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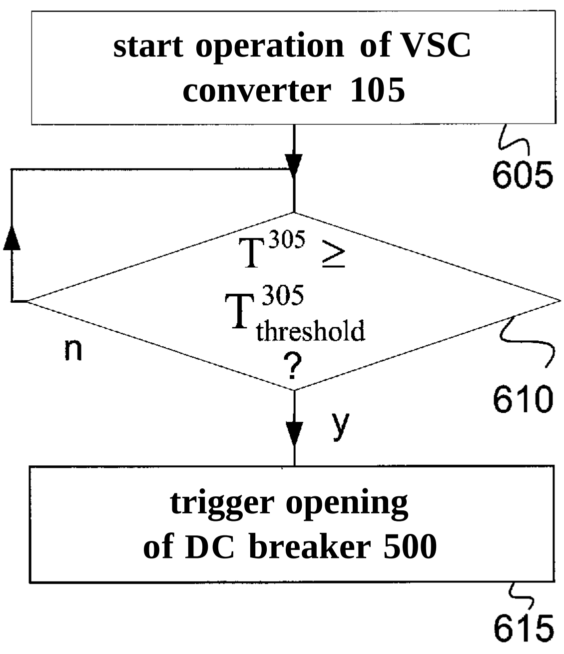
(54) Title: AN HVDC TRANSMISSION SYSTEM, AN HVDC STATION AND A METHOD OF OPERATING AN HVDC STATION

Fig. 6



(57) Abstract: The present invention relates to an HVDC converter station for interconnection of a DC transmission line and an AC system of at least one AC phase. The HVDC converter station comprises a VSC converter and a DC breaker connected in series between the VSC converter and the DC transmission line. The HVDC converter station comprises a protection system configured to monitor the temperature of a reverse-conducting component of the reverse-conducting switch arrangement, and trigger the opening of the DC breaker if the temperature of the reverse-conducting component exceeds a temperature threshold.

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AN HVDC TRANSMISSION SYSTEM, AN HVDC STATION AND A METHOD OF OPERATING AN HVDC STATION

Technical field

The present invention relates to the field of power transmission, and in particular to the field of AC/DC converter stations for use in high power transmission.

Background

High Voltage Direct Current (HVDC) transmission of power has proved to be an efficient alternative to Alternating Current (AC) transmission in many power transmission situations. In particular, HVDC transmission using Voltage Source Converter (VSC) converter stations show many advantageous features. A VSC converter comprises a number of electric valves, each comprising a unidirectional switch and an anti-parallel diode, where the unidirectional switch can be controlled to switch off, as well as to switch on. By controlling the switching of the electric valves, the VSC converter can operate as an inverter or rectifier. The unidirectional switches and the diodes are typically made of semi-conducting material. Since the magnitudes of current and voltage in an HVDC station are typically extremely high, the demands on the semi-conducting devices in terms of current and voltage withstanding capability are very high. Therefore, the material costs involved in manufacturing an HVDC station are high.

Summary

A problem to which the present invention relates is how to reduce the materials consumption in the production of an HVDC station.

One embodiment provides an HVDC converter station for interconnection of a DC transmission line and an AC system of at least one AC phase, where the HVDC converter station comprises a VSC converter and a DC breaker. The VSC converter has at least two electric valves, each valve having a reverse-conducting switch arrangement. The DC breaker is connected to a DC interface of the VSC converter in a manner so that the DC breaker will be connected in series between the VSC converter and the DC transmission line. The HVDC converter station further comprises a protection system configured to monitor the temperature of at least one of the reverse-conducting components of the reverse-conducting switch arrangement, and to trigger the opening of the DC breaker if the temperature of the reverse-conducting component exceeds a temperature threshold.

A method of an HVDC converter station for interconnection of a DC transmission line and an AC system is also provided, wherein the HVDC converter station includes a VSC converter and a DC breaker. The method comprises: monitoring the temperature of at least one of the reverse-conducting components in order to check whether the temperature is above a temperature threshold, and if so, triggering the opening of the DC breaker.

By providing the HVDC station with a DC breaker and controlling the opening of the DC breaker in dependence on the temperature of the reverse-conducting component of the valves, the timing of the interruption of a fault current can be greatly improved. The accuracy of the triggering of the breaker can be improved by monitoring the temperature of the reverse-conducting component of at least one valve. The risk of an electric valve having to withstand a fault current, for a longer period of time than the opening time of the DC breaker, can hence be greatly reduced. Hence, a valve could, if desired, be implemented without any alternative current path to the paths provided by the reverse-conducting switch arrangement, and the reverse-conducting component would not have to be over-dimensioned. Furthermore, or alternatively, a reduction in the short circuit impedance of the HVDC station, for example a reduction in the AC impedance of the AC phase reactors, could be made. Hence, considerably materials savings could be made as compared to the presently known technology.

The monitoring of the temperature of the reverse conducting component could be performed by measuring the current flowing through the reverse-conducting component of the reverse-conducting switch arrangement, and/or by measuring the voltage across the reverse-conducting component, and then estimating the temperature of the reverse-conducting component in dependence of such current and/or voltage measurements. Current and voltage measurements in HVDC stations are well known in the art, and provide a practical means of determining the temperature of the reverse-conducting components of the HVDC station.

In one embodiment, the protection system is further configured to determine a dynamic value of the temperature threshold. The temperature threshold can for example be determined in dependence on the time derivative of the temperature of the reverse-conducting component, so that a lower temperature threshold will be used for a larger time derivative, and vice versa. Hereby is achieved that a more accurate timing of a triggering signal can be made, thus reducing the risk of any unnecessary interruption of the operation of the HVDC station caused by too early triggering of the DC breaker, as well as reducing the risk of the triggering of the DC breaker being made too late.

In one embodiment, wherein at least one AC breaker is connected to an AC interface of the VSC converter, the protection system is further configured to, in a situation where the DC breaker has been opened, determine if a current flows in a connection line interconnecting the DC interface and the DC breaker, and, if so, trigger the opening of the AC breaker(s). Hereby is achieved that the VSC converter can be protected, even if a fault occurs on the connection line between the VSC converter and the DC breaker.

Advantageously, the DC breaker is capable of breaking a current within a particular breaking time $t_{D}e$ from the onset of the opening of the DC breaker, where the particular breaking time $t_{D}e$ of the DC breaker is shorter than the time required for the worst case short circuit current to generate a destructive amount of heat in the conducting reverse-conducting component of the switch arrangement. The particular breaking time $t_{D}e$ could for example be shorter than half, or shorter than a quarter of, the fundamental frequency period of the AC system. Having such short breaking times provides for the possibility of large materials savings in terms of reduced dimensions of the reverse-conducting component of the valves; reduced dimensions of any alternative current paths (if provided); and/or reduced dimensions of any reactors providing the short circuit impedance of the HVDC station.

In one embodiment, the short circuit impedance of the HVDC converter station is less than 15 % of the base impedance of the HVDC converter station. Hereby, an efficient reactive power generation by the VSC converter can be ensured. The availability of temperature dependent fast current breaking ensures that the resulting high short circuit current will not have time to damage the reverse-conducting components of the electric valves. Typically, the majority of the short circuit impedance will be provided by a transformer connecting the HVDC station to the AC system.

In one embodiment, the rated current density of the reverse-conducting component is more than 150 % of the rated current density of the switch component of the reverse-conducting switch arrangement. In this embodiment, the electric valves can be designed such that in a worst case fault scenario, at least a majority of the current through the VSC converter will flow through at least one reverse-conducting component. In one implementation of this embodiment, the semiconductor switching elements forming part of the switch component and rectifying elements forming part of the reverse-conducting component are located in the same semiconductor chip module. In such implementation, the ratio of the area occupancy of the rectifying element to the area occupancy of the semiconductor switching element on the semiconductor chip module can be smaller than 1.0, for example 0.5.

In one embodiment, the electric valves are designed such that in a worst case fault circuit scenario, at least a majority of the current through the VSC converter will flow through at least one reverse-conducting component. In one implementation, the electric valves are designed such that the entire fault current will flow through at least one reverse-conducting component in a fault scenario. Hence, no alternative current path is required in an electric valve in addition to the paths provided by the reverse-conducting switch arrangement. Hence, no additional material or space will be consumed.

In order to minimise the risk of non-operability of the DC breaker, the connection distance between the DC breaker and DC interface should preferably be as small as possible, while maintaining a suitable air clearance. Typically, the connection distance will be smaller than 10 meters.

The DC breaker could for example comprise a main semiconductor switch of turn-off type; a non-linear resistor connected in parallel with the main semi-conductor switch; and a series connection of a high speed switch and an auxiliary semiconductor switch of turn-off type, wherein the series connection is connected in parallel to the main semiconductor switch and the non-linear resistor. By such DC breaker is achieved that the heat dissipation in the breaker will be low, since during normal operation, the current can flow through the auxiliary switch, which has a lower resistance than the main switch. In another implementation, the DC breaker is a mechanical DC breaker comprising a mechanical interrupter connected in parallel with a parallel connection of a resonant circuit and a non-linear resistor.

A DC breaker could, in order to provide current limiting possibilities, be formed of a series connection of at least two independently switchable breaker sections.

The HVDC converter station could be connected to an HVDC switchyard to form part of an HVDC grid. The HVDC switchyard then comprises at least one busbar and at least one switchyard DC breaker interconnecting the converter station DC breaker with a busbar. The converter station DC breaker could then advantageously be a DC breaker capable of providing a higher breaking speed than the switchyard DC breakers. Hereby is achieved that lower cost DC breakers could be used in the HVDC switchyard, while obtaining adequate damage preventing capability.

Similarly, in an HVDC system wherein a local HVDC station, located in the vicinity of an HVDC switchyard and connected to the HVDC switchyard, does not include a fast DC breaker, the switchyard DC breakers that interconnects such local HVDC station with the switchyard busbars could advantageously be fast DC breakers, while the DC breakers connecting remote HVDC stations with the busbars could be of lower speed.

Further aspects of the invention are set out in the following detailed description and in the accompanying claims.

Brief description of the drawings

Fig. 1 is a schematic illustration of an example of a prior art HVDC station.

Fig. 2a is a schematic illustration of an example of a VSC converter.

Fig. 2b is a schematic illustration of another example of a VSC converter.

Fig. 3 is a schematic illustration of an example of an electric valve used in a VSC converter.

Fig. 4a is a graph showing the heat dissipation in a valve diode as a function of time in case of a short circuit situation.

Fig. 4b is a graph showing, for two different HVDC station designs wherein the valve diodes are of different cross sectional areas, the heat dissipation in a valve.

Fig. 4c is a graph showing, for two different HVDC station designs having different short circuit impedance, the heat dissipation in a valve diode as a function of time in case of a short circuit situation.

Fig. 5 is a schematic illustration of an HVDC station according to an embodiment of the invention.

Fig. 6 is a flowchart schematically illustrating a method of operating an HVDC station.

Fig. 7a is a schematic illustration of an example of a protection system configured to control the operation of the DC breaker in dependence on the temperature of a diode of an electric valve.

Fig. 7b shows an example of an electrical circuit by means of which an embodiment of the protection system of Fig. 7a may be implemented.

Fig. 7c is an alternative illustration of an implementation of the protection system shown in Fig. 7a.

Fig. 8 is a schematic illustration of an example of a valve semiconductor chip module.

Fig. 9a is a schematic illustration of an embodiment of a fast DC breaker.

Fig. 9b is a schematic illustration of an embodiment of a fast DC breaker which can also operate as a current limiter.

Fig. 10a is a schematic illustration of an embodiment of an HVDC switchyard.

Fig. 10b is a schematic illustration of another embodiment of an HVDC switchyard.

Detailed description

Fig. 1 is a schematic illustration of an HVDC converter station 100, or HVDC station 100 for short. The HVDC station 100 of Fig. 1 comprises a VSC (Voltage Source Converter) converter 105 to which DC transmission lines 110 have been connected via DC interface 115. HVDC station 100 of Fig. 1, which is illustrated to be a three phase converter station, further comprises three AC phase reactors 120, or AC reactors 120 for short, each connected to an AC phase interface 125 of the VSC converter 105. HVDC station 100 of Fig. 1 is connected to an AC system 135 on the AC side via transformers 140. AC system 135 can be an AC grid to which power is provided via the DC transmission lines 110, or an

AC power source providing power to be transmitted via DC transmission lines 110. Typical nominal voltage and current ratings of an HVDC station 100 of today are for example 80 kV, 500 A or 320 kV, 2 kA. An AC phase reactor 120 can be external to the VSC converter 105 as shown in Fig. 1, or an AC phase reactors 120 can be part of the VSC converter 105 as shown in Figs. 2a and 2b. Alternatively, part of an AC phase reactor 120 can be external to the VSC converter 105, while another part is internal.

An HVDC station 100 is, when in use, connected to at least one further HVDC station 100, to or from which electric power may be transmitted or received, so that at least two HVDC stations 100 form an HVDC power transmission system.

In a high voltage power transmission system, it is of high importance that the transmission paths can be broken in case of a short circuit or earth fault situation. Hence, the HVDC station 100 of Fig. 1 is equipped with an AC breaker 145 connected between the AC system 135 and the AC phase interface 125. Typically, an AC breaker 145 is provided for each AC phase, as shown in Fig. 1. Upon detection of a major fault, the AC breaker 145 will be tripped. The time required for breaking the current by means of a typical mechanical AC breaker 145 is around 40-60 ms, corresponding to 2-3 fundamental frequency periods of a 50 Hz or 60 Hz AC system 135.

An HVDC station 100 typically includes further equipment, which has been left out for illustration purposes. One of the DC transmission lines 110 can be grounded, in which case the HVDC station 105 is a monopolar converter station, or the HVDC station 100 could be a bipolar converter station. In some implementations of HVDC stations 100, the transformers 140 are omitted, while in others, the transformer impedance is such that the AC reactors 120 may be left out. The HVDC station 105 could have any number of AC phases, including one.

Examples of different VSC converter topologies will now be discussed in relation to Figs. 2a and 2b. A VSC converter 105 comprises a phase leg per AC phase, where the phase legs can be connected in series or in parallel. **Fig. 2a** is an illustration of an example of a three phase VSC converter 105 having three phase legs 200 connected in parallel with a capacitor 205, each phase leg 200 having two electric valves 210. The VSC converter 105 of Fig. 2a is a two-level converter, where the electric valves 210 can be switched in a suitable manner to synthesize an AC voltage. In the VSC converter 105 of Fig. 2a, an AC phase reactor 120 is connected between the midpoint of a phase leg 200 and an AC interface 125.

Another example of a three phase VSC converter 105 is shown in **Fig. 2b,** wherein the three phase legs 200 are also connected in parallel. A phase leg 200 of VSC converter 105 of Fig. 2b comprises two half-bridge converter cells 215 which are independently switchable and series connected in a cascaded fashion. A half-bridge converter cell 215 comprises two series connected electric valves 210, which form what may be referred to as a cell element 215. The cell element 215 is connected in parallel with a cell capacitor 220 in a half-bridge configuration. By using a cascade of series connected converter cells 215 is achieved that multiple voltage levels can be obtained at the AC side of a phase leg 200, so that a more smooth synthesis of an AC-voltage can be obtained than if a phase leg 200 formed from a single converter cell 210 is used. In the VSC converter of Fig. 2b, an AC phase reactor 120 is connected in series with the cascade of converter cells 215 of a phase leg.

The VSC converters 200 of Figs. 2a and 2b are shown as examples only, and a VSC converter 200 can be of many other topologies. For example, a VSC converter 200 can have any number N of phase legs 200, $N \geq \mathbf{1}.$ If N>1, the two or more phase legs 200 can be connected in series or in parallel. Furthermore, a phase leg 200 can be a two- or three level phase leg (cf. Fig. 2a), or comprise a series connection of two or more independently switchable converter cells arranged in a cascaded fashion (cf. Fig. 2b). Moreover, the converter cells 205 of a cascade of converter cells can be half-bridge converter cells 205, as shown in Fig. 2b, or full-bridge converter cells 205, or a combination of half-bridge and full-bridge converter cells 200. A full-bridge converter cell comprises two cell elements 215, both connected in parallel with a cell capacitor 220 in a full-bridge, or H-bridge, fashion.

However, regardless of converter topology, a VSC converter 200 comprises at least one phase leg 200 having at least two electric valves 210, each comprising a reverse-conducting switch arrangement. A reverse-conducting switch arrangement is a switch-arrangement wherein current in a first direction can be switched on and off, while the switch arrangement will always be conducting in the direction opposite to the first direction. A reverse-conducting switch arrangement comprises a switch component and a reverse-conducting component, and is typically made from semi-conducting material, such as Si. An example of an electric valve 210 comprising a reverse-conducting switch arrangement 310 is shown in **Fig. 3.** The reverse-conducting switch arrangement 310 of Fig. 3 includes a switch component in the form of a unidirectional switch 300, or switch 300 for short, and a reverse-conducting component in the form of an anti-parallel diode 305. The unidirectional switch 300 can be controlled to switch off, as well as to switch on. A switch 300, which can be controlled to switch off, as well as to switch on, is often referred to as a switch 300 of turn-off type. A switch 300 often comprises more than one switching element, connected in series and/or in parallel and arranged to switch simultaneously to form the switch 300. Similarly, a diode 305 often comprises more than one rectifying element (diode) connected in series and/or parallel to form the diode 305. A unidirectional switching element could for example be an Integrated Gate Bipolar Transistor (IGBT), an Integrated Gate-Commutated Thyristor (IGCT), a Gate Turn-Off thyristor (GTO), etc. For example, IGBT switching elements having a rated voltage of in the order of 3-5 kV or higher, for example 4.5 kV, is used to form the switch 300 in one implementation.

A reverse-conducting switch arrangement 310 could, in some implementations, be formed from a switching element(s) which, in addition to providing the switch component of the valve 210, further contributes to the reverse-conducting component of the valve 210, so that no separate rectifying element is required. The reverse-conducting IGCT and the bi-mode insulated gate transistor (BIGT) are examples of devices wherein an anti-parallel rectifying element and a switching element are integrated, using the same semiconductor area. A BIGT, or a reverse-conducting IGCT (or a plurality of interconnected BIGTs/IGCTs), could hence provide the switch component, as well as to the reverse-conducting component, of a reverse-conducting switch arrangement 310 of a valve 210. Such reverse-conducting switch arrangements 310 could be seen as if a switch component, in the form of a switch 300 of turn-off type, and a reverse-conducting component, in the form of an anti-parallel diode 305, are integrated.

When dimensioning the devices of an HVDC station 100, the worst case scenario that the devices can be expected to be exposed to, in terms of current and voltage, should be considered. The highest expected fundamental frequency fault current through a VSC converter 105 will typically occur in case of a DC pole-to-pole fault on the DC side of the VSC converter 105, i.e. if there is a short circuit between the DC transmission lines 110 connected to the DC interface 115. Such short circuit current is typically given by the following expression:

$$I_{SC}^{peak} = \frac{2\sqrt{2}}{\sqrt{3}}\frac{U_t^{max}}{X_{SC}} \qquad (1),$$

where I_{SC}^{peak} is the peak short circuit current, U_t^{max} is the maximum phase-to-phase rms voltage on the secondary side of the transformer, and X_{sc} is the short circuit impedance. The short circuit impedance is typically the sum of the AC system impedance X135 and the converter station impedance X_{100}, where the main components of the converter station impedance X100 are typically the AC reactor impedance X_{120}, the transformer impedance Xi4o and the converter impedance X105:

$$X_{SC} = X_{135} + X_{100} \approx X_{135} + X_{120} + X_{140} + X_{105} \approx X_{120} + X_{140} \qquad (2),$$

The AC system impedance X135 is the resultant impedance of all devices on the AC side beyond the transformer 140 (if any) interconnecting the HVDC station 100 and the AC system 135. Typically, the AC system impedance X135 and the VSC converter impedance X105 are considerably smaller than the sum of the AC phase reactor impedance X120 and the transformer impedance X_{140}. In many implementations of an HVDC station 100, the AC reactor impedance X_{120} is the dominant component of the converter station impedance X100, but implementations wherein e.g. the transformer impedance X_{140} is dominant could also be useful.

Regardless of converter topology, any current through the VSC converter 105 will go via at least one electric valve 210. Typically, an HVDC station 100 is equipped with a protection system, which is configured to perform measurements of various currents and voltages in order to determine whether any fault, which requires action, has occurred. In case of a detected risk for a large fault current through the VSC converter 105, the switches 300 of the electric valves 210 may be switched off. However, the anti-parallel diodes 305 cannot be switched off, and in case of a large current surge through the VSC converter 105, there is a risk that the anti-parallel diodes 305 of the valves 210 may be damaged.

The rated current of a device, for example a diode 305, is the maximum current for which the device is designed. The rated current can safely flow through the device during a very long period of time, without any increased risk of damage to the device. Furthermore, a semiconductor device such as a diode 305, or a switch 300, can typically survive a current surge of considerably larger magnitude than the rated current, if the current surge only lasts for a limited period of time. Conventionally, a valve 210 of a VSC converter 105 has been designed to withstand the worst case short circuit current I_{SC}, for which the peak value is given by expression (1), at least during the time period t_{AC} required for breaking the current by means of a mechanical AC breaker 145. As mentioned above, such breaking time t_{AC} is typically 40-60 ms, or more, corresponding to at least 2-3 fundamental frequency periods of a 50 Hz or 60 Hz AC system 135.

One conventional way in which a valve 210 has been designed to withstand the worst case short circuit scenario is to provide, in the electric valve 210, an alternative path, for example a large thyristor, connected in parallel with the switch 300 and the diode 305, which alternative path is switched off during normal operation of the VSC converter 105, but can be switched on to carry the fault current in case of a detected fault. The use of such alternative current path is disclosed for example in US2008/0232145.

In valve designs where no considerable alternative path is provided, an anti-parallel diode 305 of the HVDC station 100 of Fig. 1 has to be able to withstand the worst case scenario fault current $\hat{I}_{SC}$, at least for the time period t_{AC} required for opening the AC breakers 145. The time required for breaking the current by means of a typical mechanical AC breaker 145 is around 40-60 ms, corresponding to 2-3 fundamental frequency periods of a 50 Hz or 60 Hz AC system 135. Hence, in such design, the anti-parallel diodes 305 will have to be over-dimensioned compared to the requirements of the nominal current, so that the rated current of the diode is considerably higher than the rated current of the switches 300. The diode current carrying cross section will have to be dimensioned such that the heat W generated by the short circuit current surge during the time period t_{AC} will lie well below a fatal energy W_{fatal}^{305}. The fatal energy W_{fatal}^{305} represents an amount of dissipated energy (during a short period of time) required for the temperature of at least parts of the anti-parallel diode 305 to exceed a level above which additional charge carriers will start to appear in the diode material, resulting in a negative temperature dependency of the resistance and an avalanche-like increase of the heat dissipation in the diode 305, causing permanent damage to the diode 305. This definition of the fatal energy assumes that the temperature of the diode 305 at the onset of the fault scenario is at a steady state, normal operating conditions, temperature.

Fig. 4a is a graph showing developed heat W^{305} in a diode 305 of cross-section A as a function of time, t, for a VSC converter 105 at a worst case short circuit current I_{SC}^{α}, where t=0 represents the onset of the fault scenario. Also shown in the graph is the diode fatal heat W_{fatal}^{305}, illustrating the level of developed heat at which the diode 305 will reach, at least locally, a temperature T_{fatal} where the material of the diode will be fatally damaged. A typical AC breaker breaking time t_{AC} has also been indicated in the graph, as well as the point in time t_{fatal}^{α} where the heat dissipated in the diode 305 will cause fatal damage to the diode 305. As can be seen, the VSC converter 105 represented by the graph, having a short circuit current I_{SC}^{α}; diodes 305 of fatal heat W_{fatal}^{305}; and an AC breaker 145 of breaking time t_{AC}, would survive a short-circuit scenario, since $t_{AC} < t_{fatal}$, with a time safety margin of $t_{fatal}^{\alpha} - t_{AC}$. For a given AC breaker breaking time t_{AC}, a suitable combination of short circuit current I_{SC}^{α} (given by the rated voltage and short circuit impedance) and diode heat withstanding capability (given by the dimensioning of the diode 305) has been selected.

Compared to the costs involved in case the anti-parallel diodes 305 of a VSC converter 105 were damaged in a fault case scenario, the costs of providing additional current paths and/or providing highly over-dimensioned diodes 305 in terms of manufacturing costs, space requirements etc are small. Damaged diodes 305 could potentially result in considerable power supply downtime, and the diodes themselves are highly expensive to replace. However, as will be shown below, we suggest a way of avoiding the risk of diode damage which is as efficient as the conventional ways described above, at much reduced material cost.

In an embodiment of the present invention, a DC breaker of short breaking time t_De is included in the HVDC station 100 and connected between the DC interface 115 of the VSC converter 105 and the DC lines 110, wherein a protection system of the HVDC station 100 is configured to trigger the opening of the DC breaker upon an indication that the temperature of the reverse-conducting component of a valve 210 exceeds a temperature threshold. **Fig. 5** shows an HVDC converter station 100 having a DC breaker 500 of short breaking time t_De connected between the DC interface 115 and the DC transmission lines 110. The connection line between the VSC converter 105 and the DC breaker 500 has been indicated by reference numeral 510. The DC breaker 500 has an input 515 for receiving a trigger signal 520 from a protection system 505, which is configured to control the DC breaker in dependence on a status signal 525, indicative of a measure from which the temperature of the diode 305 of a valve 210 can be derived. The HVDC converter station 100 is shown to have one DC breaker 500 connected to one of the DC transmission lines 110 connected to the DC interface 115 of the VSC converter 105. However, a further DC breaker 500 could be connected to the other DC transmission line 110 connected to the DC interface 115.

DC breakers are conventionally used in switchyards interconnecting more than two HVDC stations 100, so as to avoid the propagation of a fault current originating from a faulty HVDC station 100 to the other HVDC stations 100 of the grid. It is typically desirable to arrange so that a possible fault in one converter station 100 can be confined to the faulty converter station 100. A DC breaker conventionally serves to disconnect the HVDC station 100 from the other HVDC stations 100 of an HVDC grid in case of a fault in HVDC station 100. Unless the faulty converter station 100 can be disconnected from the other HVDC stations 100, short circuit currents will be transmitted to the HVDC stations 100, which will then also be at risk. Such short circuit currents typically grow very rapidly into current surges, originating in particular from capacitances on the DC side of the HVDC grid. Hence, the breaking time t_De of a DC breaker 500 in this application should advantageously be short, for example in the order of 15 ms or less, depending inter alia on the distance between the interconnected HVDC stations 100.

However, a fast DC breaker 500 can be useful not only for the efficient protection of nodes in a grid of more than two HVDC stations 100, but also for the efficient design of an HVDC station 100.

By connecting a fast DC breaker 500 to the DC interface 115 of a VSC converter 105 wherein the opening of the DC breaker 500 is triggered in dependence of an indication of the temperature of a diode 305 of a valve 210 exceeding a temperature threshold, the diodes 305 of the VSC converter 105 can be of smaller cross sectional area as compared to the diodes of the prior art solution where no alternative current path is provided. In fact, a design which is optimized with regard to normal operation, while no other major alternative current path through the valve 210 is required in addition to the switch 300 and the diode 305, can be contemplated.

In order to determine whether the opening of the DC breaker 500 is required to protect the diodes 305 of VSC converter 105 from thermal breakdown as a result of fault currents through the VSC converter 105, the temperature of the diode 305 of an electric valve 210 is monitored. Such monitoring could for be a direct temperature monitoring wherein the temperature of the diode 305 is measured, or an indirect temperature monitoring, wherein a physical magnitude is measured from which the temperature of the diode may be derived or estimated, such as the current through the diode 305 or the voltage across the diode 305. A flowchart schematically illustrating a monitoring process that could be used in order to determine whether or not the DC breaker 500 should be tripped is shown in **Fig. 6.**

At step 605, the operation of the VSC converter 105 is started. Prior to starting the VSC converter 605, a diode safety temperature T^{305}_{safety} has typically been set to a value at or below the fatal temperature T^{305}_{fatal} of the diode 305. The fatal temperature is the temperature at which additional charge carriers are generated. The difference between the safety temperature and the fatal temperature is set at a suitable temperature safety distance δT_{safety} , so that:

$$T^{305}_{safety} = T^{305}_{fatal} - \Delta T_{safety} \quad (3).$$

For silicon diodes 305, the fatal temperature could typically be in the region of 620 K. A suitable diode safety temperature could then for example be around 600 K. The magnitude of the applied safety distance ΔT_{safety} could depend on the accuracy of the temperature estimate - the larger the risk that the actual temperature is higher than the estimated temperature, the larger temperature safety distance should be applied.

When the operation of the VSC converter 105 has been started in step 605, step 610 is entered, wherein it is checked whether the temperature of the diode T^{305} exceeds a temperature threshold $T^{305}_{threshold}$. If not, step 610 is re-entered, so that a more or less continuous monitoring of the diode temperature can be achieved. However, if it is determined in step 610 that the diode temperature exceeds the temperature threshold, step 615 is entered, wherein the opening of the DC breaker 500 is triggered. As will be further discussed below in relation to Fig. 9b, some embodiments of a DC breaker 500 could be triggered in step 615 to open either fully, or partially (typically with a conditional full opening at a later point in time). In one implementation of the method of Fig. 6, the DC breaker 500 will be triggered to open fully, immediately upon entry into step 615. In another implementation, the DC breaker 500 is first triggered to open partially, in order to enter into current limiting mode as described in EP0867998. By opening the DC breaker 500 partially, the current through the VSC converter 500 could be limited to a certain value. The DC breaker 500 could then be kept in the current limiting mode until the HVDC station protection system has been able to derive information on what may have caused the fault situation, and whether or not the DC breaker 500 should be fully opened. If required, the DC breaker 500 will then be opened fully. Such use of a current limitation mode could be useful in order to avoid damage of the VSC converter 105 during the time required for the protection system to assess the situation. In a fault situation wherein the protection system determines that the full opening of the DC breaker 500 is not required, the partial opening of the DC breaker 500 will save the power transmission system from the disturbances caused by breaking the DC current fully.

Once the fault causing the increased current through the HVDC station 100 has been attended to, the DC breaker 500 can be closed and normal operation of the HVDC station 100 can be resumed.

By providing the HVDC station 100 with a DC breaker 500, the opening of which is controlled in dependence on the temperature of the diode 305, the operation of the VSC converter 105 could continue in static VAR mode even when the DC transmission line 110 has to be broken, thus minimizing the impact of the breaking of the DC transmission line 110 on the AC system 135.

The temperature threshold $T^{305}_{threshold}$ of step 610 of Fig. 6 is typically determined in dependence on the diode safety temperature such that $T^{305}_{threshold} \leq T^{305}_{safety}$. The temperature threshold $T^{305}_{threshold}$ could for example be a static value, which then could for example be equal to the safety value T^{305}_{safety}, or the threshold value could be a dynamic value, determined for example in dependence on the time derivative of the diode temperate as well as in dependence on the safety temperature T^{305}_{safety}. An example of an expression that could be used for determining a dynamic value of the temperature threshold $T^{305}_{threshold}$ is given below:

$$T^{305}_{threshold} = T^{305}_{safety} - (t_{DC} + \Delta t_{safety}) \frac{dT^{305}}{dt} \qquad (4)$$

where Δt_{safety} is a time safety distance introduced to ensure that the DC breaker 500 will break the current before the safety temperature has been reached (the time safety distance may account for imprecision of the determination of the triggering point, caused for example by an increase in the temperature time derivate after the DC breaker has been triggered). If desired, the time safety distance could be set to zero, thus relying on the temperature safety distance ΔT_{safety} for safeguarding a fast enough breaking of the current. Similarly, if the time safety distance of expression (4) is sufficiently large, then ΔT_{safety} could be set to zero, so that $T^{305}_{safety} = T^{305}_{fatal}$.

In an implementation wherein the temperature threshold $T^{305}_{threshold}$ is a static value, the temperature safety distance ΔT_{safety} could for example be set so that the diode temperature will fall below the fatal temperature even if the temperature exhibits the highest expected time derivative during the duration of the DC breaker breaking time toe-

Monitoring of the diode temperature T^{305} could for example be performed by measuring the actual temperature of the diode 305, or by measuring other quantity(ies) from which the diode temperature T^{305} may be estimated, such as e.g. the current I through the diode 305, or the voltage V^{305} across the diode 305. The current I is directly related to the heat dissipation in the diode 305 and can be estimated by the relation

$$P^{305}(t) = R^{305} \cdot I^2(t) + V_T \cdot I(t) \qquad (5),$$

where R^{305} is the resistance of the diode 305 and V_T is the threshold voltage of the diode 305. Similarly, the voltage V^{305} across the diode 305 is directly related to the heat dissipation in the diode 305. Expression (5) represents a first order representation of the diode 305. If further accuracy is required, a higher order representation of the diode 305 could be used, and/or the temperature dependency of R^{305} could be considered. Such higher order representations are known in the art and will not be further discussed here. If a lower accuracy would be sufficient, the dissipated power could be determined in dependence of the first term of expression (5) only.

From knowledge of the heat dissipation power P^{305}, the temperature of the diode 305 may be estimated, typically also using information on the heat properties of the diode 305. The diode temperature T^{305} may for example be calculated based on the power dissipation P(t), the initial diode temperature $T^{305}_{initial}$ and the thermal impedance Z^{305} of the diode structure:

$$T^{305}(t) = P^{305}(t) \cdot Z^{305}(t) + T^{305}_{initial} \qquad (6),$$

The initial diode temperature $T^{305}_{initial}$ is the temperature of the diode 305 at the point in time when the fault occurred, and can typically be assumed to be a known steady state temperature (or the value of the last diode temperature measurement, if such measurements are conducted). The thermal impedance Z^{305} of the diode structure advantageously includes the thermal impedance of the diode 305, as well as of associated heatsinks and cooling system. The diode structure can thus be represented by a series of n thermal entities, each having a thermal time constant τ_i and thermal resistance Π_i, so that the thermal impedance Z^{305} can be expressed as:

$$Z^{305}(t) = \sum_{i=1}^{n} \Pi_i \left(1 - e^{-t/\tau_i}\right) \qquad (7)$$

The proposed method of determining a temperature of a device by use of expressions (6) and (7) is known in the art, and described in for example *"Power Electronics, converter applications and design " by Mohan, Undeland and Robbins*, Chapter 29, 3rd Edition. Other methods of determining a temperature may alternatively be employed.

As discussed in relation to step 610 of Fig. 6, the diode temperature T^{305} is compared to the temperature threshold $T^{305}_{threshold}$, which can take, in one implementation, a dynamic value. The dynamic value of $T^{305}_{threshold}$ can be determined, as suggested by expression (4), in dependence of the temperature time derivative. An estimate of the diode temperature T^{305} at the time of breaker opening, $T^{305}(t_{trigger}+t_{DC})$, can obtained by extrapolation of the temperature time derivative:

$$T^{305}(t_{trigger} + t_{DC}) = T^{305}(t_{trigger}) + (t_{DC} + \Delta t_{safety}) \frac{dT^{305}(t_{trigger})}{dt}$$

For purposes of such extrapolation, and for determining a dynamic temperature threshold $T^{305}_{threshold}$, one could, for example, assume that the current I through the diode 305 (voltage V^{305} across the diode) will continue to rise, for example according to a linear relationship, or according to another pre-determined relationship, so as to obtain an extrapolation of the heat dissipation $P^{305}(t)$. By use of for example expression (6), the diode temperature $T^{305}(t)$ may be determined.

In one implementation using current or voltage measurements as an indication of the diode temperature T^{305}, step 610 of Fig. 6 is initially provided by a more or less continuous check of whether the current (voltage) has exceeded the expected normal operations current (voltage). Monitoring of the diode temperature T^{305}, for example by use of expression (6), could then start upon detection of an increased current (voltage). If the current (voltage) magnitude returns to the expected normal operations magnitude before the diode

temperature exceeds the temperature threshold $T^{305}_{threshold}$, the temperature monitoring could be discontinued, while the current (voltage) monitoring would continue.
In another implementation, the diode temperature T^{305} is determined also under normal operating conditions.

In one implementation of the method shown in Fig. 6, the cooling effects of any heat sinks and cooling systems are neglected, and the diode temperature can then be estimated directly from the dissipated heat. In fact, no explicit determination of the diode temperature has to be made in this implementation, but an implicit determination of the diode temperature can be made by determining the dissipated heat, using a predefined relationship between the dissipated heat and the diode temperature T^{305}. This implementation yields a less accurate determination of the point in time when the DC breaker 500 should be triggered than when cooling effects are considered. In this implementation, step 610 of Fig. 6 could for example include a monitoring of the current I and/or voltage V^{305} to detect an increased power dissipation, and if such increased power dissipation is detected, the dissipated heat could be monitored and a check performed as to whether the dissipated heat since detection of the increased current (voltage) exceeds a heat threshold value. The heat threshold value could for example be determined by

$$W^{305}_{threshold} = W^{305}_{safety} - \left(t_{DC} + \Delta t_{safety}\right)P^{305}(t) \qquad (8a),$$

or, in order to obtain a more accurate value:

$$W^{305}_{threshold} = W^{305}_{safety} - \int_0^{t_{DC}+\Delta t_{safety}} \left(P^{305}(t)\right) dt \qquad (8b),$$

where W^{305}_{safety} is determined from the safety temperature T^{305}_{safety} by use of a pre-determined relationship between the dissipated heat W and the diode temperature T^{305}. Expressions (8a) and (8b) assume that the cooling of the diode losses P can be neglected during the short time period of the fault.

The protection system configured to perform the method illustrated by Fig. 6 could for example be part of a general protection system of an HVDC station 100, or could be a separate protection system. The protection system could for example be implemented by use of hardware only. An example of a protection system 505, configured to perform the method of Fig. 6, is shown in **Fig. 7a.** The protection system 505 of Fig. 7a comprises a temperature determination mechanism 705 and a trigger mechanism 710, as well as an input 715 configured to receive a status signal 525 from the VSC converter 105, and an output 720 configured to deliver a trigger signal 520 to the DC breaker 500. An input of the temperature determination mechanism 705 is connected to the input 715, and the temperature determination mechanism 705 is configured to determine the temperature of the diode 305 in dependence of a received status signal 525. As mentioned above, the status signal 525 is a signal indicative of a measure from which the temperature of the diode 305 may be derived, and could for example be a measurement of the current I through the diode 305, of the voltage U^{305} across the diode 305, or of the diode temperature T^{305}. The temperature determination mechanism 705 is configured to determine the temperature of the diode 305 in dependence on a received status signal 525. When the status signal 525 is indicative of the current I through the diode 305, the temperature determination mechanism 705 could for example be configured to determine the diode temperature in accordance with expressions (5)-(7). An output of the temperature determination mechanism 705 is connected to an input of trigger mechanism 710, and configured to deliver a signal 723, indicative of a determined temperature T^{305}. When the status signal 525 is indicative of a measurement of the diode temperature T^{305}, temperature determination mechanism 705 could be omitted, and an input of trigger mechanism 710 could be directly connected to input 715.

Trigger mechanism 710 of Fig. 7a is configured to receive a signal indicative of the diode temperature T^{305}, and to compare a received value of the diode temperature T^{305} to a temperature threshold $T^{305}_{threshold}$. Trigger mechanism 710 is further connected to the output 720, and configured to deliver a trigger signal 520 to the output 720 if the received value of the diode temperature T305 exceeds the temperature threshold $T^{305}_{threshold}$. In an implementation wherein the temperature threshold is dynamic, for example in dependence on the time derivative of the diode temperature, the trigger mechanism is further configured to update the threshold value, for example in accordance with expression (4). In such implementation, trigger mechanism 710 could for example comprise a buffer for storing previous values of the diode temperature T^{305}, by use of which the temperature derivate may be determined.

The protection system 505 could, by use of suitable electrical circuitry, be implemented by means of hardware only. An example of an electrical circuit whereby an embodiment of the protection system 500 can be implemented is shown in **Fig. 7b.** Protection system 505 of Fig. 7b comprises a temperature determination mechanism 705 which is configured to receive a status signal 525, indicative of the current I through the diode 305. Temperature determination mechanism 705 of Fig. 7b comprises a multiplier 721, configured to receive the status signal 525 at two inputs, in order to generate a signal indicative of I^2. An output of multiplier 722 is connected to an amplifier 722 of gain R^{305}, the output of which is connected to an adder 724. Temperature determination mechanism 705 further comprises an amplifier 723 of gain V_T, configured to receive the status signal 525 and to deliver an amplified output to the adder 724. The output of adder 724 is thus a signal indicative of the heat power dissipation P^{305} in the diode 305. Temperature determination mechanism 705 further comprises a set of series connected 1st order filters 725, each comprising a resistor and a capacitor and each representing one term in expression (7). The output of the set of 1st order filters 725 is connected to an adder 726, to which a signal source configured to generate a signal indicative of the initial temperature $T^{305}_{initial}$ is also connected. An output signal from the adder 726 will hence be a signal indicative of the diode temperature 305, and the output of adder 726 forms the output of the temperature determination mechanism 705, which is connected to an input of a trigger mechanism 710. Trigger mechanism 710 of Fig. 7b comprises a subtractor 727 and a comparator 728. The input to trigger mechanism 710 is connected to the positive input of subtractor 727, while the negative input is connected to a signal source configured to deliver a signal indicative of the threshold temperature $T^{305}_{threshold}$. An output signal from subtractor 727 will hence be indicative of the difference between the present diode temperature T^{305} and the threshold temperature $T^{305}_{threshold}$. The output of subtractor 727 is connected to an input to comparator 728. Comparator 728 is configured to generate a trigger signal 520 when a positive input signal is supplied at its input, i.e. when the diode temperature exceeds the temperature threshold. The output of comparator 728 is connected to the output 720 of the protection system 505.

The electrical circuit of Fig. 7b can be altered in many ways. For example, the set of 1st order filters 725 and the adder 726 could be replaced by a filter arrangement which is connected between a controllable current source and a grounded voltage source generating a voltage corresponding to $T^{305}_{initial}$, where the diode temperature could be output at the connection point to the controllable current source. The comparator 728 could be replaced by a comparator having two signal inputs, of which the T^{305} signal will be connected to one, and a $T^{305}_{threshold}$ signal to the other. Moreover, the trigger mechanism 710 could further comprise circuitry for generating a dynamic threshold temperature. Furthermore, if status signal 525 is indicative of voltage instead of current, the temperature determination mechanism will be altered accordingly. If the status signal is indicative of diode temperature, mechanism 705 could be omitted.

In an alternative implementation of protection system 505, the protection system 505 is at least partly implemented by computer software. **Fig. 7c** shows an alternative illustration of a protection system 505 which is at least partly implemented by means of computer programs. Fig. 7b shows the protection system 505 comprising a processor 730 connected to a computer program product 735 in the form of a memory, as well as to an input 715 and an output 720. The input 715 is configured to receive data by means of which the diode temperature can be estimated - the input 715 could for example be connected to a temperature sensor, a current measurement device arranged to measure the current through the diode 305, and/or a voltage measurement device arranged to measure the voltage across the diode 305. The output 720 is arranged to generate a DC breaker trigger signal, and is typically connected to the input 515 of the DC breaker 500. The memory 735 of protection system 505 stores computer readable code means in the form of a computer program 740, which, when executed by the processor 730, causes the protection system 505 to perform the temperature dependent DC breaker control method of Fig. 6. The processor 730 could be a single CPU (Central processing unit), or could comprise two or more processing units. For example, the processor may include general purpose micro-processor(s), instruction set processors and/or related chips sets and/or special purpose micro-processor(s) such as ASICs (Application Specific Integrated Circuit). The processor may also comprise board memory for caching purposes. The mechanisms 705 and 710 of protection system 505 would hence in this embodiment be implemented by means of a processor 730, in combination with software 740 for performing temperature dependent control of the DC breaker 500. In Fig. 7b, the software 740 is shown to be stored on one physical memory 735, however, software 740 could be divided onto more than one physical memory 735. A memory 735 could be any type of non-volatile computer readable means, such as a hard drive, a flash memory, an EEPROM (electrically erasable programmable read-only memory) a DVD disc, a CD disc, a USB memory, etc, or any combination thereof.

Since a switch 300 can be turned off at the occurrence of a fault current, a switch 300 is conventionally designed to have a rated current density similar to the nominal current of the VSC converter 105. In normal operation, the current density can be higher in a diode 305 than in a switch 300, since the losses are typically higher in a switch 300 than in a diode 305 at the same current density. However, until now, a diode 305 of a valve 210 for high voltage applications, and wherein no major alternative current path is provided, has been designed to have a rated current density similar to the rated current density of the switch 300 of the valve 210, so as to ensure that the diode 305 could withstand any fault currents. By connecting a fast DC breaker 500 to the DC interface 115, where the DC breaker 500 will be triggered to open when the temperature of the diode 305 exceeds a temperature threshold, anti-parallel diode 305 of a valve 210 can, in one embodiment, be designed to have a rated current density which is more than 150% of the rated current density of the switch 300 of the valve 210. The required thickness, and thus the resistance, of the semiconducting material, increases with increasing operating voltage of the switch or switching element, thus effecting the heat power dissipation at surge current, which is a limiting factor in the reduction in materials consumption of the diode 305. By providing accurate timing of a DC breaker, the rated current density of a diode 305 in a reverse-conducting switching arrangement 310 can be at least 150 % of the switch 300 of the switching arrangement 310 also in switching arrangements wherein the operating voltage of the switch (or switching element) is high, for example in a reverse-conducting switching arrangement 310 including IGBTs having a rated voltage of 3-5 kV or higher, such as 4.5 kV.

The anti-parallel diodes 305 are, in this embodiment, typically dimensioned in accordance with the nominal current of the VSC converter 105, and the valves 210 can be designed so that at least a major part, if not all, of the current in a short circuit situation will flow through the anti-parallel diodes 305 (provided that the switches 300 have been turned off). Hence, great savings can be made in the materials consumption, as well as the space requirements, of the HVDC station 100. A safety margin can, if desired, be provided in that the rated current of the anti-parallel diode exceeds the nominal current of the VSC converter 105, mainly in order to ensure that the anti-parallel diode 305 will withstand, during a long life time, the nominal currents during normal operation.

A DC breaker 500 is sufficiently fast if it is capable of breaking a current within a particular breaking time t_{DC} from the onset of the opening of the DC breaker 500, where the breaking time t_{DC} of the DC breaker is shorter than the time required for the worst case short circuit current to generate a destructive amount of heat in a conducting anti-parallel diode. The short breaking time t_{DC} of the DC breaker 500 thus allows for an increase of the expected short circuit current density, j_{SC}^{305}, of the diodes 305, manifested for example as a reduction of the cross section area of the anti-parallel diodes 305, and/or a reduction in the VSC converter impedance X_{105}^{α}, resulting in an increase in the short circuit current I_{SC} (at maintained rated voltage) (cf. expression (1)). Typically, t_{DC} of a fast DC breaker 500 is in the order of a tenth of t_{AC} of a typical AC breaker 145 (cf. Fig. 4a). As will be discussed below, DC breakers 500 having breaking times t_{DC} as short as 2 ms are presently available, corresponding to one tenth of a fundamental frequency period of the AC system 135. By the term fast DC breaker 500 is here meant a DC breaker of breaking time t_{DC} of around 10 ms or shorter, i.e. a breaking time corresponding to half of a fundamental frequency period in a 50 or 60 Hz AC system 135, or shorter.

Fig. 4b illustrates a comparison between a conventional, AC-breaker-limited HVDC station design a (having no alternative current path) and a DC-breaker-limited HVDC station design Δ wherein the cross sectional area of the anti-parallel diodes 305 of the VSC converter 105 has been reduced compared to the conventional design, $A_{305}^{\Delta} < A_{305}^{\alpha}$. The VSC converter impedance X_{105} is assumed to be same for the two designs, as is the rated voltage, and thus, $I_{305}^{\Delta} = I_{305}^{\alpha}$, although the current density is higher for design Δ: $j_{305}^{\Delta} > j_{305}^{\alpha}$. However, the impedance of diodes 305 of design Δ will be higher than the impedance of diodes of design a , since the cross section of the diode 305 is smaller: $X_{305}^{\Delta} = \frac{A_{305}^{\Delta}}{A_{305}^{\alpha}} X_{305}^{\alpha}$. Thus, the heat dissipation as a function of time will be higher for the design Δ by a factor $\frac{A_{305}^{\Delta}}{A_{305}^{\alpha}}$. Furthermore, since the volume of the anti-parallel diodes 305 in design Δ is smaller than the volume of design a , a lower amount of dissipated heat W^{305} will be required for the diodes of design Δ to reach the fatal temperate T_{fatal} than for the diodes of design a : $W_{fatal}^{305,\Delta} = \frac{A_{305}^{\Delta}}{A_{305}^{\alpha}} W_{fatal}^{305,\alpha}$, assuming similar cooling (the forced or natural cooling achieved during such short time periods is typically negligible). In the designs for which the heat dissipation is illustrated in Fig. 4c, $\frac{A_{305}^{\Delta}}{A_{305}^{\alpha}} = \frac{2}{3}$. HVDC station design Δ has a DC breaker 500 of breaking time toe, which is approximately a tenth of the breaking time of the AC breaker 145 of design a . Due to this short breaking time toe, the heat $W^{705}(t_{DC})$ developed until the DC breaker 500 has managed to break the current is well below the fatal heat level $W_{fatal}^{305,\Delta}$. Hence, a reduction in cross sectional area to 2/3 of the diode area in a conventional VSC converter 105 would be well within the limits of feasible reductions, and even further reductions could be made. Hence, considerable savings on the materials from which the diode 305 is formed could be made.

In one aspect of the invention, the reduction in current surge sensitivity due a short and accurate breaking time t_De is exploited to reduce the material consumption of the valves 210, as illustrated in Fig. 4b. For example, the diode cross section, and hence the amount of semiconducting material required to form the diodes 305, can be reduced compared to a conventional VSC converter 105 wherein the diodes 305 are designed to withstand the short circuit current during 2-3 periods. Furthermore, compared to a conventional valve 210 having a thyristor or other alternative current path that can be temporarily provided in case of a large fault current, such alternative current path can be omitted or considerably reduced in terms of current carrying capability. Hence, the manufacturing costs of the valves 210 can be considerably reduced.

Oftentimes, switching and rectifying elements used to form the switch 300 and the diode 305 are arranged in the same semiconductor chip module, the size of which typically has an upper limit given by manufacturing considerations. By allowing for a reduction in semiconductor material consumption of the diode 305 of a valve 210, there will be more space in the semiconductor chip module for the switching elements, thus allowing for an increase in the rated current of the switch 300 of the semiconductor chip module. Hence, the operating power of the VSC converter 105 could be increased with maintained semiconductor consumption. Alternatively, the number of semiconductor chip modules used to form the switch 300 and the diode 305 of an electrical valve 210 could be reduced with maintained power. As an example, a semiconductor chip module could be designed so that the switching elements occupy 2/3 of the semiconductor chip module area, while the rectifying elements occupy 1/3 of the semiconductor chip module area - as mentioned above, the rated current density of the diode 305 can oftentimes be higher than the rated current density of the switch 300, since the losses will generally be lower in a diode 305, than in a switch 300, at the same current density. The diode cross section area A_{305} will in this example be 2/3 of the diode cross sectional area of a semiconductor chip module of the same size, but where the rectifying elements occupy half the semiconductor chip module area, which is a typical semiconductor chip module in the conventional valve design wherein the diodes 305 are over-dimensioned. With maintained power rating, the current density would hence increase to 150% of such half-half semiconductor chip module. However, the corresponding increase of the cross sectional area of the switch 300 will allow for an increased power rating of the HVDC station 100, which would result in a further increase in the short circuit current density in the diodes 305. A semiconductor chip module 800 having switching elements 805 occupying 2/3 of the cross sectional area and rectifying elements 810 occupying 1/3 of the area is shown in **Fig. 8.** Conventional symbols are shown to indicate current direction. Other ratios of the area occupied by the rectifying elements 810 to the area occupied by the switching elements 805 than ½ and 1/3 could be used, such as 2/5, ¼, 3/7, or any other suitable ratio. However, the ratio should not be so low so that the diode area will not be sufficient for reliably carrying the rated current during normal operation of the HVDC station 100.

Since not only the short circuit scenario but also the normal operating conditions set constraints on the design of the diodes 305, it is often the case that the size of the diode 305 will have to be larger than the minimum size allowed in the short circuit scenario. However, the availability of fast breaking of a short circuit current can also be exploited in a reduction of the short circuit impedance of the HVDC station 100. In one aspect of the invention, the provision of accurate timing the control of the DC breaker, and a short breaking time t_Dc, is exploited to reduce the impedance of the AC reactors 120 (cf. Fig. 4c), thus allowing for a higher reactive power generation from the VSC converter 105. Furthermore, a reduction in the size of the AC phase reactors 120 results in a reduced space and materials consumption of the HVDC station 100.

Such reduction in size of the AC phase reactors is often combined with an optimization of the diode size to the normal operation conditions. For purposes of illustration, however, a comparison between two different HVDC station designs having diodes 305 of the same designs will be discussed. **Fig. 4c** illustrates a comparison between a conventional, AC-breaker- limited HVDC station design a (having no alternative current path) and a DC-breaker- limited HVDC converter design δ wherein the availability of fast current breaking is exploited in that the impedance of the HVDC station 100 is designed to give a higher short circuit current Isc- A graph similar to that of Fig. 4a is presented, which shows the developed heat W^{305} in a diode 305 of cross-section A as a function of time t for the two different VSC converter designs α and δ in a worst case short circuit situation, where the impedance X_{i00} of the VSC converter is lower in design δ than in design a : $X^{\alpha}_{100} > X^{\delta}_{102i}$. Hence, the short circuit current ¾ . of design δ is larger than ¾ of design a : $I^{\delta}_{100} > X$¾ $_{\alpha}$. The design δ assumes a fast DC breaker 500, while the design a is also suitable where the breaking of the current is a slower, mechanical AC breaker 145. The fatal heat level W^{305}_{fatal}, illustrating the level of developed heat at which the diode 305 will be fatally damaged, is also shown in the graph. Furthermore, a breaking time t_De of a fast DC breaker 500 has been indicated, as well as a breaking time t_Ac of a typical mechanical AC breaker 145. t_De of Fig. 4b is approximately a tenth of t_Ac of Fig. 4b. The graph of Fig. 4c clearly shows that the short circuit impedance can be considerably reduced, without risking that the diode 305 will be damaged before the current is broken, when a fast DC breaker 500, which is operated in dependence on the diode temperature, is connected to the VSC converter 105. For example, compared to an HVDC station 100 having diodes of the same design and having a breaking time (T_{AC}) of 50 ms, the short circuit impedance can be typically be reduced by approximately a factor 3 when a breaker of breaking time 10 ms is used.

Reactive power generation can for example be important when the DC breaker 500 has been opened, in order to minimize the disturbances of the breaking of the DC current on the AC system 135. If inductance of the AC reactors 120 is reduced by M %, the reactive power generation from the VSC converter 105 can be increased by $\frac{100}{100-M}$ %. The impedance of the AC reactors 120, X_{120}, typically forms a considerable part of the short circuit impedance, Xsc, and a reduction in X_{120} will thus result in an increase of the amplitude of the short circuit current (cf. expressions (1) and (2)). The fast breaking speed obtained by use of the fast DC breaker 500 on the DC side of the VSC converter 105 allows for a VSC converter design where X_{120} is reduced with maintained current rating of the diodes 305, or (albeit less so) with a reduced current rating of the diodes 305. As an alternative to providing an increase in the reactive power generation by reducing the impedance of the AC reactors 120, the voltage rating of the converter 105 could, particularly in a transformerless HVDC station 100, be reduced with maintained power rating by reducing the impedance of the AC reactors 120.

In one implementation example, the impedance of the AC reactors 120 is selected such that the short circuit impedance of the circuit, X_{SC}, is around 15 %, or less, of the base impedance of the VSC converter 105, X^{105}_{base}:

$$X_{sc} \approx X_{120} + X_{140} \lesssim 0.15 \cdot X^{105}_{base} \qquad (9)$$

The base impedance of the VSC converter 105 is given by the ratio of the rated voltage on the AC side of the VSC converter 105 to the rated AC current through the VSC converter 105:

$$X^{105}_{base} = \frac{rated\ AC\ voltage}{rated\ AC\ current} \qquad (10)$$

In implementations of the HVDC station 100 wherein a phase includes a transformer 140, the transformer impedance X_{140} should not be reduced below the impedance level required for protection of the transformer itself, which is often around 10 % of the base impedance X^{105}_{base}. In some implementations wherein a transformer 140 is present, the AC phase reactor 120 of a phase could actually be omitted. In other implementations of the HVDC station 100 (e.g. in a transformerless implementation), the AC phase reactor impedance is the dominant impedance. The sum of X_{120}^{*} and X_{140} could for example lie within the interval 5% -15% of the base impedance. In one example, this sum is approximately 10 % of the base impedance X_{base}^{105}.

Although a diode design which is optimized in relation to the nominal current of the VSC converter 105 is often desired, there may be circumstances where it is advantageous to have over-dimensioned diodes 305 in relation to normal operating conditions, so that the increased breaking speed is fully exploited to allow an HVDC station design of even lower short circuit impedance.

It should be noted that the W(t) curves in Figs. 4a-4c assume that the momentary magnitude of the AC current is zero at the triggering of the breaker 500/145 (at t=0), and that the current thereafter increases in the direction in which the diode 305 conducts current. Obviously, the triggering of a breaker 500/145 could occur at a different point in time, and if so, the W(t) curves would be shifted along the t-axis. Depending on the ratio of t_{D}e to the fundamental frequency period, this may affect the point in time at which the fatal heat level, W_{fatal}^{305}' is reached. When designing an HVDC station 100 having a fast DC breaker 500, a time safety margin should be preferably be applied, so that $W^{305}(t_{D}c)$ will be well below W_{fatal}^{305}, and t_{D}c will be well below t_{fatal}, regardless of where in the fundamental frequency period the triggering of the DC breaker 500 occurs.

To demonstrate the improvements that can be achieved by the invention, the following example is given: A silicon based diode 305 which is currently available and today used in applications wherein a maximum short circuit current of around 16.4 kA can last for a maximum of 2-3 fundamental frequency periods (40-60 ms), could, in combination with a DC breaker 500 having a breaking time t_{D}e of around 2 ms, be used in applications wherein the maximum short circuit current would be around 50 kA.

When dimensioning the diodes 305 of the VSC converter 105 in accordance with the normal operating conditions, while providing no major alternative current path in an electric valve 210 to the paths provided by the reverse-switching arrangement 310, it is important to minimize any risk of the DC breaker 500 not operating properly. In order to ensure proper operation of the DC breaker 500, the connection line 510 between the VSC converter 105 and the DC breaker 500 could advantageously be kept short, in order to minimize the risk for any earth fault between the VSC converter 105 and the DC breaker 500. A suitable distance between the VSC converter 105 and the DC breaker 500 could for example lie in the range of 2-10 meters, depending on the rated voltage of the VSC converter 105 - if the distance is too short, there may be a risk for flashovers from the VSC converter 105 to the DC breaker 500, wherefore a safety margin for air clearance is typically required. Roughly, a distance of 1 m per 100 kV is typically required (for voltages above several 100 kV, a larger distance may be required). For example, for a VSC converter 105 rated for 320kV DC, a suitable distance between the VSC converter 105 and the DC breaker 500 could be 3 m. Advantageously, the VSC converter 105 and the DC breaker 500 could be located in the same building at the HVDC station site, with no bushing used along the connection line 510 between the VSC converter 105 and the DC breaker 500, in order to minimize the risk for flash-over. Since the temperature requirements of the VSC converter 105 and the DC breaker 500 are similar, this would typically be feasible. Furthermore, the connection line 510 could advantageously be mechanically supported, for example by support insulators with over-dimensioned creepage and air clearance, to provide a robust connection in order to minimize the risk for earth fault or short circuit situations, and/or the VSC converter 105 and the DC breaker 500 could be mechanically integrated in a common valve hall.

In order to further improve the safety of the HVDC station 100, the protection system could be configured to determine, upon opening of the DC breaker 500, whether the current in the connection line 510 in the vicinity of the DC interface 115, has gone down to zero when the DC breaker 500 has opened. If not, this is an indication that the fault may have occurred in the connection line 510, and the protection system could be configured to then trigger the opening of the AC breaker(s) 145.

Fast DC breakers 500 as discussed above could be of any design which can provide a breaking time approximately 10 ms, or less, for example 5ms, 2 ms or shorter. The DC breaker 500 could be for example be an electronic DC breaker, such as an electronic DC breaker as described in EP0867998, wherein a semi-conductor switch of turn-off type is connected in parallel with a surge diverter to form an electronic DC breaker. Suitable fast electronic switches are also disclosed in patent application PCT/EP2009/065233, of which examples are shown in Figs. 9a and 9b.

The DC breaker 500 of **Fig. 9a** is an electronic DC breaker 500 comprising a parallel connection of a (main) electronic switch 900 of turn-off type and a surge diverter 905. The DC breaker 500 of Fig. 9a further comprises a series connection of a high speed disconnector 910 and an auxiliary electronic switch 915 of turn-off type, where this series connection is connected in parallel to the main electronic switch 900 and the surge diverter 905. The DC breaker 500 of Fig. 9a further comprises a reactor 920 connected in series with the parallel connection, the reactor 920 providing current limitation. The on-resistance of the auxiliary switch 915 of Fig. 9a is considerably smaller than that of the main switch 900. Moreover, the current breaking power of the auxiliary electronic switch 915 is considerably lower than that of the main switch 900. During normal operation of a VSC converter 105 to which the DC breaker 500 of Fig. 9a is connected, the current will flow through the series connection of the auxiliary switch 915 and the high speed disconnector 910. Upon detection of a possible need for breaking the current, the auxiliary switch 915 will be opened and the current will be commutated to the main switch 900. When no current flows through the high speed disconnector 910, the high speed disconnector 910 will be opened, ensuring a high voltage withstanding capability of the series connection of the high speed disconnector 910 and the auxiliary switch 915. In order to break the current, the main switch 900 will then be opened. By the DC breaker shown in Fig. 9a, efficient, high-speed breaking of the current can be obtained by means of the main switch 900, while the drawback of enhanced power dissipation in the main switch 900 can mostly be avoided, since during normal operation, basically no current will flow through the main switch 900. The opening of the auxiliary switch 915 could advantageously be triggered upon an indication that the current may have to be broken, while the triggering of the main switch 900 could be made conditional on a confirmation from the protection system that the breaking of the current is actually required.

In Fig. 9a, the auxiliary switch 915 is shown to include one switch base element comprising two semiconducting power electronic switching elements of turn-off type connected in anti-parallel, while the main switch 900 is shown to comprise a series connection of a plurality of such switch base elements. Other types of switch base elements could further alternatively be used, such as for example switch base elements wherein a switching element of turn-off type is connected in parallel with an anti-parallel diode (forming a unidirectional switch base element); or two such unidirectional switch base elements of opposite direction connected in series; or simply a switching element on its own. The auxiliary switch 915 could include further switch base elements, and/or the switch base elements of the auxiliary switch 915 and the main switch 900 could be of different types.

Suitable switching elements of turn-off type for use in an electronic DC breaker 500 are for example IGBTs, GTOs and IGCTs. Surge diverters for use in an electronic DC breaker 500 could for example be made from a material having non-linear resistivity, such as ZnO or SiC resistors, in a known manner.

The DC breakers 500 of EP0867998 and of Fig. 9a are given as examples only, and the DC breaker 500 could be implemented in alternative ways. In one embodiment the DC breaker 500 could comprise a series connection of two or more independently switchable breaker sections, so that DC breaker 500 could operate as a current limiting arrangement as well as a DC breaker 500. An example of such DC breaker 500 which may operate as a current limiter, as well as a DC breaker 500, is shown in **Fig. 9b** (see also Fig. 4 of EP0867998). The current limiting DC breaker of Fig. 9b comprises a series connection of three different breaker sections 925, where each breaker element 925 comprises a series connection of high speed disconnector 910 and an auxiliary switch 915; a main switch 900 and a surge diverter 905, where the main switch 900, the surge diverter 905 and the series connection of910 & 915 are connected in parallel. The breaker elements 925 are independently switchable, so that one or two of the breaker elements 925 could be opened, while (a limited) current would still be flowing through the DC breaker 500. The current limiting DC breaker 500 of Fig. 9b is shown as an example only, and may be altered in many ways. For example, a current-limiting DC breaker 500 could include any number L of breaker elements 925, L>2. The series connection of910 & 915 could be omitted from the breaker elements 925. If desired, instead of each breaker section 925 having its own auxiliary switch 915 and disconnector 910, one set of series connection of910 & 915 could be provided in parallel with the entire series connection of L breaker elements 925.

The present invention should not be construed to be limited to the use of electrical DC breakers. Assuming for example that a mechanical DC breaker becomes available that has a breaking time $\mathbf{t_{D}e}$ of 10 ms or less, such fast mechanical DC breaker 500 could advantageously be used as a fast DC breaker 500.

As mentioned above, DC breakers 500 have been developed for interconnecting more than two HVDC stations 100 into a network of HVDC stations forming a grid, so that a faulty HVDC station 100 can be disconnected from the grid without causing any harm to the remaining HVDC stations 100 of the grid. In order to achieve this, an HVDC switchyard is conventionally provided, wherein DC transmission lines 110 from different HVDC stations 100 are interconnected via switchyard DC breakers. An example of an HVDC switchyard 1000 is shown in **Fig. 10a.** The HVDC switchyard 1000 of Fig. 10a interconnects, via two busbars 1005, four DC transmission lines 110 from four different HVDC stations, of which one is shown. An HVDC switchyard 1000 if often located in the vicinity of one of the HVDC stations 100 that it interconnects, such HVDC station 100 here being referred to as a local HVDC station 100 - the distant HVDC stations, typically located at a distance of 100 km or more from the HVDC switchyard 1000, are referred to as distant HVDC stations 100.

The HVDC switchyard 1000 of Fig. 10a is a so called one and a half breaker switchyard, where six switchyard DC breakers 1010 are provided to separate the four DC transmission lines 110 from each other. Other configurations of HVDC switchyards 1000 could alternatively be used, such as the so called two breaker configuration known in the art. Furthermore, an HVDC switchyard 1000 could interconnect any number of HVDC stations 100. In Fig. 10a, the two DC breakers 1010 that interconnect the local HVDC station with the busbars 1005 are denoted lOlOi.

If an earth fault, or short circuit fault, occurs in one of the HVDC stations 100, or in one of the transmission lines 110 connected to the HVDC switchyard 1000, the switchyard DC breakers 1010 connecting such faulty HVDC station/DC transmission line to the HVDC switchyard 1000 will be opened, so that the faulty HVDC station/DC transmission line will be disconnected from the remaining HVDC stations 100, which could then continue in operation.

As mentioned above, it is important that the disconnection of the faulty HVDC station/DC transmission line can be performed at high speed, since the current surges brought about by such fault will travel fast through the HVDC grid. If the DC breakers 1010 of the HVDC switchyard 1000 are too slow, discharge in the HVDC switchyard will significantly lower the DC voltage at the in-feeding HVDC stations 100, which may result in the disconnection of these in-feeding HVDC stations 100, and possibly a collapse of the entire HVDC grid. However, if a local HVDC station 100 (located in the vicinity of the HVDC switchyard 1000) is provided with a fast DC breaker 500, i.e. a DC breaker of breaking time of 10 ms or shorter as discussed above, it is often sufficient to use, as the switchyard DC breakers 1010, DC breakers of lower operating speed. DC breakers of lower operating speed, for example mechanical DC breakers, are typically far less costly than fast DC breakers, and a big reduction in materials consumption and monetary expense can be achieved by using DC breakers of different speed in a local HVDC station 100 and the HVDC switchyard 1000.

In Figs. 10a and 10b, fast DC breakers are indicated by a rectangle surrounding the breaking symbol, while the symbols indicating slower DC breakers have no such surrounding rectangle. In the configuration shown in Fig. 10a, all switchyard DC breakers 1010 are DC breakers of a slower type, while the HVDC station DC breaker 500 is a fast DC breaker.

A local HVDC station 100 is typically more vulnerable than the distant HVDC stations 100 to the current surge occasioned by an earth fault or short circuit in the grid, since the lengthy DC transmission lines 110 interconnecting the distant HVDC stations 100 with the HVDC switchyard 1000 provide an impedance which slows down the propagation of the current surge. By using slower DC breakers 1010 in the HVDC switchyard 1000, any fault current will have time to grow larger in the vicinity of the HVDC switchyard 1000 than if fast DC breakers were used in the switchyard 1000, and hence, the HVDC transmission lines 110 and the busbars 1005 will be exposed to higher currents. However, the HVDC transmission lines 110 and busbars 1005 are typically far less sensitive to current magnitude than the devices of an HVDC station 100, and the HVDC transmission lines 110 and busbars 1005 will generally not be damaged by the occurring current surges.

Hence, in order to save on monetary expenses and semiconducting material, the switchyard DC breakers 1010 could advantageously be mechanical DC breakers, if any local HVDC station(s) 100, connected to the HVDC switchyard 1000 and located in the vicinity of HVDC switchyard 1000, is equipped with a fast DC breaker 500.

Upon detection of a major fault in an HVDC station 100 or DC transmission line 100 connected to the HVDC switchyard 1000, the fast DC breaker 500 of a local HVDC station 100 will be tripped, as well as the ones of the switchyard DC breakers 1010 which connect the faulty HVDC station/DC transmission line to the switchyard 1000. The opening of the fast DC breaker 500 will be completed well before the critical time at which the current surge would otherwise have caused damage to the local HVDC station 100. Once successful opening of the relevant switchyard DC breakers 1010 has taken place, the DC breaker 500 of the local HVDC station will be closed, so that this local HVDC station 100 can continue the interrupted energy transfer via the HVDC grid. In the time period during which the local HVDC station 100 was disconnected from the grid, SVC operation of the local HVDC station 100 could continue, thereby minimizing the disturbances caused by the fault in the AC system 135.

The use of DC breakers of different breaking speed when connecting a local HVDC station 100 to an HVDC switchyard 1000 is not limited to HVDC stations 100 wherein the HVDC station 100 is configured to trip a DC breaker 500 interconnecting the HVDC station with the HVDC switchyard 1000 in dependence of a temperature of a reverse-conducting component, but could be applied to HVDC grids comprising HVDC stations 100 of any design. In fact, the use of DC breakers of different speed when connecting a local HVDC station 100 to an HVDC switchyard 1000 is not limited to HVDC stations 100 comprising a DC breaker 500. When interconnecting a local HVDC station 100 which does not include a DC breaker 500, the HVDC switchyard 1000 itself could include DC breakers of different speed, so that the local HVDC station 100 is connected to the HVDC switchyard via fast DC breakers 1010 (e.g. electronic DC breakers) of the HVDC switchyard 1000, while the remote HVDC stations 100 would be connected to the HVDC switchyard 1000 via slower DC breakers 1010 (e.g. mechanical DC breakers). An example of such configuration is shown in **Fig. 10b,** where a local HVDC station 100 is connected to an HVDC switchyard 1000 via two fast DC breakers lOlOi, forming part of the HVDC switchyard, while the HVDC switchyard furthermore comprises slower DC breakers 1010 for connection of remote HVDC stations 100.

Although various aspects of the invention are set out in the accompanying independent claims, other aspects of the invention include the combination of any features presented in the above description and/or in the accompanying claims, and not solely the combinations explicitly set out in the accompanying claims.

One skilled in the art will appreciate that the technology presented herein is not limited to the embodiments disclosed in the accompanying drawings and the foregoing detailed description, which are presented for purposes of illustration only, but it can be implemented in a number of different ways, and it is defined by the following claims.

Claims

1. An HVDC converter station (100) for interconnection of a DC transmission line (110) and an AC system (135) of at least one AC phase, the HVDC converter station comprising:

a VSC converter (105) having at least two electric valves (210), each having a reverse-conducting switch arrangement (310) comprising a switch component (300) and a reverse-conducting component (305); and

a DC breaker (500) connected to a DC interface (115) of the VSC converter in a manner so that the DC breaker will be connected in series between the VSC converter and the DC transmission line; and

a protection system (505) configured to

monitor the temperature of the reverse-conducting component (305) of at least one of the reverse-conducting switch arrangement, and

trigger the opening of the DC breaker if the temperature of the reverse-conducting component exceeds a temperature threshold.

2. The HVDC converter station of claim 1, wherein

the protection system is configured to monitor the temperature of the reverse conducting component of the switch arrangement by:

measuring the current flowing through the reverse-conducting component, and/or by measuring the voltage across the reverse-conducting component of the switch arrangement, and

estimating the temperature of the reverse-conducting component in dependence of such current and/or voltage measurements.

3. The HVDC converter station of claim 1 or 2, wherein

the protection system is further configured to determine a dynamic value of the temperature threshold.

4. The HVDC converter station of any one of the above claims, further comprising at least one AC breaker connected to an AC interface of the VSC converter, wherein;

the protection system is further configured to, if the DC breaker has been opened:

determine, if a current flows in a connection line (510) interconnecting the DC interface and the DC breaker, and, if so,

trigger the opening of the AC breaker(s).

5. The HVDC converter station of any one of the above claims, wherein:

the rated current density of the reverse-conducting component is more than 150 % of the rated current density of the switch component (300) of the reverse-conducting switch arrangement.

6. The HVDC converter station of claim 5, wherein

the rated current of the anti-parallel diode of an electric valve is substantially the same as the rated current of the semiconductor switch of the electric valve.

7. The HVDC converter station of claim 5 or 6, wherein

a semiconductor switching element (805) forming part of the semiconductor switch and a rectifying element (810) forming part of the anti-parallel diode are located in the same semiconductor chip module (800); and

the ratio of the area occupancy of the rectifying element to the area occupancy of the semiconductor switching element on the semiconductor chip module is smaller than 1.0, for example 0.5.

8. The HVDC converter station of any one of the above claims, wherein

the DC breaker is capable of breaking a current within a particular breaking time t_De from the onset of the opening of the DC breaker, where the particular breaking time t_De of the DC breaker is shorter than the time required for the worst case fault current to generate a destructive amount of heat in the conducting reverse-conducting component of the switch arrangement.

9. The HVDC converter of claim 8, wherein

the particular breaking time t_De is shorter than half of the fundamental frequency period of the AC system.

10. The HVDC converter station of any one of the above claims, wherein

the short circuit impedance of the HVDC converter station is less than 15 % of the base impedance of the HVDC converter station.

11. The HVDC converter station of any one of the above claims, wherein

the electric valves are designed such that in a worst case fault scenario, at least a majority of the current through the VSC converter will flow through at least one reverse-conducting component.

12. The HVDC converter station of any one of the above claims, wherein

the connection distance between the DC breaker and the DC interface is less than 10 meters.

13. The HVDC converter station of any one the above claims, wherein the DC breaker comprises:

a main semiconductor switch (900) of turn-off type;

a non-linear resistor (905) connected in parallel with the main semi-conductor switch; and

a series connection of a high speed switch (910) and an auxiliary semiconductor switch (915) of turn-off type, wherein the series connection is connected in parallel to the main semiconductor switch and the non-linear resistor.

14. The HVDC converter station of any one of the above claims, wherein

the DC breaker comprises a series connection of at least two independently switchable breaker sections (925), so that the DC breaker could operate as a current limiter.

15. An HVDC system comprising the HVDC converter station of any one the above claims, the HVDC system further comprising:

an HVDC switchyard (1000) connected to the HVDC converter station via the DC breaker, wherein

the HVDC switchyard comprises at least one busbar (1005) and at least one switchyard DC breaker (1010) connecting the converter station DC breaker (500) with at least one of the at least one busbars; wherein the converter station DC breaker is capable of providing a higher breaking speed than the switchyard DC breakers.

16. A method of operating an HVDC converter station (100) for interconnection of a DC transmission line (110) and an AC system (135), wherein

the HVDC converter station includes a VSC converter (105) and a DC breaker (500);

the VSC converter includes at least two electric valves (210), each having a reverse-conducting switch arrangement (310); and

the DC breaker is connected in series between the transmission line and a DC interface (115) of the VSC converter, the method comprising:

monitoring (610) the temperature of at least one of the reverse-conducting components in order to check whether the temperature is above a temperature threshold, and if so,

triggering (615) the opening of the DC breaker.

17. The method of claim 16, wherein

the monitoring of the temperature of the reverse-conducting component is performed by

measuring the current flowing through the reverse- conducting component, and/or by measuring the voltage across the reverse-conducting component of the switch arrangement, and

estimating the temperature of the reverse-conducting component in dependence of such current and/or voltage measurements.

18. The method of any one of claims 16 or 17, further comprising

determining, and from time to time updating, a dynamic value of the temperature threshold.

19. The method of any one of claims 16-18, wherein the HVDC station further comprises at least one AC breaker connected to an AC interface of the VSC converter, the method further comprising, if the DC breaker has been opened:

determining if a current flows in a connection line (510) interconnecting the DC interface and the DC breaker, and, if so,

triggering the opening of the AC breaker(s).

Fig. 1

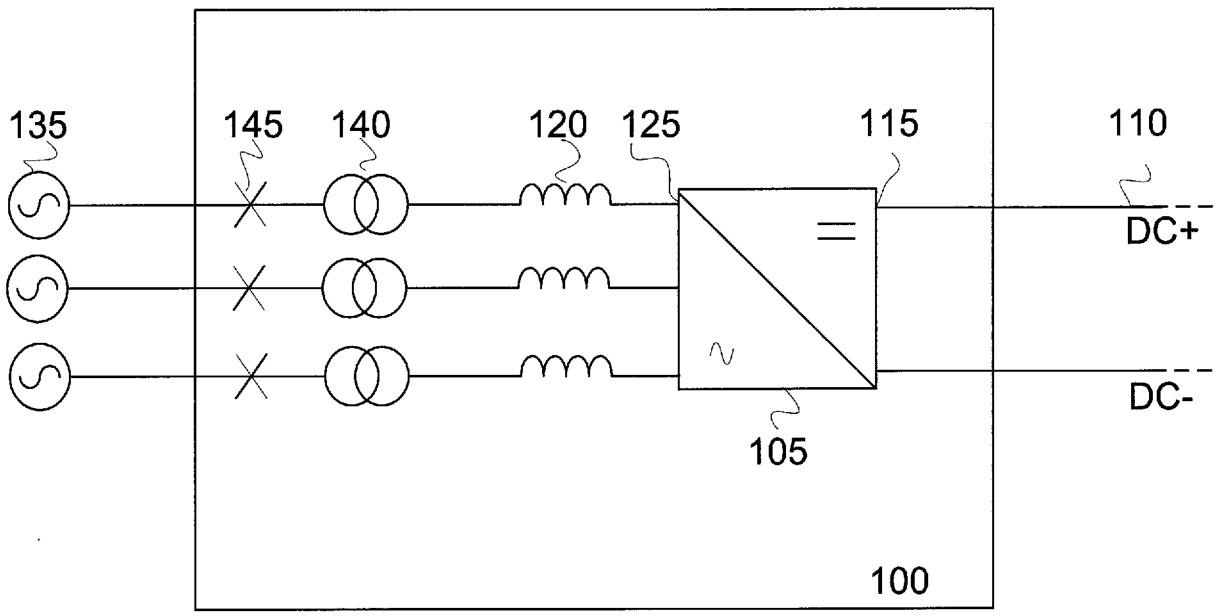


Fig. 3

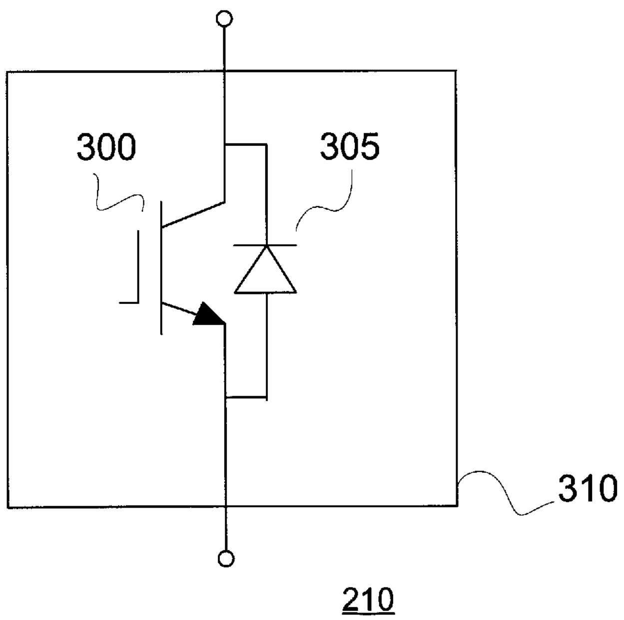


Fig. 2a

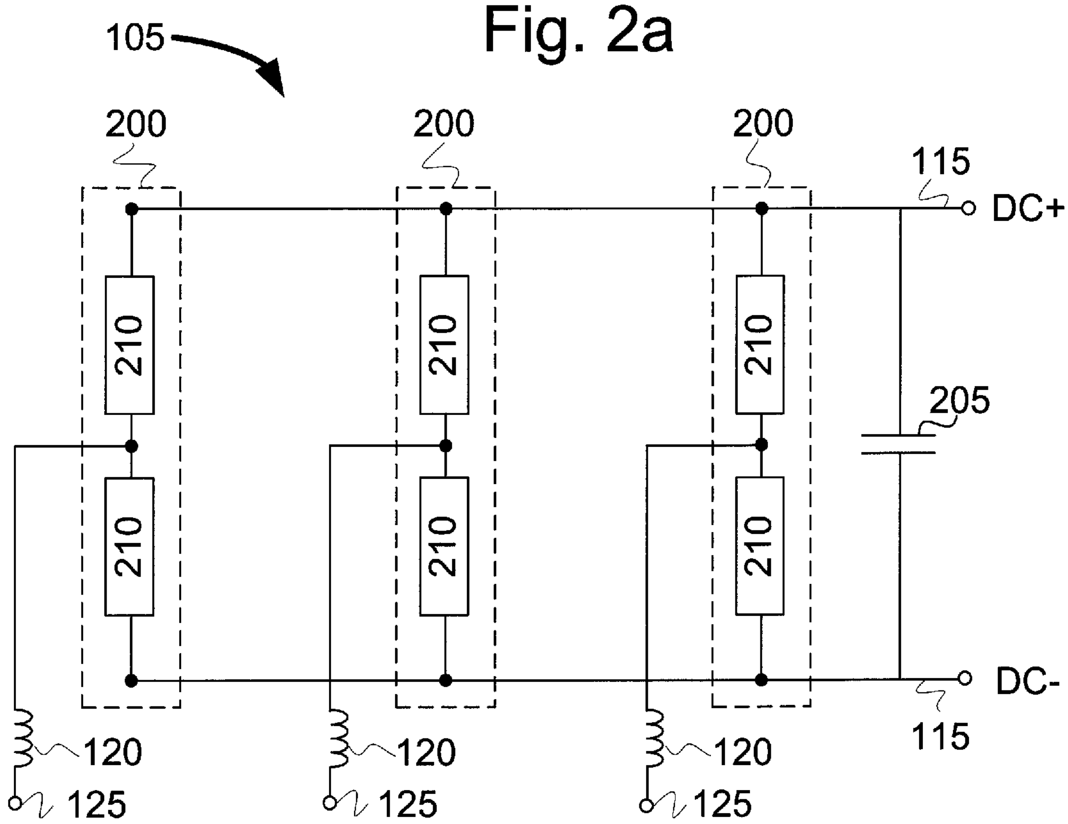

105
200
200
200
115
DC+
210
210
210
205
210
210
210
DC-
115
120
120
120
125
125
125

Fig. 2b

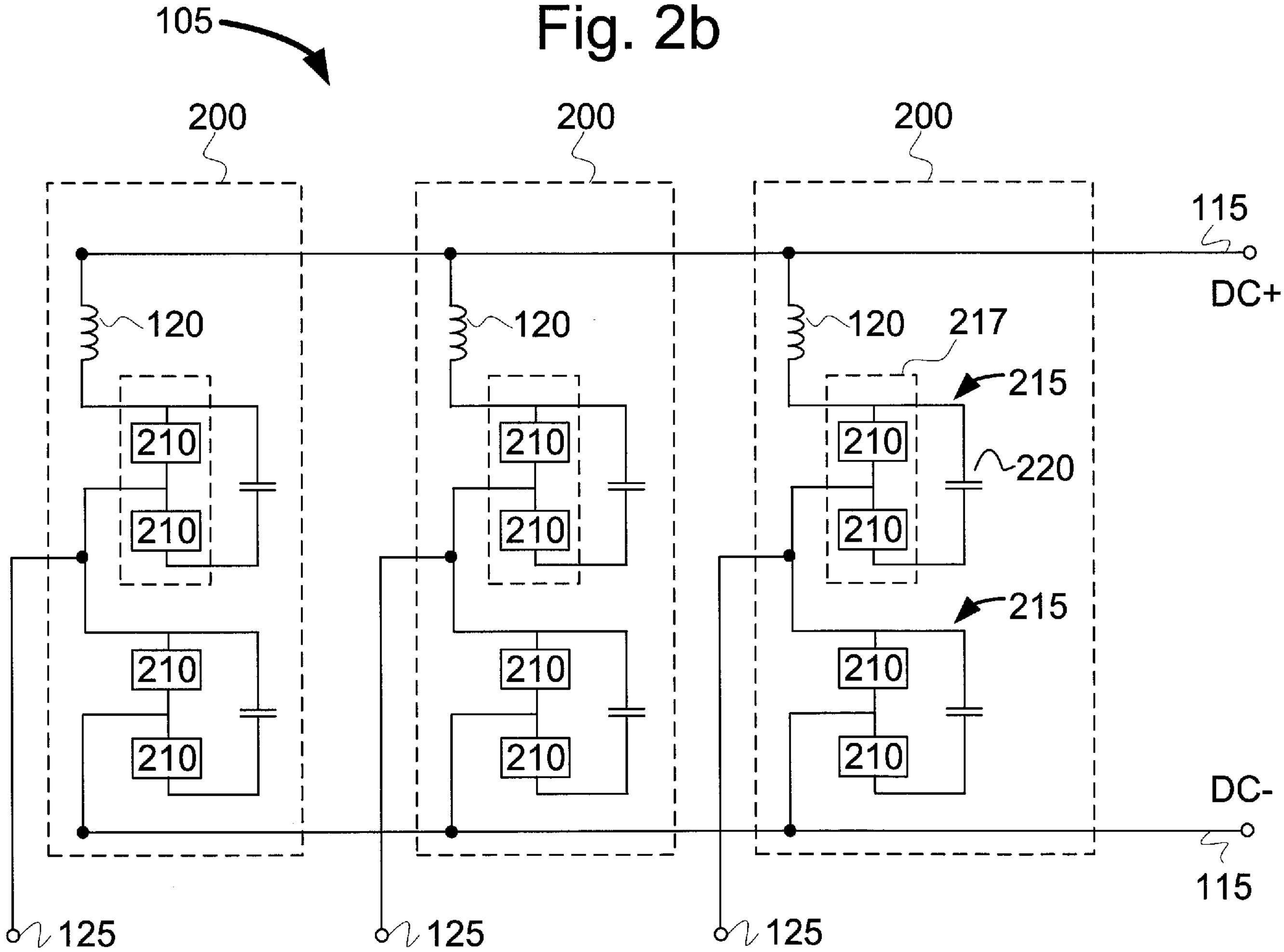

105
200
200
200
115
DC+
120
120
120
217
215
210
210
210
220
210
210
210
215
210
210
210
210
210
210
DC-
115
125
125
125

Fig. 4a

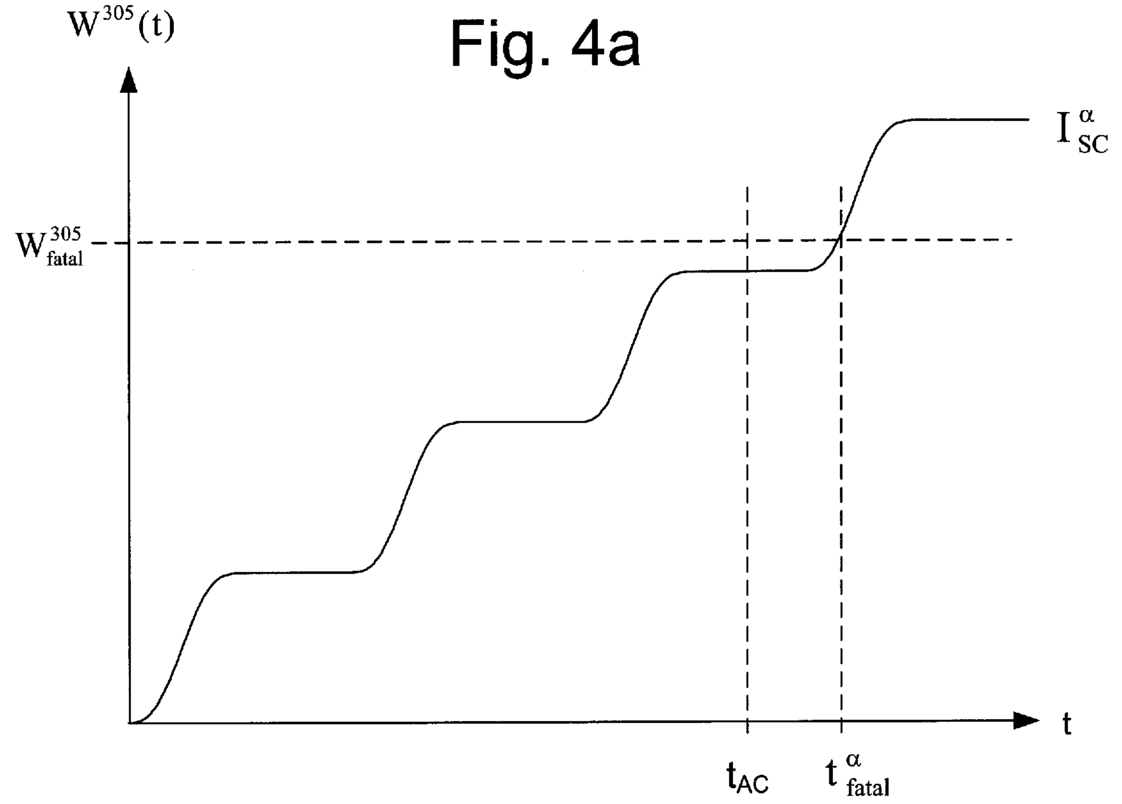

$W^{305}(t)$
I^{α}_{SC}
W^{305}_{fatal}
t
t_{AC}
t^{α}_{fatal}

Fig. 4b

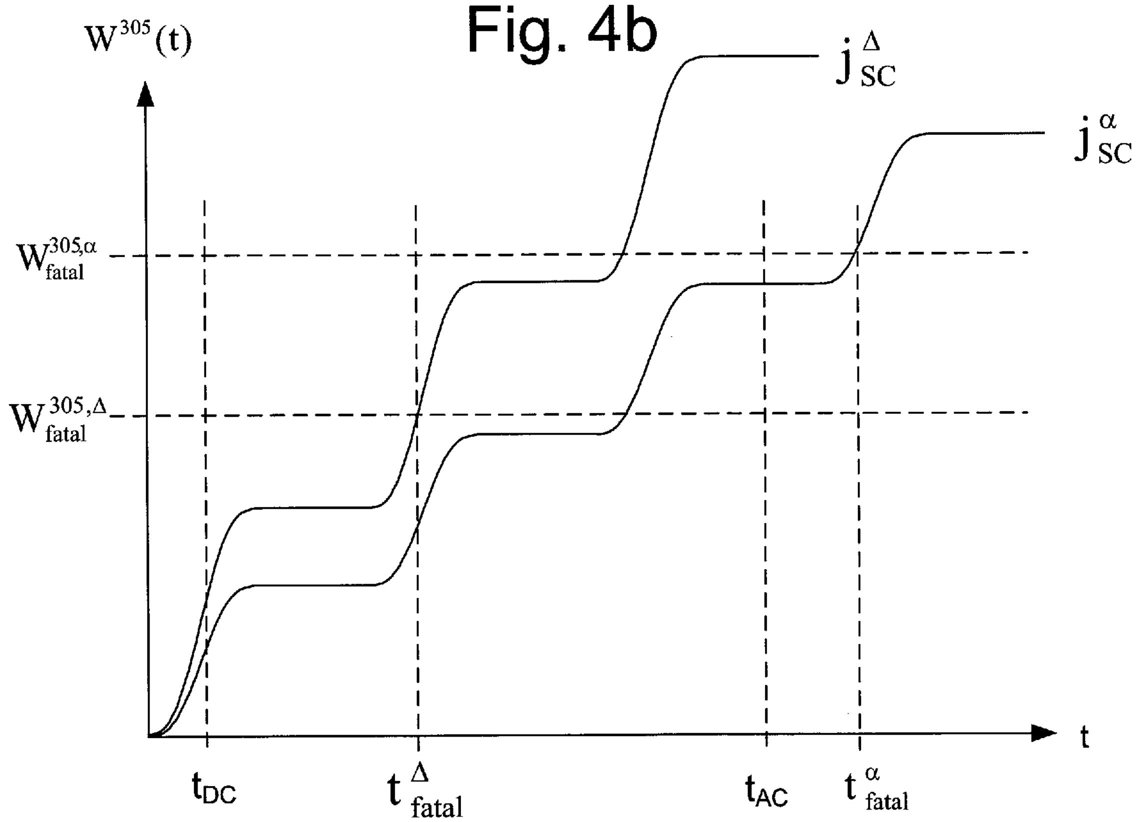

$W^{305}(t)$
j^{Δ}_{SC}
j^{α}_{SC}
$W^{305,\alpha}_{fatal}$
$W^{305,\Delta}_{fatal}$
t
t_{DC}
t^{Δ}_{fatal}
t_{AC}
t^{α}_{fatal}

Fig. 4c

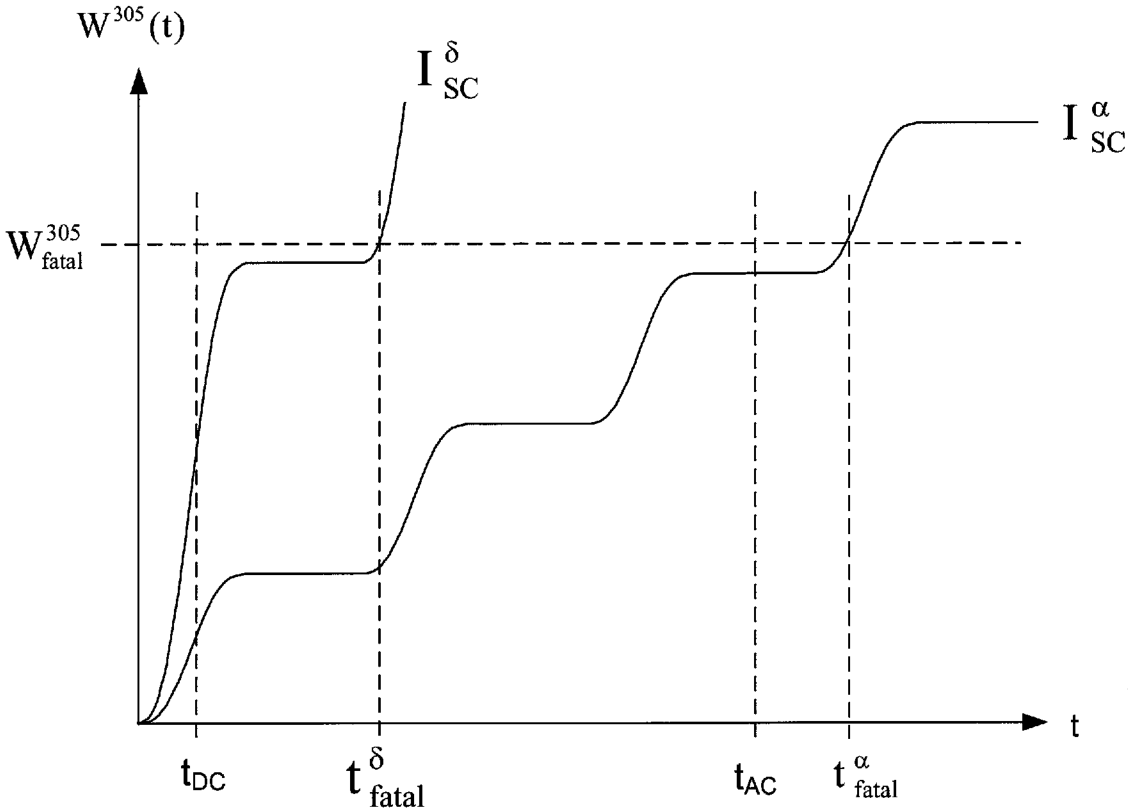
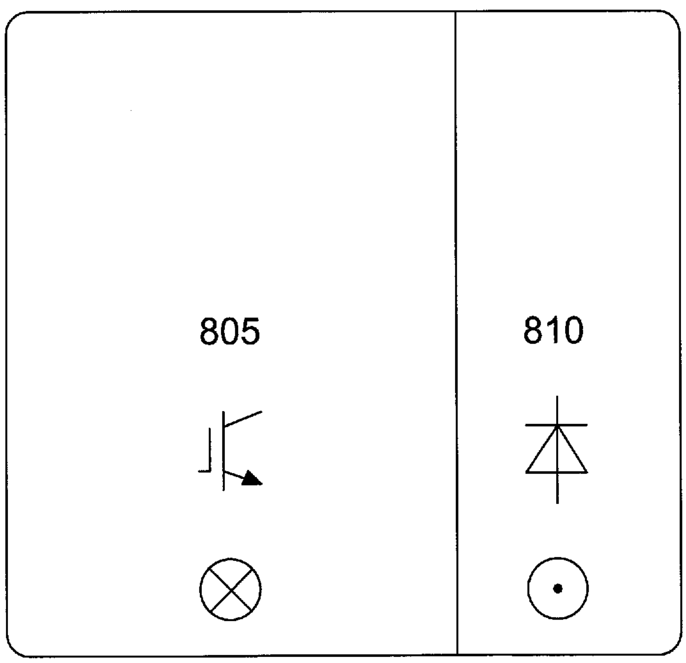


Fig. 8



800

Fig. 5

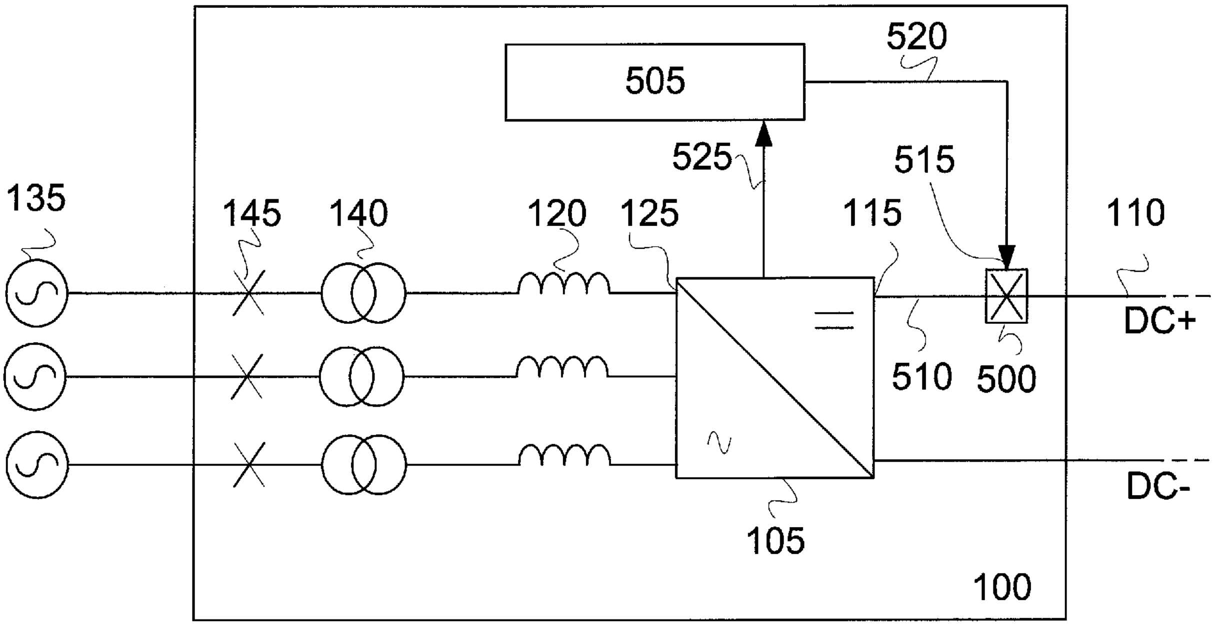

505
520
525
515
135
145
140
120
125
115
110
DC+
510
500
DC-
105
100

Fig. 6

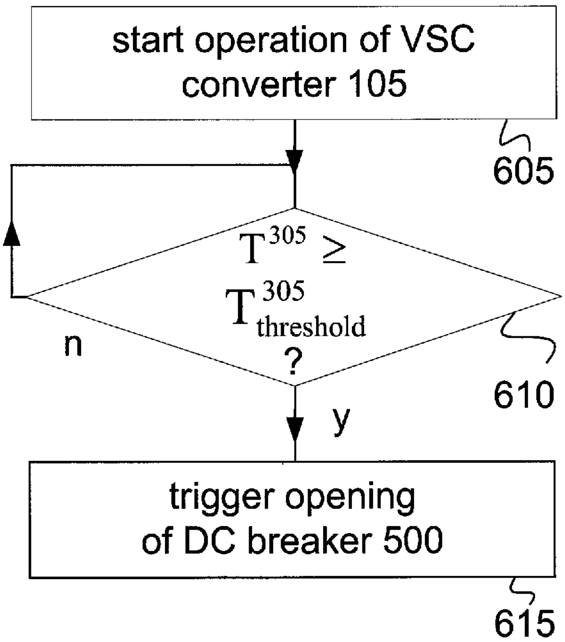

start operation of VSC converter 105
605
$T^{305} \geq T^{305}_{threshold}$?
n
610
y
trigger opening of DC breaker 500
615

Fig. 7a

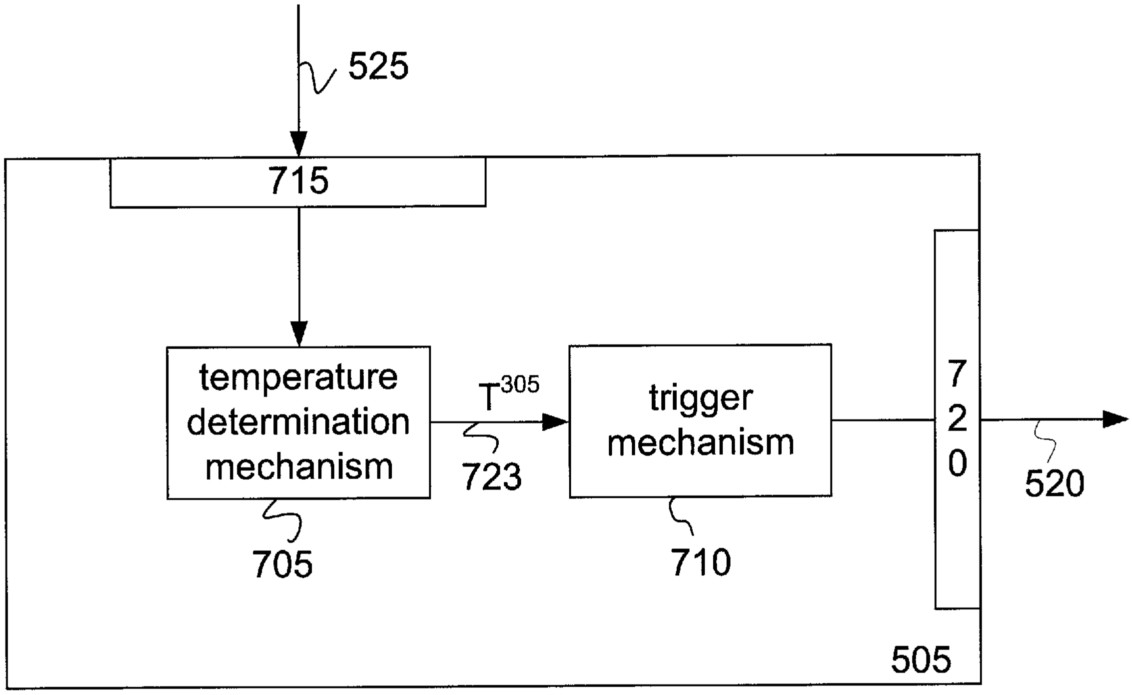

525
715
temperature
determination
mechanism
T^{305}
723
trigger
mechanism
7
2
0
520
705
710
505

Fig. 7c

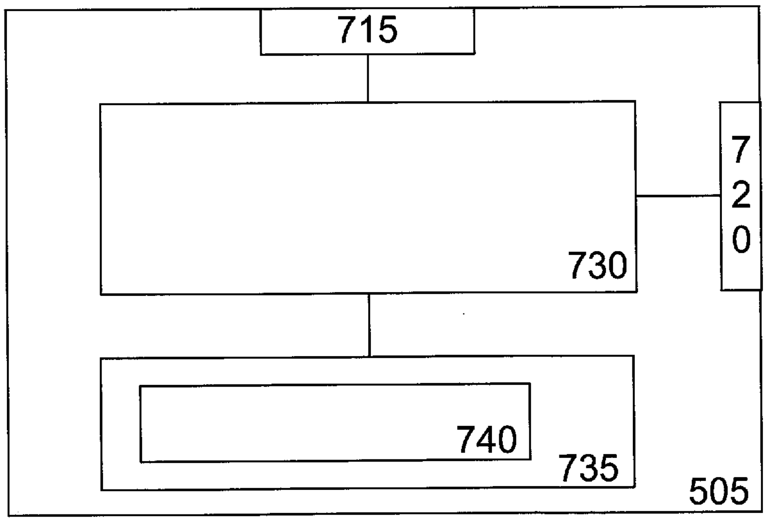
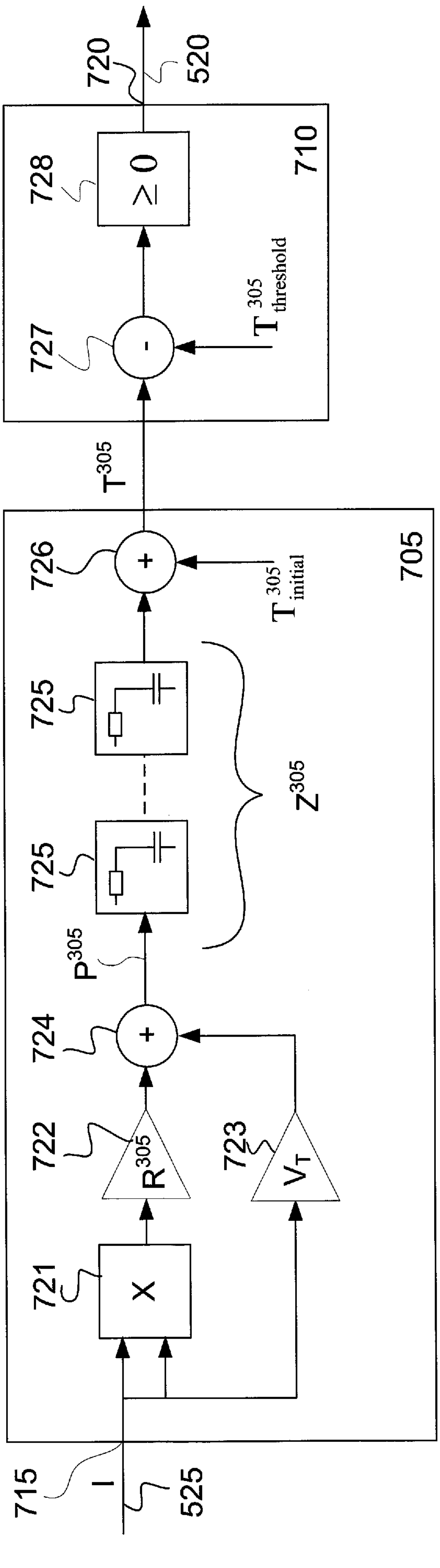

715
7
2
0
730
740
735
505

Fig. 7b


715
I
525
721
X
722
R^{305}
723
V_T
724
+
P^{305}
725
725
Z^{305}
726
+
$T^{305}_{initial}$
705
T^{305}
727
-
$T^{305}_{threshold}$
728
≥ 0
710
720
520

505

Fig. 9a

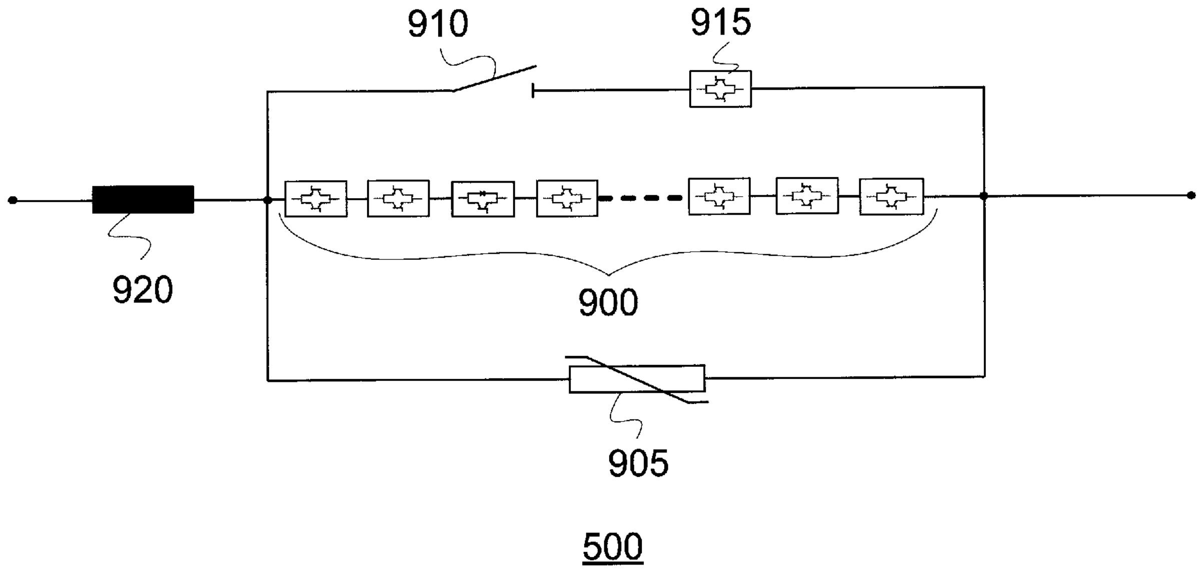

910
915
920
900
905
500

Fig. 9b

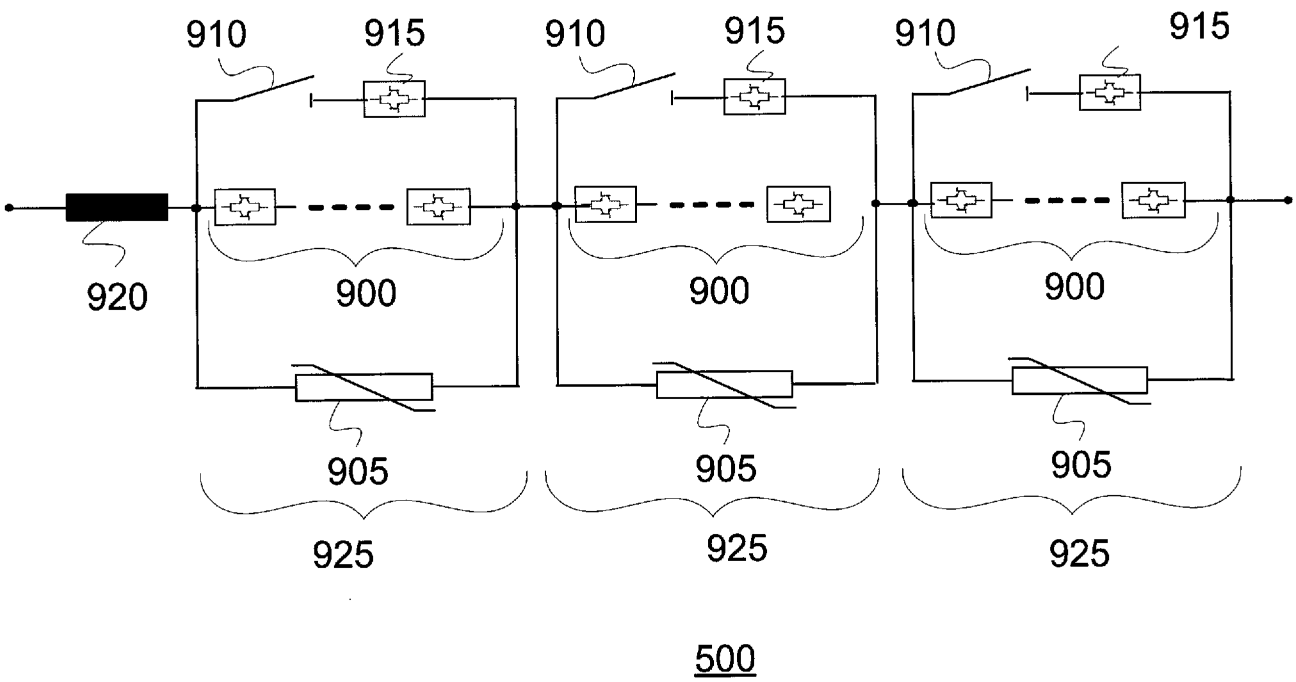

910
915
910
915
910
915
920
900
900
900
905
905
905
925
925
925
500

Fig. 10a

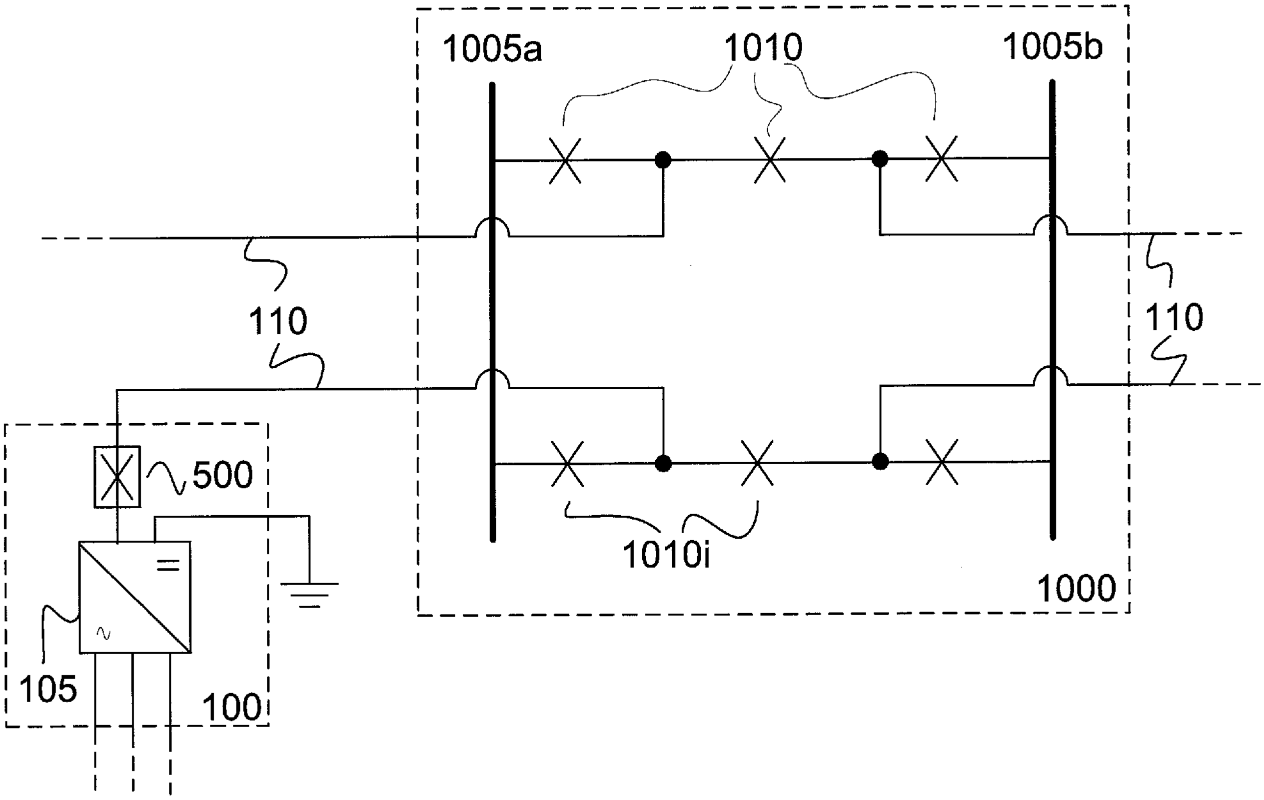
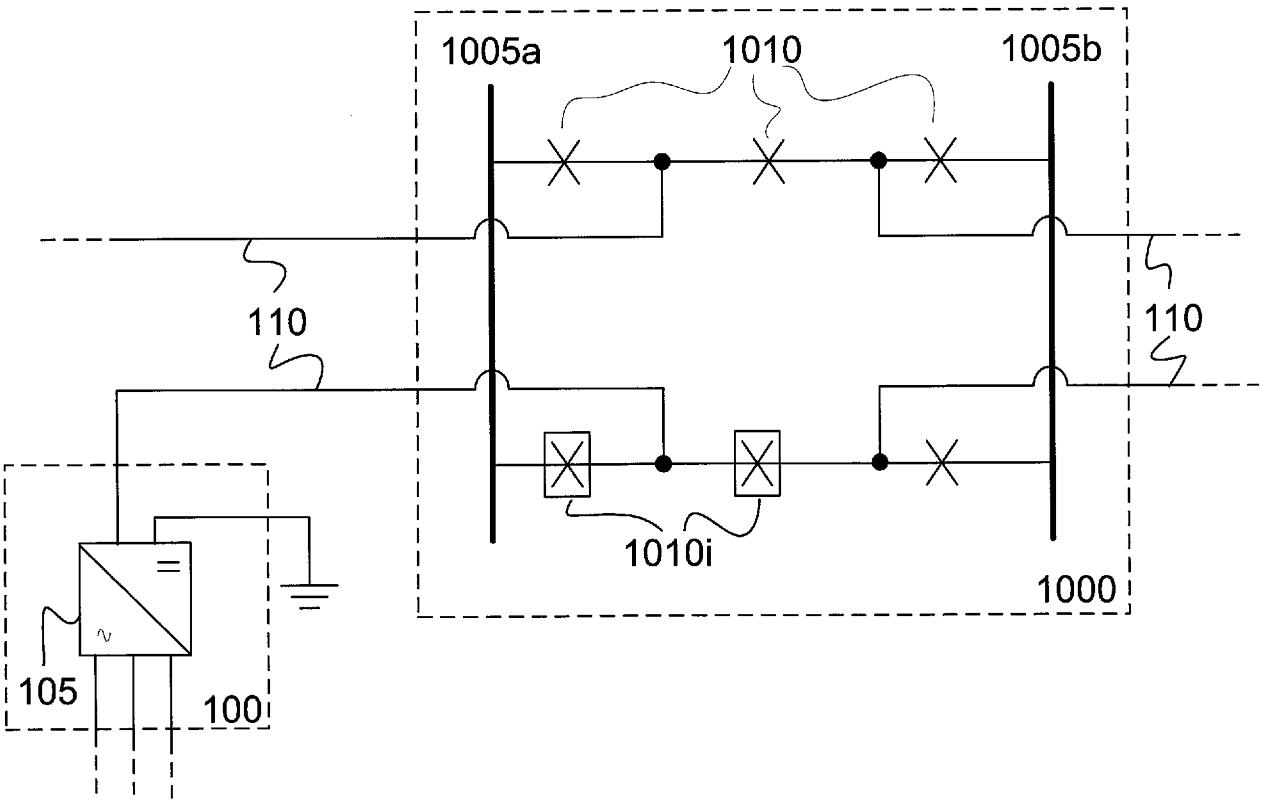


Fig. 10b



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP201Q/059272

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02H7/125
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02H H01H H02J H02M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal , INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2010/025758 AI (SIEMENS AG [DE] ; DOMMASCHK MIKE [DE] ; DORN JOERG [DE] ; EULER INGO [DE]) 11 March 2010 (2010-03-11) page 3, line 27 - line 29 page 4, line 22 - line 32 page 9, line 12 - page 12, line 7; figures 3-6 -----	1-19
Y	EP 1 583 197 A2 (VACON OYJ [FI]) 5 October 2005 (2005-10-05) paragraph [0006] - paragraph [0010] ; claims 1, 2 -----	1-19

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
8 March 2011	15/03/2011

Name and mailing address of the ISA/	Authorized officer
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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP201Q/059272

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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A	GB 2 315 172 A (SMITHS INDUSTRIES PLC [GB]) 21 January 1998 (1998-01-21) claims 1-3; figure 1 -----	1
A	DE 14 38 700 AI (SIEMENS AG) 10 April 1969 (1969-04-10) page 14, paragraph 2; figures 1-19 -----	1, 16

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP201Q/059272

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