device.

[0057] In use, the vacuum interrupter 26 is connected in series with the voltage generator 28 between the terminals 10 of the first power switching apparatus so that the first end of the first rod 40 is connected via the isolator 18 to the negative terminal of the DC electrical circuit, the first end of the second rod 42 is connected in series with the voltage generator 28, and the voltage generator 28 is connected to the positive terminal of the DC electrical circuit.

[0058] The first power switching apparatus further includes a control unit 16. In use, the control unit 16 controls the voltage generator 28 to selectively generate a voltage, and switches the semiconductor switching devices to either enable the voltage generator 28 to insert the generated voltage in series with the vacuum interrupter 26, or provide a low impedance path for the current flowing through the second switching assembly 14 when the voltage generator 28 is not controlled to generate a voltage.

[0059] The vacuum interrupter 26 and voltage generator 28 are rated so that the series combination of the maximum arc voltage of the vacuum interrupter 26 and the voltage created by the voltage generator 28 is high enough to establish a voltage drop across the second switching assembly 14 that is high enough to match or exceed the forward voltage drop across the pulsed power switch 20.

[0060] During normal operation of the connected DC electrical circuit, the tubular bellows 38 is controlled to move the first rod 40 to the first position to bring the first and second contact electrodes 44,46 into contact, and the control unit 16 switches the semiconductor switching devices to provide the low impedance path for the current flowing through the second switching assembly 14. At the same time the pulsed power switch 20 remains in an open state. This allows current to flow between the positive and negative terminals of the connected DC electrical circuit via the electrically conductive rods 40,42 of the vacuum interrupter 26 and the low impedance path provided by the semiconductor switching devices of the voltage generator 28, whilst no current flows through the first

switching assembly 12.

[0061] 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.

[0062] The current interruption process is initiated by controlling the tubular bellows 38 to move the first rod 40 towards its second position so as to separate the first and second contact electrodes 44,46. The separation of the first and second contact electrodes 44,46 results in the formation of a gap between the first and second contact electrodes 44,46, which leads to the formation of an arc in this gap.

[0063] The arc consists of metal vapour plasma, which continues to conduct the current flowing between the first and second contact electrodes 44,46. This is because the metal vapour plasma remains electrically charged under an electric field generated between the two electrodes 44,46. Electrons and negatively charged plasma ions travel from the first contact electrode 44 to the second contact electrode 46, and so the flow of current remains established between the two contact electrodes 44,46. Similarly, positively charged plasma ions travel from the second contact electrode 46 to the first contact electrode 44.

[0064] Figure 2 illustrates, in graph form, the behaviour of the arc voltage across the terminals 10 of the first power switching apparatus during its operation.

[0065] An increase in the gap between the contact electrodes 44,46 of the vacuum interrupter 26 causes a rise 52 in arc voltage between the contact electrodes 44,46. When the first rod 40 reaches its second position, i.e. the contact electrodes 44,46 are at their maximum separation, the maximum arc voltage of the vacuum interrupter 26 is established. Meanwhile the magnitude of the arc current drawn between the contact electrodes 44,46 drops until it reaches a lower limit which is proportional to the arc voltage generated.

[0066] At this stage 54 the voltage drop across the second switching assembly 14 is not high enough to match or exceed the forward voltage drop of the pulsed power switch 20.

[0067] Once the maximum arc voltage of the vacuum interrupter 26 is established, the control unit 16 controls the voltage generator 28 to generate a voltage and switches the semiconductor switching devices to enable the voltage generator 28 to insert the generated voltage in series with the vacuum interrupter 26. The series combination of the maximum arc voltage of the vacuum interrupter 26 and the voltage created by the voltage generator 28 causes a rise 56 in voltage drop across the second switching assembly 14. This in turn causes in the voltage drop across second switching assembly 14 to match or exceed the forward voltage drop of the pulsed power switch 20, thus enabling switching of the pulsed

power switch 20 to its closed state.

[0068] During the time 58 in which the pulsed power switch 20 is in its open state, the arc current only flows through the second switching assembly 14.

[0069] The control unit 16 then sends a control signal 17 to the pulsed power switch 20 to switch 60 to its closed state in order to transfer the residual current from the second switching assembly 14 to the first switching assembly 12. This allows the current in the vacuum interrupter 26 to drop instantly to zero and thereby allows full dielectric recovery of the vacuum interrupter 26. This is followed by the pulsed power switch 20 being switched back to an open state to complete the current interruption process. At this stage the isolator 18 can be opened.

[0070] The duration of the conduction of the pulsed power switch 20 has to be longer than the time needed for the vacuum interrupter 26 to achieve full dielectric recovery, which is typically in the range of 10 μ s.

[0071] The duration of current interruption is limited by the time required to mechanically move the first rod 40 from the first position to the second position, which could be 1 to 40 ms and would depend on the opening speed of the first rod 40, and the time to operate the voltage generator 28, which is typically 1 ms.

[0072] The parallel connection of the first and second switching assemblies 12, 14 in the first power switching apparatus therefore improves the current interruption process. In addition the parallel connection of the first and second switching assemblies 12, 14 in the first power switching apparatus results in a simple layout of the first power switching apparatus, which in turn reduces the manufacturing and installation costs of such an apparatus.

[0073] Moreover the inclusion of the voltage generator 28 in the first power switching apparatus enables use of the vacuum interrupter assembly 25 with a wider range of pulsed power switches with relatively high forward voltage drops, thus providing additional flexibility when it comes to design and construction of the components of the first power switching apparatus.

[0074] It is envisaged that the first switching assembly 12 can be switched to modify the magnitude of current flowing in the vacuum interrupter 26 during the current interruption process to minimise any adverse effects of high current densities on the contact electrodes 44, 46 to thereby improve the lifetime of the vacuum interrupter assembly 25. A second power switching apparatus according to a second embodiment of the invention is shown in Figure 3. The second power switching apparatus of Figure 3 is similar in structure and operation to the first power switching apparatus of Figure 1, and like features share the same reference numerals.

[0075] The second power switching apparatus differs from the first power switching apparatus in that, in the second power switching apparatus, the voltage generator 28 is replaced by a gas filled switch 62.

[0076] The gas filled switch 62 is filled with gas at high pressure in the range of 10 to 100 bar. In the embodiment

shown, the gas is hydrogen. It is envisaged that the gas in the gas filled switch 62 may be argon, nitrogen, a hydrogen-argon mixture or a hydrogen-nitrogen mixture.

[0077] The structure and operation of the gas filled switch 62 is similar to that of the vacuum interrupter 26. In use, the control unit 16 controls the gas filled switch 62 by moving its first rod 64 relative to its second rod 66 to open or close a gap between its contact electrodes 68. When a gap is formed between the contact electrodes 68 of the gas filled switch 62, an arc voltage is created between the opened contact electrodes 68 and thereby inserted in series with the vacuum interrupter 26, by virtue of the series connection of the vacuum interrupter 26 and gas filled switch 62.

[0078] The vacuum interrupter 26 and gas filled switch 62 are rated so that the series combination of the maximum arc voltage of the vacuum interrupter 26 and the arc voltage created by the gas filled switch 62 is high enough to establish a voltage drop across the second switching assembly 14 that is high enough to match or exceed the forward voltage drop of the pulsed power switch 20.

[0079] Once the current interruption process is initiated and the maximum arc voltage of the vacuum interrupter 26 is established 54, the control unit 16 controls the gas filled switch 62 to create an arc voltage in the gas filled switch 62, and so the arc voltage of the gas filled switch 62 is inserted in series with the arc voltage of the vacuum interrupter 26. The series combination of the arc voltages of the vacuum interrupter 26 and gas filled switch 62 causes a rise 56 in voltage drop across the second switching assembly 14. This in turn causes the voltage drop across the second switching assembly 14 to match or exceed the forward voltage drop of the pulsed power switch 20, thus enabling switching of the pulsed power switch 20 to its closed state.

[0080] The control unit 16 then sends a control signal 17 to the pulsed power switch 20 to switch 60 to its closed state in order to transfer the residual current from the second switching assembly 14 to the first switching assembly 12. This allows the current in the vacuum interrupter 26 to drop instantly to zero and thereby allows full dielectric recovery of the vacuum interrupter 26. This is followed by the pulsed power switch 20 being switched back to an open state to complete the current interruption process. At this stage the isolator 18 can be opened.

[0081] The duration of current interruption is limited by the time required to mechanically move the first rod 40 from the first position to the second position, which could be 1 to 40 ms and would depend on the opening speed of the first rod 40, and the time to operate the gas filled switch 62, which is typically 1 to 20 ms.

[0082] A third power switching apparatus according to a third embodiment of the invention is shown in Figure 4. The third power switching apparatus of Figure 4 is similar in structure and operation to the first power switching apparatus of Figure 1, and like features share the same reference numerals.

[0083] The third power switching apparatus differs from the first power switching apparatus in that, in the third power switching apparatus:

- the second switching assembly 14 omits the voltage generator 28, and the vacuum interrupter 26 is connected directly between the terminals 10 of the third power switching apparatus; and
- the second switching assembly 14 further includes a magnetic field generator 70 in the form of a solenoid, which is located outside the cylindrical housing 30 of the vacuum interrupter 26.

[0084] The magnetic field generator 70 further includes a DC current source associated with the solenoid. In use, the control unit 16 controls the magnetic field generator 70 by controlling the DC current source to supply a DC current to the magnetic field generator 70 so that the magnetic field generator 70 generates a magnetic field inside the vacuum tight enclosure. The magnetic field generator 70 is arranged with respect to the vacuum interrupter 26 so that, during the current interruption process, a magnetic field created by the magnetic field generator 70 is substantially perpendicular to the direction of an arc current drawn between the contact electrodes 44,46 of the vacuum interrupter 26.

[0085] Once the current interruption process is initiated and the maximum arc voltage of the vacuum interrupter 26 is established, the control unit 16 controls the magnetic field generator 70 to create the magnetic field which interacts with the electric field present between the contact electrodes 44,46 of the vacuum interrupter 26. In the presence of the combined electric and magnetic fields present between the two contact electrodes 44,46, the electrons and the negatively-charged plasma ions are forced to deviate from their path and not reach the second contact electrode 46, i.e. the negatively charged metal vapour plasma is forced away from reaching the anode 46. This creates a sheath region around the second contact electrode 46 and thereby causes a substantial rise 56 of the arc voltage in the vacuum interrupter 26. This in turn causes the magnitude of the arc current to drop rapidly to a lower limit which is proportional to the arc voltage generated.

[0086] The increase in arc voltage in the vacuum interrupter 26 in turn causes a rise in voltage drop across the second switching assembly 14, and thereby causes the voltage drop across the second switching assembly 14 to match or exceed the forward voltage drop of the pulsed power switch 20, thus enabling switching of the pulsed power switch 20 to its closed state.

[0087] The control unit 16 then sends a control signal 17 to pulsed power switch 20 to switch 60 to its closed state in order to transfer the residual current from the second switching assembly 14 to the first switching assembly 12. This allows the current in the vacuum interrupter 26 to drop instantly to zero and thereby allows full dielectric recovery of the vacuum interrupter 26. This is

followed by the pulsed power switch 20 being switched back to an open state to complete the current interruption process. At this stage the isolator 18 can be opened.

[0088] The duration of current interruption is limited by the time required to mechanically move the first rod 40 from the first position to the second position, which could be 1 to 40 ms and would depend on the opening speed of the first rod 40, and the time to operate the magnetic field generator 70, which is typically 1 to 5 ms.

[0089] It is envisaged that, in other embodiments of the invention, the shape of each contact electrode may vary depending on the magnitude of current to be interrupted. For example, each contact electrode may be shaped in the form of any one of:

- a butt electrode;
- a multi-arm electrode;
- a cup, e.g. a slotted cup;
- a coil, e.g. a slotted coil.

[0090] In other embodiments, it is envisaged that the vacuum interrupter assembly may include a plurality of series-connected and/or parallel-connected vacuum interrupters.

[0091] Multiple vacuum interrupters may be connected to define different configurations of the vacuum interrupter assembly in order to improve its operating voltage and current characteristics. For example, connecting multiple vacuum interrupters in series increases the dielectric strength of the vacuum interrupter assembly and thereby permits the use of the vacuum interrupter assembly at higher operating voltages, while connecting multiple vacuum interrupters in parallel permits the vacuum interrupter assembly to interrupt higher levels of current.

[0092] It is envisaged that, in other embodiments of the invention, the first switching assembly may include a plurality of series-connected and/or parallel-connected pulsed power switches.

[0093] As with the vacuum interrupter assembly, multiple pulsed power switches may be connected to define different configurations of the first switching assembly in order to vary its operating voltage and current characteristics to match the power requirements of the associated power application.

[0094] For example, multiple vacuum interrupters and pulsed power switches can be connected in series and parallel to interrupt continuous current ≥ 6 kA and short-circuit current ≥ 100 kA at an operating voltage of ≥ 400 kV of a HVDC multi-terminal 10 network.

[0095] Depending on the opening speed of the rods and the time taken to diffuse the arc, the maximum duration of conduction of the pulsed power switch 20 may be up to 1 ms.

[0096] The use of parallel-connected pulsed power switches in the first 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 first switching assembly. This in turn renders the first switching assembly compatible for use in current interruption processes in which the time taken to initially separate the opposed contact electrodes and the time taken to diffuse the arc is longer than the duration of current conduction in a single pulsed power switch.

[0097] The power switching apparatus of Figures 1, 3 and 4 are compatible for use, but are not limited to, applications such as AC power networks, AC and DC high voltage circuit breakers, AC generator circuit breakers, transmission lines, railway traction, ships, superconducting magnetic storage devices, high energy fusion reactor experiments, stationary power applications, renewable energy resources such as fuel cells and photovoltaic cells and high voltage direct current (HVDC) multi-terminal networks.

Claims

1. A power switching apparatus for switching an AC or DC current, the power switching apparatus comprising first and second switching assemblies connected in parallel, wherein

the first switching assembly includes at least one switching element, the first switching assembly conducting and carrying current only in its closed state, the first switching assembly being controllable to switch to its closed state only when a voltage drop across the first switching assembly matches or exceeds its forward voltage drop, wherein the or each switching element is controllable to modify, in use of the power switching apparatus, a current flowing through the second switching assembly, and the second switching assembly includes:

a vacuum interrupter assembly including at least one vacuum interrupter;
an electrical device coupled with the vacuum interrupter assembly; and
a control unit;

wherein, in use of the vacuum interrupter assembly to interrupt current, the control unit controls the electrical device to create a voltage or magnetic field which increases the voltage drop across the second switching assembly so that the voltage drop across the second switching assembly matches or exceeds the forward voltage drop of the first switching assembly.

2. A power switching apparatus according to Claim 1 wherein the or each vacuum interrupter includes a pair of contact electrodes, the contact electrodes being connectable to an electrical network.

3. A power switching apparatus according to Claim 2 wherein at least one contact electrode is movable relative to the other contact electrode to open or close a gap between the contact electrodes.

4. A power switching apparatus according to Claim 3 wherein the control unit controls the electrical device to create the voltage or magnetic field on or after formation of a gap between the contact electrodes of the or each vacuum interrupter in order to increase the voltage drop across the second switching assembly so that the voltage drop across the second switching assembly matches or exceeds the forward voltage drop of the first switching assembly.

5. A power switching apparatus according to any preceding claim wherein the control unit controls the electrical device to create the voltage or magnetic field on or after formation of a predetermined arc voltage in the or each vacuum interrupter in order to increase the voltage drop across the second switching assembly so that the voltage drop across the second switching assembly matches or exceeds the forward voltage of the first switching assembly drop.

6. A power switching apparatus according to any preceding claim wherein the or each switching element is a pulsed power switch.

7. A power switching apparatus according to any preceding claim wherein the electrical device is any one of:

- a voltage generator;
- a gas filled switch;
- a magnetic field generator.

8. A power switching apparatus according to Claim 7 wherein the voltage generator includes at least one semiconductor switching device.

9. A power switching apparatus according to any preceding claim wherein the electrical device is connected in series with the vacuum interrupter assembly when the electrical device is controllable to create a voltage.

10. A power switching apparatus according to any of Claims 1 to 7 wherein the electrical device is located outside the vacuum interrupter when the electrical device is controllable to create a magnetic field.

11. A power switching apparatus according to any of Claims 1 to 7 and 10 wherein the electrical device is arranged with respect to the or each vacuum interrupter to enable the electrical device to create a magnetic field that is substantially perpendicular to the direction of an arc current formed in the or each vac-

uum interrupter when the electrical device is controllable to create a magnetic field.

12. A power switching apparatus according to any preceding claim wherein the vacuum interrupter assembly includes a plurality of series-connected and/or parallel-connected vacuum interrupters. 5
13. A power switching apparatus according to any preceding claim wherein the first switching assembly includes a plurality of series-connected and/or parallel-connected switching elements. 10
14. A power switching apparatus according to Claim 13 when dependent from Claim 6 wherein the first switching assembly includes a plurality of parallel-connected pulsed power switches, the first switching assembly being controllable to sequentially open or close the plurality of parallel-connected pulsed power switches. 15
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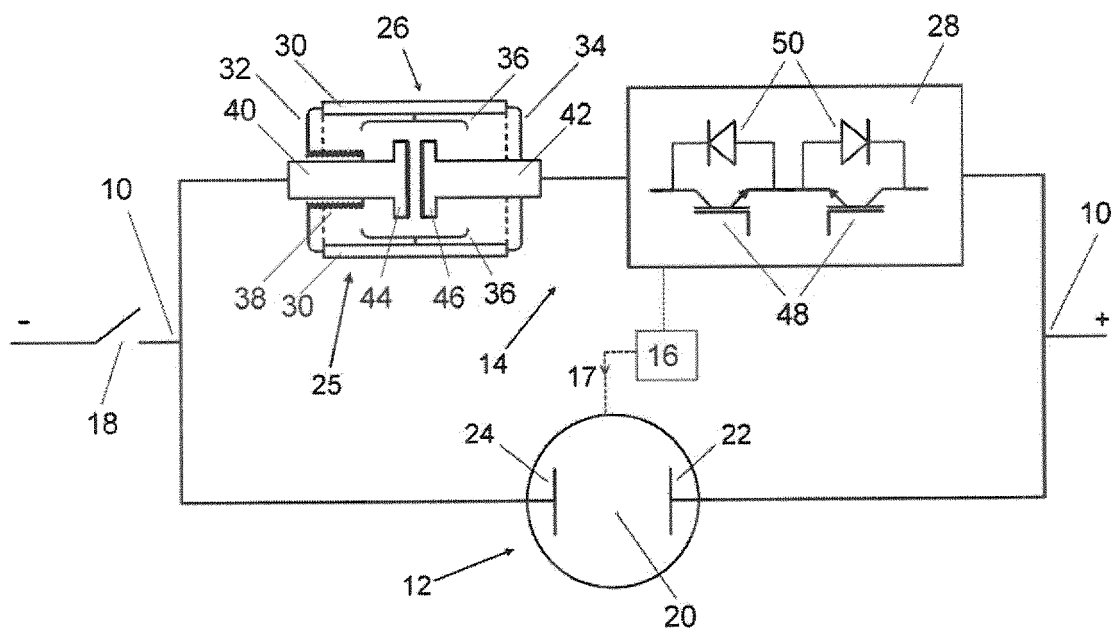


Figure 1

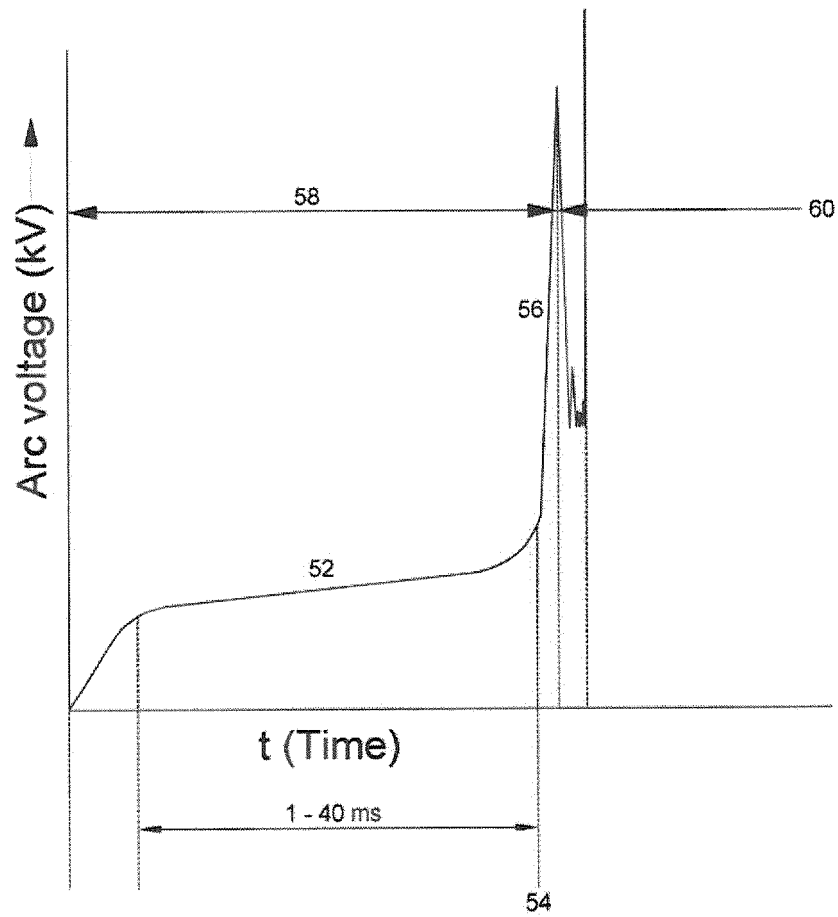


Figure 2

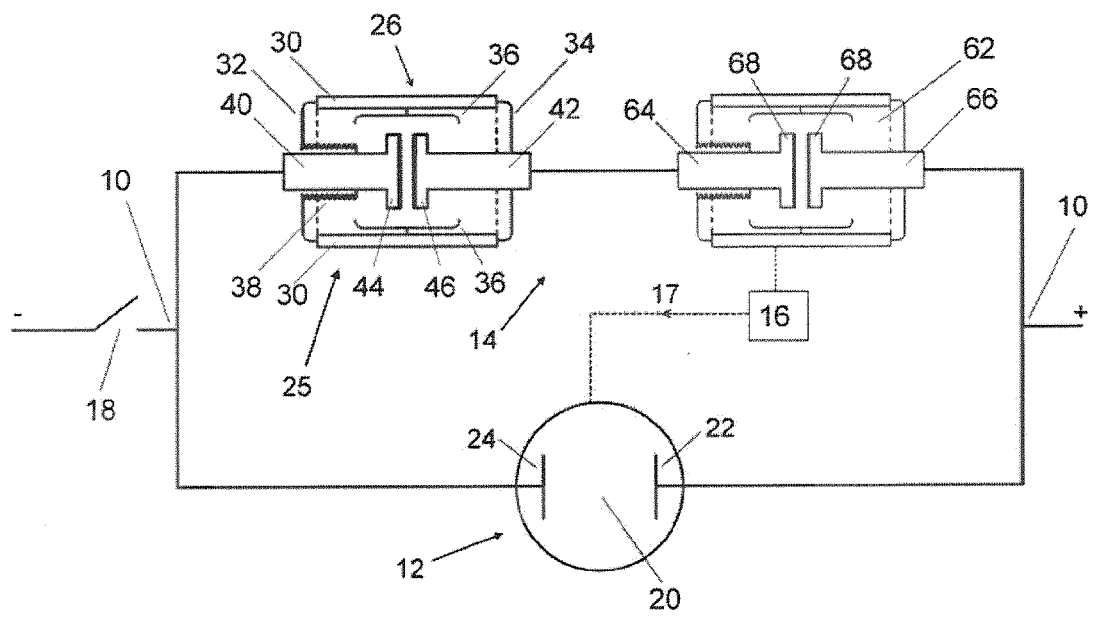


Figure 3

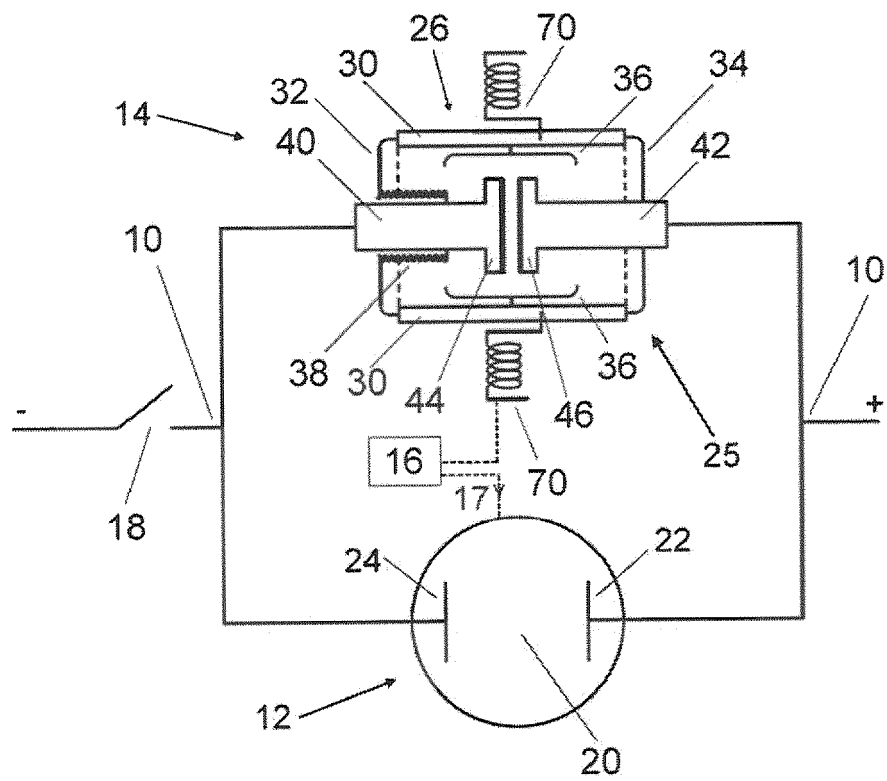


Figure 4



EUROPEAN SEARCH REPORT

Application Number
EP 12 27 5183

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The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 6 May 2013	Examiner Drabko, Jacek
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

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EPO FORM 1503 03.82 (P04C01)

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06-05-2013

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