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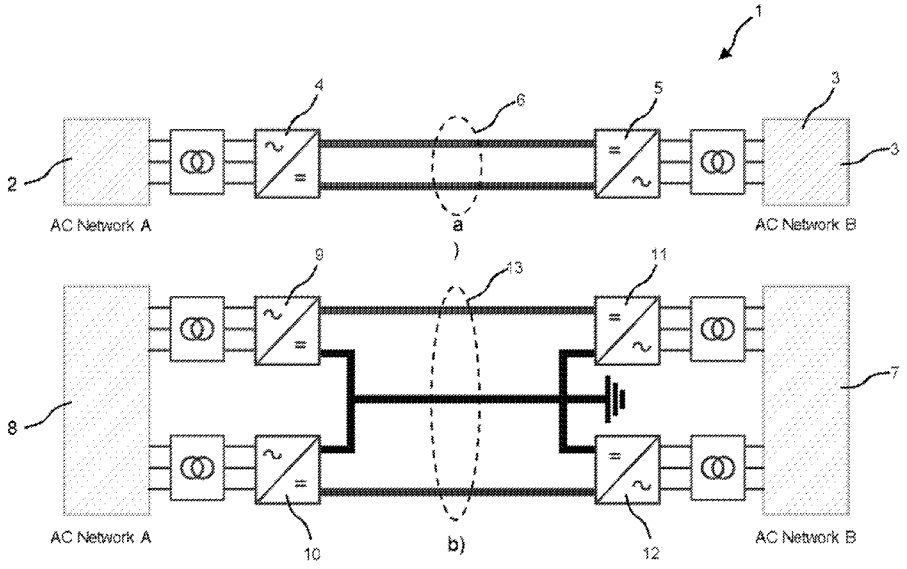


Fig. 1

(57) Abstract: A Voltage Source Converter, VSC, of a VSC-High Voltage Direct Current, HVDC, network, said VSC arranged to be connected to HVDC cables comprised by said HVDC network for transporting DC power, said VSC further being arranged for receiving said DC power and for converting said DC power to Alternating Current, AC, power in an AC network, a controller arranged for providing an active current reference based on a set-point of the active power reference and a measured active power transfer, said measured active power being an actual power flow between said VSC and said AC network and a non-linear modulation block arranged for non- linearly modulating said active current reference based on a measured DC voltage level at said HVDC cables.

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Title

A VOLTAGE SOURCE CONVERTER (VSC) OF A VSC-HIGH VOLTAGE DIRECT CURRENT (HVDC) NETWORK, AS WELL AS CORRESPONDING OPERATING METHOD

Technical field

The present disclosure is directed to the field of High Voltage Direct Current, HVDC, networks and, more specifically, to Voltage Source Converter(s) arranged from withdrawing DC power from a HVDC network.

Background

Voltage Source Converter, VSC, based High Voltage Direct Current, HVDC, technology has emerged as a significant advancement in the field of electric power transmission and distribution. Unlike traditional alternating current, AC, systems, VSC-HVDC provides a means of efficiently transmitting power over long distances using direct current, DC. This technology offers numerous advantages such as increased controllability, enhanced power quality, and improved grid integration of renewable energy sources.

In a VSC-HVDC system, the fundamental components include VSC converters at both ends of the transmission line, which are responsible for converting AC power to DC power and vice versa. These converters utilize power electronics devices, such as Insulated Gate Bipolar Transistors, IGBTs, to control the conversion process. The VSCs may enable bidirectional power flow, allowing efficient transmission of electricity from generation centres to load centres or interconnecting different AC networks.

HVDC networks, employing VSC technology, have gained popularity due to their ability to facilitate long-distance power transmission, interconnection of asynchronous grids, and integration of renewable energy sources. By employing HVDC links, power can be transmitted over thousands of kilometres with lower losses compared to conventional AC transmission systems. This makes HVDC networks

suitable for interconnecting offshore wind farms, remote generation sites, and international power exchanges.

One aspect of VSC-HVDC networks is related to post-fault active power recovery. During disturbances or faults in an AC or DC networks, the VSC-HVDC link may experience temporary disruptions or reduced power transmission. Post-fault active power recovery refers to the strategies and techniques employed to restore and resume normal power transmission after a fault has occurred and been cleared. These recovery methods include voltage and current control, control coordination between converters, and fault ride-through capabilities.

The development of effective post-fault active power recovery mechanisms is important for maintaining a reliable and resilient VSC-HVDC network, ensuring uninterrupted power flow and minimizing the impact of faults on the overall power system performance.

In summary, VSC-HVDC networks have impacted the field of power transmission and distribution, offering enhanced controllability and efficient long-distance power transmission. Post-fault active power recovery plays a role in ensuring the resilience and reliability of VSC-HVDC links, enabling them to recover and resume normal operation after disturbances or faults. With ongoing advancements in VSC and HVDC technologies, these networks continue to play a significant role in the modernization and development of power systems worldwide.

Summary

Following the above, it would be advantageous to achieve a Voltage Source Converter, VSC, that is able to provide an effective solution for a post-fault active power recovery.

In a first aspect of the present disclosure, there is provided a Voltage Source Converter, VSC, of a VSC-High Voltage Direct Current, HVDC, network, said VSC arranged to be connected to HVDC cables comprised by said HVDC network for transporting DC power, said VSC further being arranged for receiving said DC power and for converting said DC power to Alternating Current, AC, power in an AC network,

- a controller arranged for providing an active current reference based on a set-point of the active power reference and a measured active power, said

measured active power being an actual power flow between said VSC and said AC network ;

- a non-linear modulation block arranged for non-linearly modulating said active current reference based on a measured DC voltage level at said HVDC cables.

The present disclosure is directed to an non-linear function-based DC voltage control for regulating any post-fault active power recovery, PFAPR, process in a VSC-HVDC link. The above described control is effective to prevent a DC voltage collapse during the activation of the fault ride-through function.

The regulation of the active power during post-fault conditions at the AC network has been defined by transmission system operators, as one of the fundamental requirements that modern VSC-HVDC links must comply. Typically, this active power regulation process is referred as the post-fault active power recovery, PFAPR, function, and it is characterized by two main aspects.

The first aspect concerns with the time period in which the pre-fault active power level is expected to be restored and the second aspect concerns with the AC voltage level in which the active power is expected to be restored. This is explained in a bit more detail with respect to the figures.

It is noted that a VSC-HVDC link may be capable of operating under a point-to-point or a multi-terminal network configuration. The present disclosure is appliable to both configurations.

The present disclosure is directed to a situation wherein a three-phase fault event occurs at the AC network side of either the inverter or the rectifier unit of a Point-to-Point VSC-HVDC link. It is noted that the present disclosure does not exclude any other type of fault event. The presence of a fault at the AC network side may will affect the power balance at the corresponding VSC unit.

The voltage drop at the AC network, due to the fault even, may lead to the activation of a so-called FRT control function at the rectifier of the corresponding VSC unit.

FRT, i.e. Fault Ride-Through, control refers to the capability of the system to remain operational and ride through faults or disturbances in the AC networks without tripping or experiencing a complete shutdown. FRT fault control is a

feature in VSC-HVDC systems as it ensures the continuity of power transmission even during fault conditions.

When a fault occurs in the AC or DC networks, it can cause disturbances such as voltage dips or short circuits. In traditional AC systems, these disturbances may lead to protective measures that isolate the affected section from the network to prevent further damage. However, in VSC-HVDC systems with FRT fault control, the converters are designed to withstand and ride through such faults, maintaining continuous operation.

If the DC voltage regulation is blocked in the corresponding VSC unit, and the inverter of the other VSC unit connected to the HVDC network keeps subtracting power from the point-to-point network, the DC voltage level across the entire link will start to drop. Consequently, if the DC voltage level drops beyond its low limit value, i.e. a DC voltage collapse, then, the VSC-HVDC link will no longer be able to develop the PFAPR process in case the fault at the AC network is cleared.

It is further noted that the present disclosure is especially useful in situation where there is no communication interface between the difference VSC unit of the HVDC network.

Following the above, the present disclosure is directed to an active power adjustment strategy based on a non-linear active current modulation.

The non-linear active current modulation is thus implemented at the VSC unit, more specifically at the inverter unit of the VSC unit, and it may generate a dependency between the amount of DC power subtracted by the VSC unit and the voltage level at its DC terminals, i.e. at the HVDC cables. This is better explained with respect to the specific examples of the present disclosure.

In essence, the VSC unit may comprise a control unit for controlling the amount of power drawn from the DC link of the HVDC network. Such a controller may have two inputs. The first input is related to the set-point of the active power reference. That is the parameter to which the controller aims to control the withdrawn power. The second parameter is the measured active power, the measured active power thus being the current power flow between the VSC unit and the AC network.

The control unit may, for example comprise a PI controller or the like for controlling those two input. The output of the controller is an active current reference. Typically, the active current reference is used for controlling the rectifier unit of the

VSC. In accordance with the present disclosure, the active current reference is first non-linearly modulated based on a measured DC voltage level at the HVDC cables. This coupled the power drawn from the HVDC cables to the actual DC voltage level at the HVDC cables.

In an example, the non-linear modulation block is arranged for non-linearly modulating said active current reference based on a difference between said measured DC voltage level at said HVDC cables and a set steady-state DC voltage level , said set steady-state DC voltage level being associated to a lowest voltage level in which said VSC is expected to operate correctly.

The inventors have found that there might be a minimum required DC voltage level at the HVDC links to ensure that the system will function properly. The minimum required DC voltage level may be represented by a set steady-state DC voltage. The difference between the set steady-state DC voltage and the actual measured DC voltage at the HVDC cables may be considered a headroom voltage. The headroom voltage may refer to the available voltage margin or the difference between the actual voltage level and the minimum allowable voltage level in the system.

In a further example, the set steady-state DC voltage is between 94% - 100% of a nominal DC voltage at said HVDC cables.

In another example, the non-linear modulation block is arranged for non-linearly modulating said active current reference by multiplying said measured DC voltage level at said HVDC cables with a gain factor.

The gain factor may be anywhere between 500 – 3000. The gain factor may be determined by experimental results, or simulations.

In a further example, the non-linear modulation block is arranged for non-linearly modulating said active current reference by multiplying the active current reference with a modulation parameter, said modulation parameter being determined by:

$$1 - e^{-\alpha(DC_{meas} - LVT)}$$

wherein α is said gain factor, DCmeas is said measured active power and LVT is said set steady-state DC voltage level.

In yet another example, the non-linear modulation block further comprises a limiter for limiting said measured DC voltage at said HVDC cables,

wherein said limited measured DC voltage is used for non-linearly modulating said active current reference.

It is noted that if the difference between the measured DC voltage and the LVT becomes negative, the difference between the two may also become negative. The change in the sign of the compensation, i.e. modulation, may induce an active power reversal event at the VSC that may help to boost the DC voltage during the blocking period of faulting VSC unit.

Thus, the difference between the measured DC voltage and the LVT may need to be controlled by limiting the measured DC voltage level that can be used. This limitation is accomplished by introducing a limiter. The calibration of the low limit value of the limiter block may depend on the desired level of active power reversal during the blocking period of the faulty VSC unit.

In a second aspect of the present disclosure, there is provided a method of operating a Voltage Source Converter, VSC, in accordance with any of the previous claims, wherein said method comprises the steps of:

- providing, by said controller, said active current reference based on a set-point of the active power reference and a measured active power, said measured active power being an actual power flow between said VSC and said AC network;
- non-linearly modulating, by said non-linear modulation block, said active current reference based on a measured DC voltage level at said HVDC cables.

It is noted that the advantages as explained with respect to the first aspect of the present disclosure, being the Voltage Source Converter, VSC, are also applicable to the second aspect of the present disclosure, being the method of operating such a VSC.

In an example, the step of non-linearly modulating further comprises:

- non-linearly modulating said active current reference based on a difference between said measured DC voltage level at said HVDC cables and a set steady-state DC voltage level, said set steady-state DC voltage level being associated to a lowest voltage level in which said VSC is expected to operate correctly.

In a further example, the set steady-state DC voltage is between 94% - 100% of a nominal DC voltage at said HVDC cables.

In yet another example, the step of non-linearly modulating further comprises:

- non-linearly modulating said active current reference by multiplying said measured DC voltage level at said HVDC cables with a gain factor.

In a further example, the step of non-linearly modulating further comprises:

- non-linearly modulating said active current reference by multiplying the active current reference with a modulation parameter, said modulation parameter being determined by:

$$1 - e^{-\alpha(DC_{meas} - LVT)}$$

wherein α is said gain factor, DCmeas is said measured active power and LVT is said set steady-state DC voltage level.

In an example the gain factor is between 500 – 3000.

In yet another example, the non-linear modulation block further comprises a limiter for limiting said measured DC voltage at said HVDC cables, wherein the method further comprises the step of:

- limiting, by said limiter, said measured DC voltage at said HVDC cables,

wherein said step of non-linearly modulating uses said limited measured DC voltage for modulating said active current reference.

In a third aspect of the present disclosure, there is provided a High Voltage Direct Current, HVDC, network comprising a plurality of Voltage Source Converters, VSCs, in accordance with any of the examples provided above, and comprising HVDC cables connecting those VSCs to one another.

In a fourth aspect, there if provided a computer program product comprising a computer readable medium having instructions stored thereon which, when executed by a Voltage Source Converter, VSC, cause said VSC to implement a method in accordance with any of the examples as provided above.

The present disclosure is described in conjunction with the appended figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

In the appended figures, similar components and/or features may have the same reference label. Further, various components of the same type may be distinguished by following the reference label by a dash and a second label that distinguishes among the similar components. If only the first reference label is used in the specification, the description is applicable to any one of the similar components having the same first reference label irrespective of the second reference label.

The above and other aspects of the disclosure will be apparent from and elucidated with reference to the examples described hereinafter.

Brief description of the drawings

Fig. 1 discloses examples of HVDC links based on VSC units;

Fig. 2 discloses a general description of an modular Multi-level Converter unit;

Fig. 3 discloses a general description of the control layers of an VSC/MMC unit;

Fig. 4 discloses a generation structure of an inner control block as shown in figure 3;

Fig. 5 disclose basic examples of control modes conforming the outer control block;

Fig. 6 discloses voltage response of a VSC unit in relation to a fault condition;

Fig. 7 discloses an example of an expandable VSC HVDC link interconnecting one Offshore AC network with an Onshore AC network;

Fig. 8 discloses an expandable VSC HVDC link experiencing a three phase fault at the Onshore AC network;

Fig. 9 discloses a graphical description of the VSC unit in accordance with the present disclosure.

Detailed description

It is noted that in the description of the figures, same reference numerals refer to the same or similar components performing a same or essentially similar function.

A more detailed description is made with reference to particular examples, some of which are illustrated in the appended drawings, such that the manner in which the features of the present disclosure may be understood in more detail. It is noted that the drawings only illustrate typical examples and are therefore not to be considered to limit the scope of the subject matter of the claims. The drawings are incorporated for facilitating an understanding of the disclosure and are thus not necessarily drawn to scale. Advantages of the subject matter as claimed will become apparent to those skilled in the art upon reading the description in conjunction with the accompanying drawings.

The ensuing description above provides preferred exemplary embodiment(s) only, and is not intended to limit the scope, applicability or configuration of the disclosure. Rather, the ensuing description of the preferred exemplary embodiment(s) will provide those skilled in the art with an enabling description for implementing a preferred exemplary embodiment of the disclosure, it being understood that various changes may be made in the function and arrangement of elements, including combinations of features from different embodiments, without departing from the scope of the disclosure.

Unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise," "comprising," and the like are to be construed in an inclusive sense, as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to." As used herein, the terms "connected," "coupled," or any variant thereof means any connection or coupling, either direct or indirect, between two or more elements; the coupling or connection between the elements can be physical, logical, electromagnetic, or a combination thereof. Additionally, the words "herein," "above," "below," and words of similar import, when used in this application, refer to this application as a whole and not to any particular portions of this application. Where the context permits, words in the Detailed Description using the singular or plural number may also include the plural or singular number respectively. The word "or," in reference to a list of two or more items, covers

all of the following interpretations of the word: any of the items in the list, all of the items in the list, and any combination of the items in the list.

These and other changes can be made to the technology in light of the following detailed description. While the description describes certain examples of the technology, and describes the best mode contemplated, no matter how detailed the description appears, the technology can be practiced in many ways. Details of the system may vary considerably in its specific implementation, while still being encompassed by the technology disclosed herein. As noted above, particular terminology used when describing certain features or aspects of the technology should not be taken to imply that the terminology is being redefined herein to be restricted to any specific characteristics, features, or aspects of the technology with which that terminology is associated. In general, the terms used in the following claims should not be construed to limit the technology to the specific examples disclosed in the specification, unless the Detailed Description section explicitly defines such terms. Accordingly, the actual scope of the technology encompasses not only the disclosed examples, but also all equivalent ways of practicing or implementing the technology under the claims.

Fig. 1 discloses examples of HVDC links based on VSC units.

A High Voltage DC link based on Voltage Source Converter technology, i.e. a VSC-HVDC link, may be considered an electrical system in which and AC/DC and DC/AC energy conversion process is developed. Moreover, the VSC-HVDC link is comprised by DC cables, transformers, and VSC units which are utilized for interconnecting synchronous or asynchronous transmission networks. Furthermore, a VSC-HVDC link can be classified from an AC side point of view, as a non-embedded, i.e. AC networks synchronously decoupled, or as an embedded, i.e. AC networks synchronously coupled, interconnector.

On the other hand, from a DC side point of view, VSC-HVDC links 1 can be classified as a point-to-point, PtP, or a multi-terminal, MT, DC network. These two types of DC side classifications can be further extended based on the possible configurations existing for VSC-HVDC links as for example.

A PtP DC network is shown in figure 1, the top side. The AC network A is indicated with reference numeral 2. The AC network B is indicated with reference

numeral 3. Two VSCs are deployed, as indicated with reference numerals 4 and 5. The VSCs are connected to one another via HVDC cables 6.

An MT DC network is shown in figure 1, bottom side. The AC network is indicated with reference numeral 8. The AC network B is indicated with reference numeral 7. Four VSCs are deployed, as indicated with reference numerals 9, 10, 11 and 12. The VSCs are connected to one another via HVDC cables 13.

Independently of the classification utilized, the DC/AC or AC/DC energy conversion process in a HVDC link is basically carried out by the VSC units which have the role of generating the necessary DC and AC voltage waveforms in the corresponding DC or AC networks.

The generation of these DC and AC voltage waveforms in a VSC unit may be established by means of several control systems which are designed to regulate the power flow between the electrical networks, i.e. coupled by the HVDC link using cables, during energization, normal, and fault conditions.

The design and the adjustment of such control systems may be influenced by the electrical properties of the HVDC link and by the AC network characteristics of the coupled power systems. These characteristics and properties may usually be represented in a phasor's based or a differential-equations' based simulation environment, for example a phasor, also known as root-mean square -RMS- simplified representation of a detailed differential-algebraic equation based representation, or an instantaneous Waveform, also known as electromagnetic transient -EMT- representation of a detailed differential-algebraic equation based representation. Thus, the analysis of the energy conversion process may require the implementation of EMT or RMS models capable of expressing the interplay between the AC and DC networks, from a dynamic response and a steady-state operational point of view.

The implementation of an EMT or RMS model of a VSC-HVDC link may represent the process of describing the mathematical relationships that govern the dynamic response of the currents and voltages defining the power transfer between the AC and DC networks.

Fig. 2 discloses a general description of an modular Multi-level Converter unit.

The basic elements that may constitute a VSC are mainly based on Modular Multi-level Converter, MMC technology.

As seen in figure 2, a VSC unit based on MMC technology 101 may be formed by several reactors, for example six reactors, $LMMC,$ and several structures, for example six structures, called valves which may be comprised of tens or hundreds of sub-modules 102. Within each of these sub-modules, an arrangement of semiconductors, typically IGBTs, may be managed in order to control the moment in which the sub-module's capacitor C is excluded or inserted into the corresponding, internal, current loop, i.e. iup or $ilow$.

It may be pointed out that the iup or $ilow$ currents are comprised by DC and AC components which simultaneously flow within the VSC/MMC unit, i.e. DC and AC currents simultaneously flow through the inserted capacitors within the valves.

In essence, the insertions or the exclusions of the capacitors within a single valve may be a consequence of two regulation processes. The first, i.e. outer, regulation process may define the number of capacitors that may need to be inserted in order to produce the desired voltage waveform across the corresponding valve, e.g. v (+) $valvex$. The first regulation process may be developed by considering that the second, i.e. inner, regulation process, referred to as capacitor voltage balancing is properly executed.

The second, i.e. inner, regulation process may determine and define which of the capacitors are to be inserted/excluded in order to maintain the same voltage level across all the capacitors within the same valve, at all times.

The successful development of the capacitor voltage balancing, i.e. the second regulation process, allows managing the VSC/MMC unit as a power electronic device where a series of identical time-variant voltage sources, located within each valve, are inserted between the DC an AC networks.

Fig. 3 discloses a general description 201 of the control layers of an VSC/MMC unit.

The control system's modelling of a MMC unit can be divided in two main sections, i.e. control layers, which are presented in Figure 3. Each of these two sections, i.e. upper 202 and the lower-level control layers 203, may be formed by several control blocks having specific regulation targets.

For instance, the lower-level control layer 203 may generate the IGBT switching pulses for directly inserting/excluding the submodules' 206 capacitors based on the capacitor voltage balancing described above.

Furthermore, the upper-level control layer 202 may be divided in two parts, the non-island control block 204, and the island control block 205. The island control block 205 is typically utilized when an HVDC converter should self-generate the three-phase AC voltage waveform serving as the voltage reference for those networks mainly consisting of power electronic interfaced generation units, for example an offshore wind farm.

On the other hand, the non-island control block 204 may be used in those HVDC converters which are connected to power systems where, the three-phase AC voltage waveform, for example voltage reference, is already established. Thus, in the non-island control block 204, a current-based power control method may be utilized by the VSC/MMC unit, considering several mathematical formulations which give a geometrical perspective to the energy conversion process.

Fig. 4 discloses a generation structure 301 of an inner control block as shown in figure 3.

The structure of the such an inner control block may be based on PI regulators which are calibrated to define the currents' time responses, for iD and iQ, considering a short millisecond time-frame, for example around 20ms.

The calibration of the PI regulators of the current controllers is referred to the adjustment of their control gains, i.e. KPD , TID , KPQ , and TIQ. This is not further elucidated in detail in this particular disclosure.

Fig. 5 disclose basic examples 401 of control modes conforming the outer control block.

The current controllers for iD and iQ belong to the Inner Control block which receives the corresponding current references values, that is $i * gDOuter$ and $i * gQOuter$, from the Outer Control block presented in Figure 4. As shown in Figure 5, the Outer Control block may be composed, in a VSC unit operating within a PtP-HVDC link, by four control modes which are responsible of managing the AC voltage level, i.e. $UACCtrl$, the DC voltage level, i.e. $VdcCtrl$, the reactive power level, i.e. $QCtrl$, and the active power level, i.e. $PCtrl$, provided by the converter, i.e. VSC unit.

Similarly to Inner Control block as described above, the control modes within the Outer Control block may utilize dedicated PI regulators which are meant to establish the dynamic responses of the corresponding variables, e.g. ug, Vdc, q, or p, based on AC network requirements and the physical characteristics of the DC network.

Fig. 6 discloses voltage response of a VSC unit in relation to a fault condition.

Figure 6 shows two different responses, indicated by the reference numerals 601 and 602, respectively, concerning with the active power evolution of the VSC-HVDC unit before, during and after an AC fault occurs.

As an example, a VSC-HVDC unit transmits 300MW during steady-state operation, i.e., $\Delta t0$, as shown in Figure 6. Next, a three-phase fault to ground event occurs at its AC terminals, and the resulting, RMS, AC voltage drop is observed during the $\Delta t1$ period.

Note that five different time periods are shown in Figure 6: i) the time period $\Delta t0$ where the pre-fault conditions are presented, ii) the time period $\Delta t1$ associated with the fault duration, iii) the time period $\Delta t2$ in which 90% of the pre-fault AC voltage level is achieved, iv) the time period $\Delta t3$ in which at least 90% of the pre fault active power level is restored, and v) the time period $\Delta t4$ in which the active power should be restored. Note also in Figure 6 that the active power response indicated by reference numeral 601 is not properly restored within the time period associated with $\Delta t3$. By contrast, the active power response indicated by reference numeral 602 is restored within the time period defined by $\Delta t3$.

Fig. 7 discloses an example of an expandable VSC HVDC link interconnecting one Offshore AC network with an Onshore AC network.

The analysis of the PFAPR process may start by defining the power flow characteristics concerning the studied point-to-point VSC-HVDC link. A point-to-point VSC-HVDC link can be used to transmit active power between two AC networks. In an onshore-to-onshore, point-to-point VSC-HVDC link, the active power can be transmitted from Onshore Network A towards Onshore Network B, or vice versa.

On the other hand, a point-to-point VSC-HVDC link can also be utilized to transmit active power between an Offshore AC Network and an Onshore AC Network as shown in figure 7. Unlike the onshore-to-onshore case, the offshore-to-

onshore, point-to-point VSC-HVDC link, the active power may be transmitted, during steady-state operation, from Offshore Network towards the Onshore Network A.

If the active power can only be transmitted in one direction, and there is an event that blocks the capabilities of VSC A unit for transferring active power towards the Onshore Network A, the HVDC link will experience a DC voltage rise.

The DC voltage rise will occur since the Offshore Network supplies power into the point-to-point HVDC link during the blocking event increasing in that way the electrostatic energy of the HVDC cables. Consequently, a DC Chopper is typically included in this type of offshore-to-onshore, point-to-point VSC-HVDC links.

The DC Chopper is designed to temporarily dissipate the power supplied by the Offshore Network, while VSC A attempts to restore its AC/DC power balance. The dissipation of the power is carried out by regulating the insertion and extraction of a resistor within the HVDC network, without violating its thermal limits. The potential use of the power dissipation capabilities of the DC Chopper during the multi-terminal expansion of a point-to-point VSC-HVDC links.

Fig. 8 discloses an expandable VSC HVDC link experiencing a three phase fault at the Onshore AC network.

The PFAPR process is explained by considering a three-phase fault event occurring at AC network side of either the inverter or the rectifier unit of an (Onshore-to-Onshore) Point-to-Point VSC-HVDC link. In this regard, Figure 7 shows a point-to-point VSC-HVDC link in which the DC power is transmitted from the rectifier unit VSC A, towards the inverter unit VSC B. Next, Figure 7 also indicates that the presence of a fault at $VPCCA$ bus which will affect the power balance at VSC A unit.

The voltage drop at the AC network A, i.e. fault at $VPCCA$ bus, may lead to the activation of the FRT control function at the rectifier VSC A unit. This activation will modify the priority level given to the active and the reactive currents of VSC A, jeopardizing in that way regulation process of the DC voltage during the fault event at AC network A.

At this point, it can be inferred from Figure 7 that if the DC voltage regulation is blocked in VSC A unit, and the inverter VSC B unit keeps subtracting power from the point-to-point network, the DC voltage level across the entire link will start to drop. Consequently, if the DC voltage level drops beyond its low limit value

(i.e. a DC voltage collapse), then, the VSC-HVDC link will no longer be able to develop the PFAPR process in case the fault at the AC network A is cleared.

Typically, in this type of fault conditions, a communication interface detects the blocking condition of VSC A and then, a reduction of the active power level demanded by VSC B is developed to avoid the DC voltage collapse across the link.

If the communication interface is not available during the blocking of VSC A, then a sophisticated active power reduction strategy may be designed. The present disclosure is directed to an active power reduction strategy proposed in this dissertation is based on a simple non-linear active current modulation.

The non-linear active current modulation may be implemented at the inverter unit shown in Figure 7, and it essentially generates a dependency between the amount of DC power subtracted by VSC B, and the voltage level at its DC terminals.

There is a non-linear modulation provided by the following equation:

$$i^*_{gD} = \lambda_{MOD} \cdot i^*_{gDP}$$

The term λ_{MOD} may be provided by the following equation:

$$\lambda_{MOD} = 1 - e^{-\alpha(DC_{meas} - LVT)}$$

The signal i^*_{gD} represents the input to the Inner Control block which is generated through the non-linear modulation of the active current reference, i.e. i^*_{gDP}, generated by the active power controller, i.e. $PCtrl$, of VSC B. The non-linear modulation is developed through the term λ_{MOD}, and a visual representation of its influence over the control systems of VSC B is provided in Figure 9.

The above provided expressions show that the term λ_{MOD} comprises an exponential function which depends on the DC voltage level measured, DC_{meas}, at the DC terminals of VSC B, a constant low voltage threshold, LVT,, and the gain α.

The parameter LVT may represent the constant value defining the minimum steady-state DC voltage level in which a converter unit is expected to operate without saturating its modulation index.

For example, an LVT = 0.97pu is referred to a VSC-HVDC unit capable of operating 3% below its nominal DC voltage value, during steady-state conditions.

The difference between the DC_{meas} and the LVT constant may be amplified by the term $alpha$. This amplification term is used to control the rate of

change of the term λ_{MOD}, when the DC voltage level at the DC terminals of VSC B, i.e., DC_{meas}, gets close to the LVT constant value.

It is noted that if the difference between the $DCmeas$ and the LVT becomes negative, the λ_{MOD} term will also become negative. The change in the λ_{MOD} term sign may induce an active power reversal event at VSC B that will help to boost the DC voltage during the blocking period of VSC A unit. Thus, the difference between the DC_{meas} and the LVT may need to be controlled by limiting the DC_{meas} level that can be used by the above provided expression.

This limitation is developed by introducing a limited, as shown in Figure 9. The calibration of the low limit value of the limiter block will depend on the desired level of active power reversal during the blocking period of the rectifier VSC A unit. For example, if during the blocking period of VSC A, the maximum level of active power reversal is setup to 50%, then, a low limit value of 0.9698pu can be used, when the LVT is equal to 0.97pu, and the α gain is equal to 2000.

Fig. 9 discloses a graphical description of the VSC unit in accordance with the present disclosure.

The fast active power reduction during a critical DC voltage drop is a desirable characteristic for supporting the DC voltage profile of the HVDC link shown in Figure 8. Nevertheless, the consequences of using higher α values, e.g. above 3000, in a real power electronic converter application would require the use of real-time processors able to compute the non-linear function λ_{MOD} in a time frame smaller than 1 ms.

Besides, the use of lower α values, e.g. below 500, may not be recommended since its decrement can affect the performance of the VSC-HVDC network during its steady-state operation.

It is further noted that the development of the non-linear DC voltage support method, i.e. provided by VSC B, may be a first step to enable the PFAPR process by the VSC A unit. Consequently, once the electrical fault has been cleared, and the AC voltage at $VPCCA$ level starts to recover, there may be a change in the prioritization of the active and reactive current at the rectifier station VSC A. Consequently, the VSC A unit may start to progressively restore the DC voltage level across the HVDC link increasing the $DCmeas$ value. Thus, it is ensured that the non-linear DC voltage support provided by the VSC B unit will not interfere with the DC

voltage boosting process developed by the VSC A unit. Instead, it may progressively restore the demand of active power according to the DC voltage profile evolution based on the equation provided above.

To reduce the number of claims, certain aspects of the technology are presented below in certain claim forms, but the applicant contemplates the various aspects of the technology in any number of claim forms. For example, while some aspect of the technology may be recited as a computer-readable medium claim, other aspects may likewise be embodied as a computer-readable medium claim, or in other forms, such as being embodied in a means-plus-function claim.

In the description above, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of implementations of the disclosed technology. It will be apparent, however, to one skilled in the art that embodiments of the disclosed technology may be practiced without some of these specific details.

Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure and the appended claims. In the claims, the word “comprising” does not exclude other elements or steps, and the indefinite article “a” or “an” does not exclude a plurality. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage. Any reference signs in the claims should not be construed as limiting the scope thereof

CLAIMS

1. A Voltage Source Converter, VSC, of a VSC-High Voltage Direct Current, HVDC, network, said VSC configured to be connected to HVDC cables comprised by said HVDC network for transporting DC power, said VSC further being configured to receive said DC power and for converting said DC power to Alternating Current, AC, power in an AC network,

- a controller configured to provide an active current reference based on a set-point of the active power reference and a measured active power transfer, said measured active power being an actual power flow between said VSC and said AC network;

- a non-linear modulation block configured to non-linearly modulate said active current reference based on a measured DC voltage level at said HVDC cables,

wherein the non-linear modulation block is arranged for non-linearly modulating said active current reference based on a difference between said measured DC voltage level at said HVDC cables and a set steady-state DC voltage level, said set steady-state DC voltage level being associated to a lowest voltage level in which said VSC is expected to operate correctly,

wherein the non-linear modulation block is arranged for non-linearly modulating said active current reference by multiplying said measured DC voltage level at said HVDC cables with a gain factor,

wherein the non-linear modulation block is arranged for non-linearly modulating said active current reference by multiplying the active current reference with a modulation parameter, said modulation parameter being determined by:

$$1 - e^{-\alpha(DC_{meas} - LVT)}$$

wherein α is said gain factor, DC_{meas} is said measured active power and LVT is said set steady-state DC voltage level.

2. A VSC in accordance with claim 1, wherein said set steady-state DC voltage level is between 94% - 100% of a nominal DC voltage at said HVDC cables.

3. A VSC in accordance with any of the claims 1– 2, wherein said gain factor is between 500 – 3000.

4. A VSC in accordance with any of the previous claims, wherein the non-linear modulation block further comprises a limiter for limiting said measured DC voltage level at said HVDC cables, wherein said limited measured DC voltage is used for non-linearly modulating said active current reference.

5. A method of operating a Voltage Source Converter, VSC, in accordance with any of the previous claims, wherein said method comprises the steps of:

- providing, by said controller, said active current reference based on a set-point of the active power reference and a measured active power, said measured active power being an actual power flow between said VSC and said AC network;
- non-linearly modulating, by said non-linear modulation block, said active current reference based on a measured DC voltage level at said HVDC cables wherein said step of non-linearly modulating further comprises:
- non-linearly modulating said active current reference based on a difference between said measured DC voltage level at said HVDC cables and a set steady-state DC voltage level, said set steady-state DC voltage level being associated to a lowest voltage level in which said VSC is expected to operate correctly;
- non-linearly modulating said active current reference by multiplying said measured DC voltage level at said HVDC cables with a gain factor; and
- non-linearly modulating said active current reference by multiplying the active current reference with a modulation parameter, said modulation parameter being determined by:

$$1 - e^{-\alpha(DC_{meas} - LVT)}$$

wherein α is said gain factor, DC_{meas} is said measured active power transfer and LVT is said set steady-state DC voltage level.

6. A method in accordance with claim 9, wherein said set steady-state DC voltage is between 94% - 100% of a nominal DC voltage at said HVDC cables.

7. A method in accordance with any of the claims 5 – 6, wherein said gain factor is between 500 – 3000.

8. A method in accordance with any of the claims 5 – 7, wherein non-linear modulation block further comprises a limiter for limiting said measured DC voltage at said HVDC cables, wherein the method further comprises the step of:

- limiting, by said limiter, said measured DC voltage at said HVDC cables,

wherein said step of non-linearly modulating uses said limited measured DC voltage level for modulating said active current reference.

9. A High Voltage Direct Current, HVDC, network comprising a plurality of Voltage Source Converters, VSCs, in accordance with any of the claims 1 – 4, and comprising HVDC cables connecting those VSCs to one another.

10. A computer program product comprising a computer readable medium having instructions stored thereon which, when executed by a Voltage Source Converter, VSC, cause said VSC to implement a method in accordance with any of the claims 5 – 8.

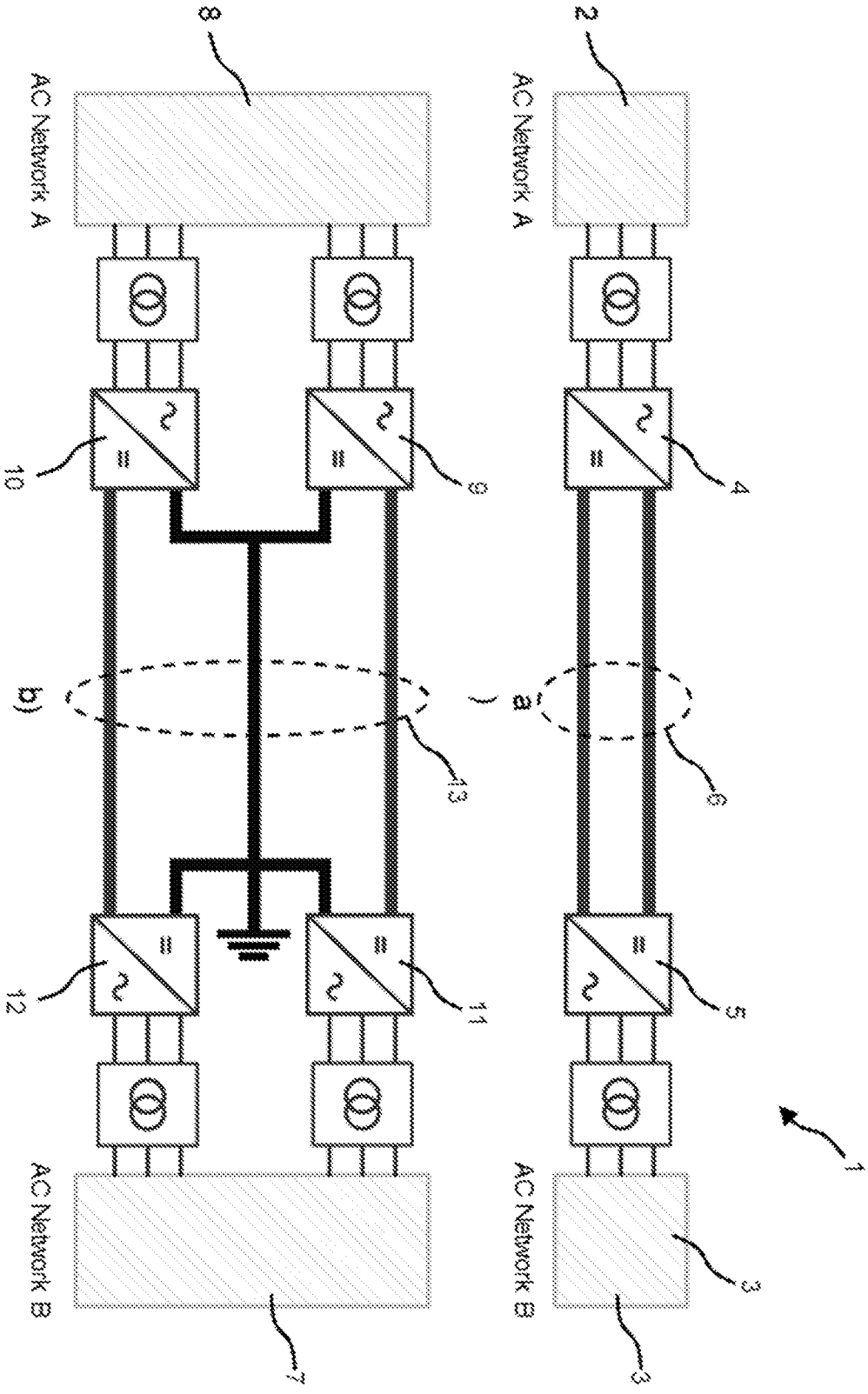

AC Network A
AC Network B
AC Network A
AC Network B
a)
b)
1
2
3
3
4
5
6
7
8
9
10
11
12
13

Fig. 1

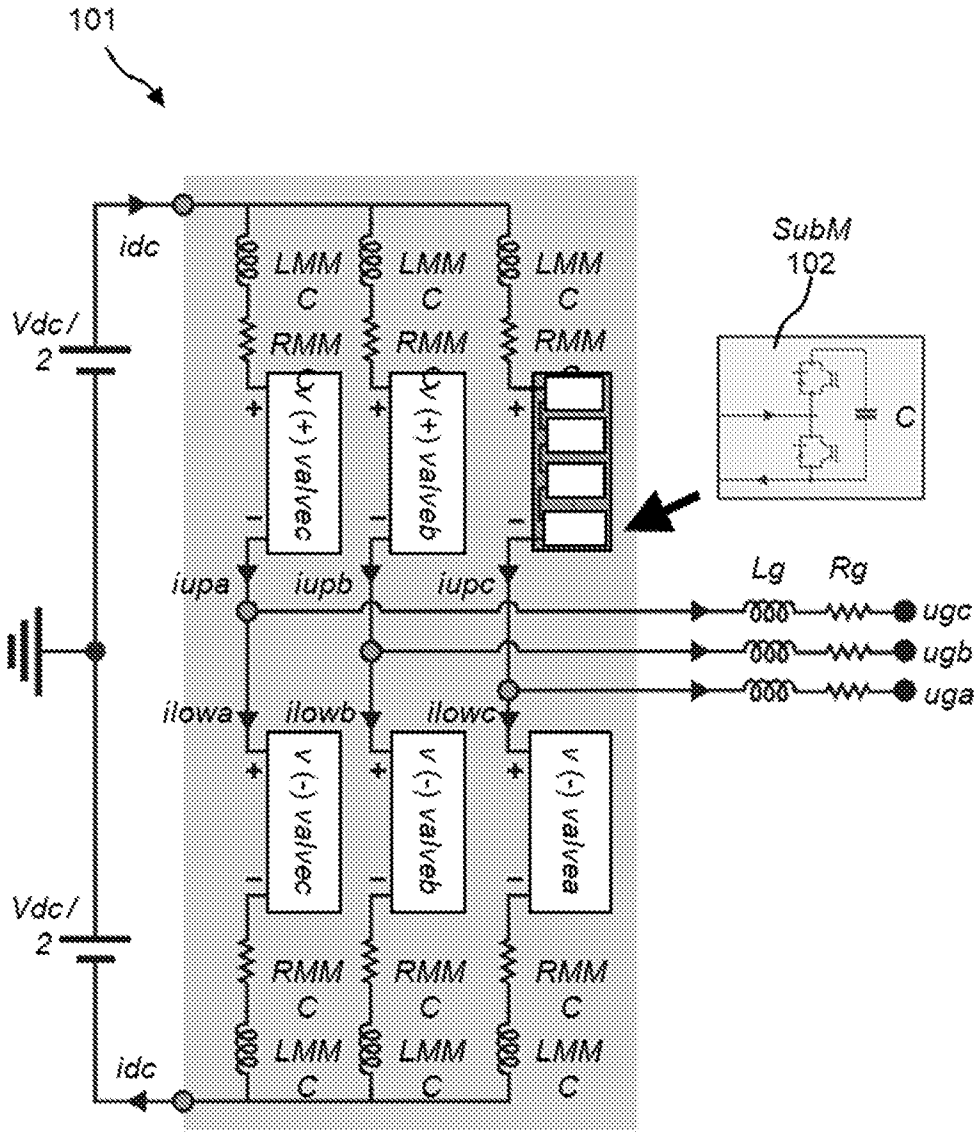

101
idc
Vdc/
2
LMM
C
RMM
C
SubM
102
C
Lg
Rg
ugc
ugb
uga
iupa
iupb
iupc
ilowa
ilowb
ilowc
idc

Fig. 2

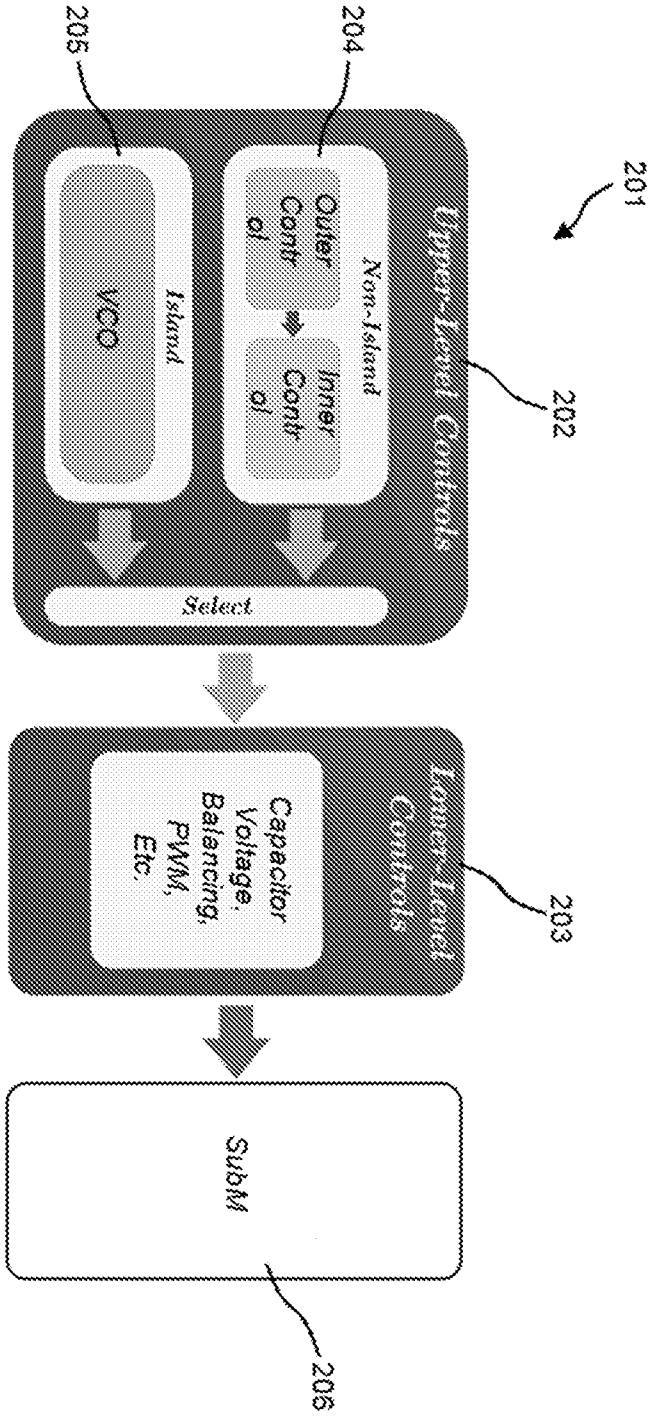

205
204
201
Upper-Level Controls
Island
VCO
Non-Island
Outer Control
Inner Control
202
Select
Power-Level Controls
Capacitor Voltage Balancing, PWM, Etc.
203
SubM
206

Fig. 3

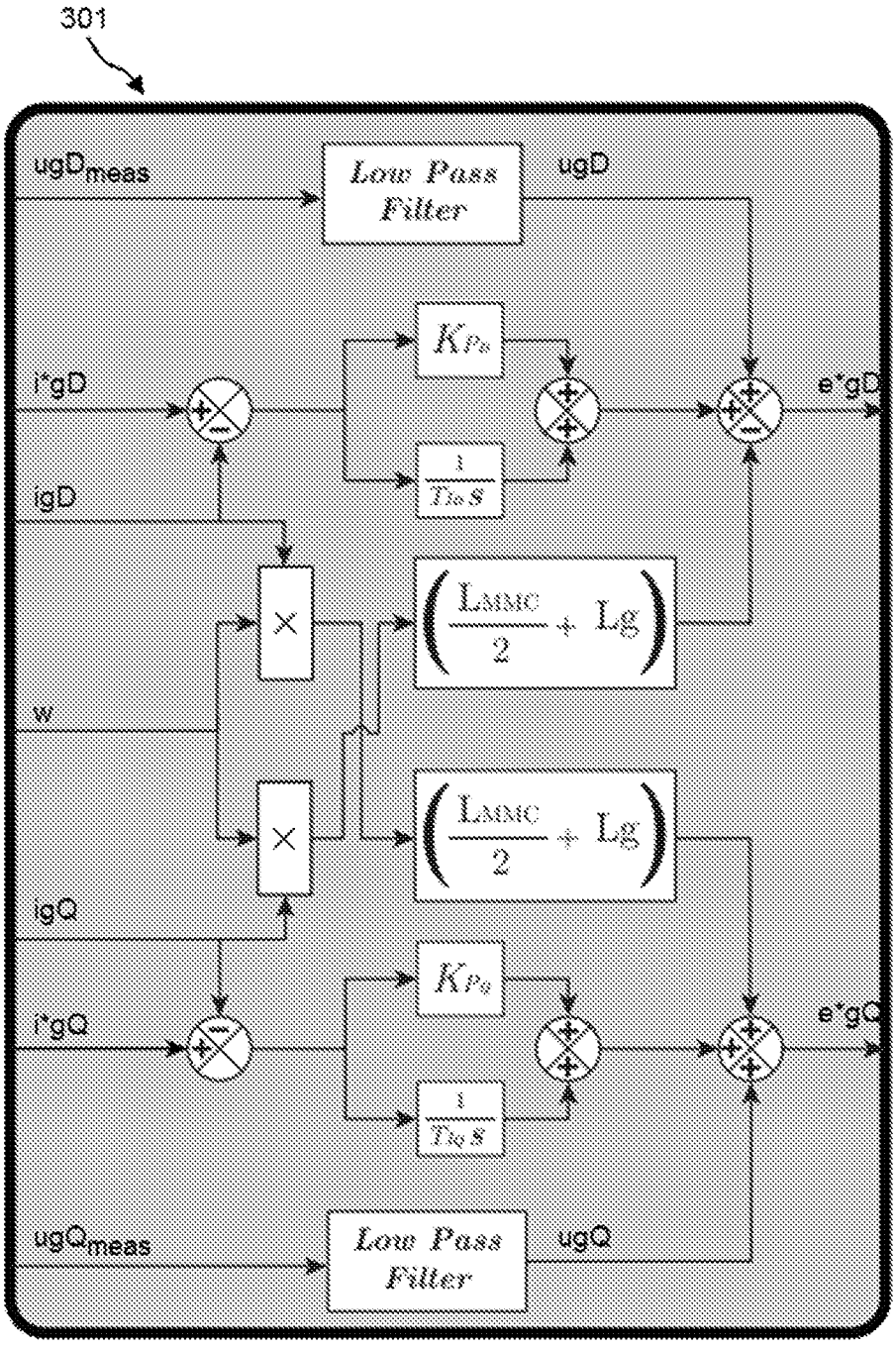

301
ugDmeas
Low Pass Filter
ugD
KPd
i*gD
e*gD
1/(Td s)
igD
(LMMC/2 + Lg)
w
(LMMC/2 + Lg)
igQ
KPq
i*gQ
e*gQ
1/(Tq s)
ugQmeas
Low Pass Filter
ugQ

Fig. 4

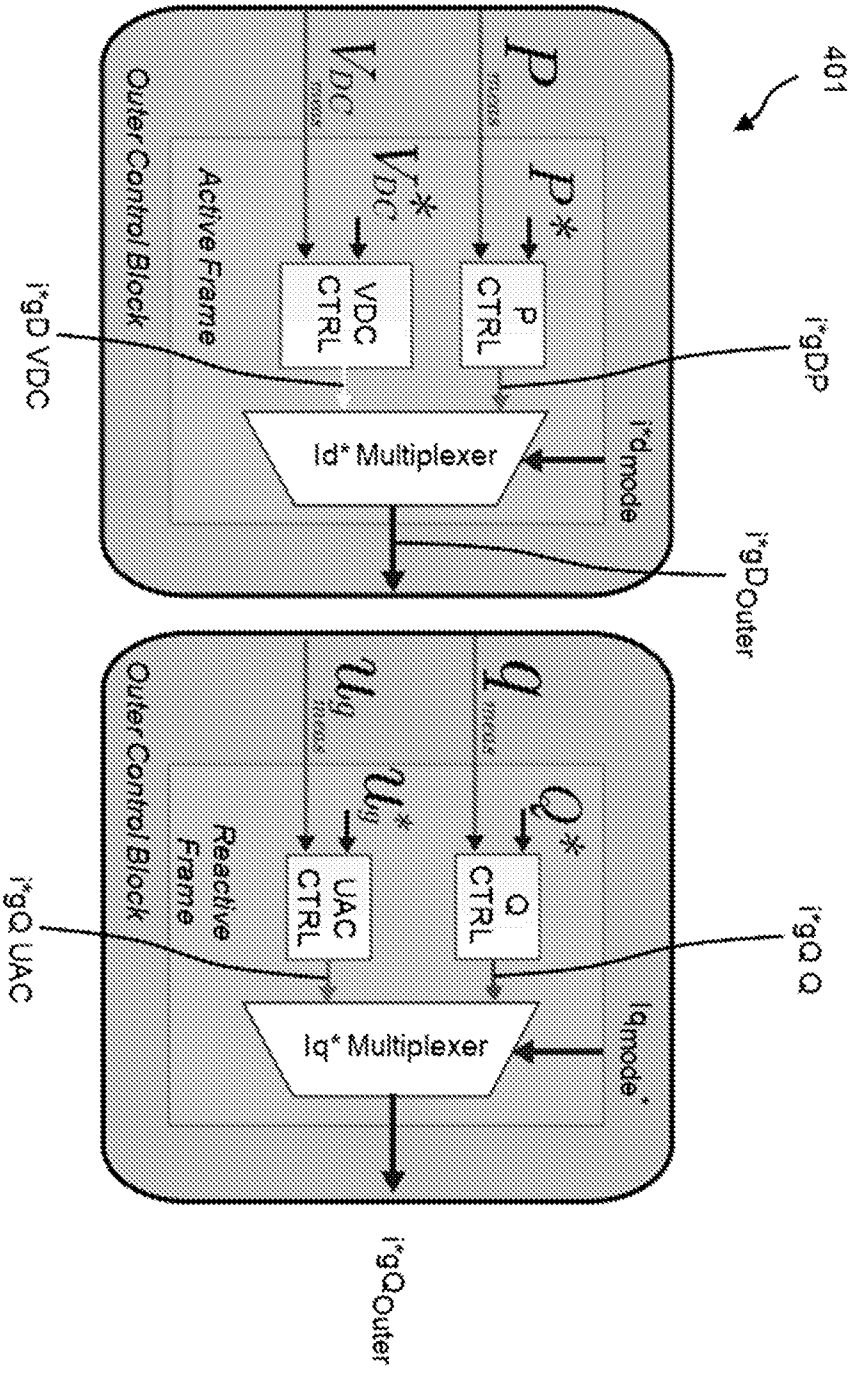

401
Outer Control Block
Active Frame
VDC CTRL
P CTRL
Id* Multiplexer
i*gD VDC
i*gDP
i*dmode
i*gDOuter
Outer Control Block
Reactive Frame
UAC CTRL
Q CTRL
Iq* Multiplexer
i*gQ UAC
i*gQ Q
Iqmode*
i*gQOuter

Fig. 5

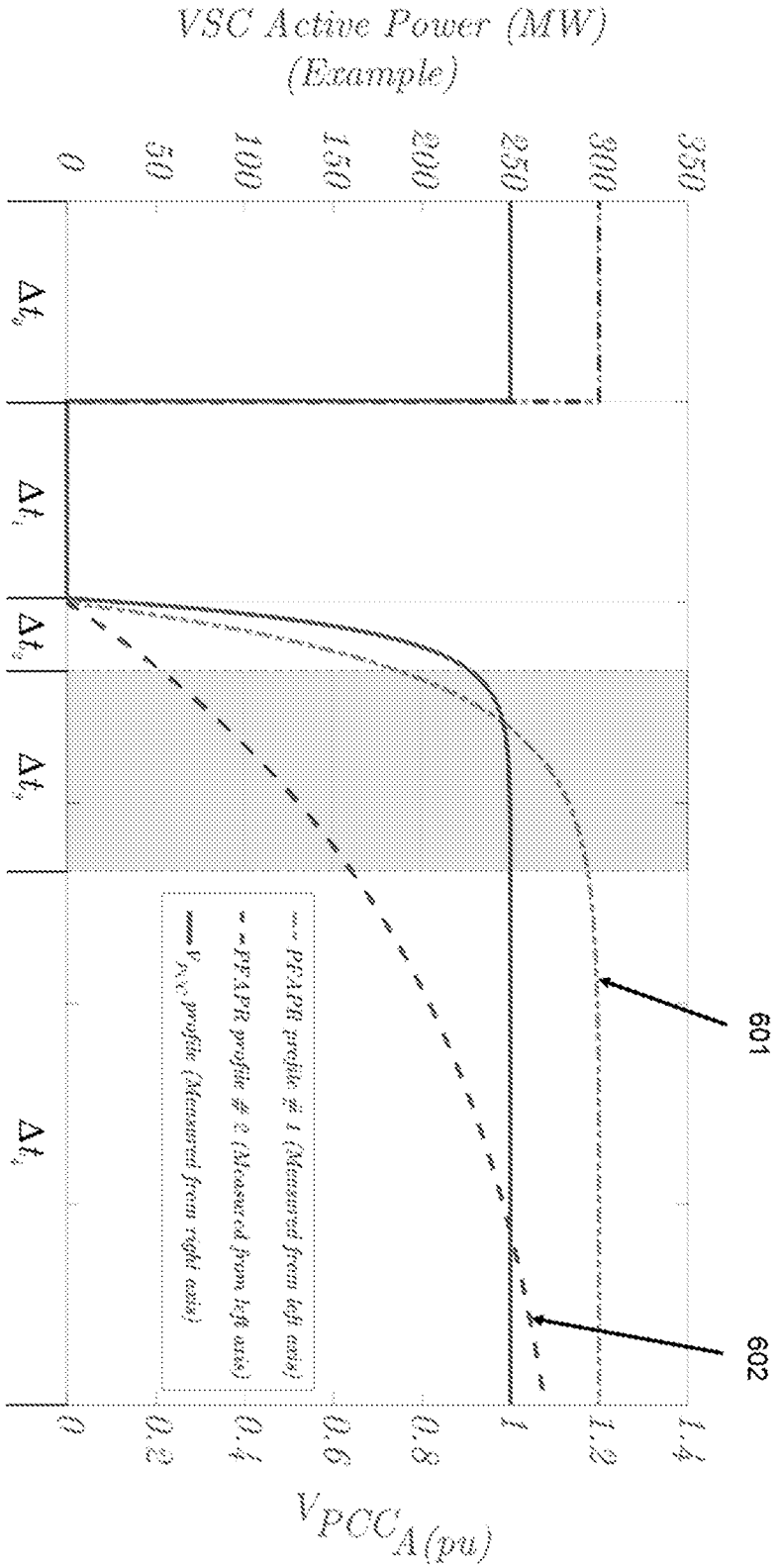

VSC Active Power (MW)
(Example)
0
50
100
150
200
250
300
350
Δt_0
Δt_1
Δt_2
Δt_3
Δt_4
PCAPR profile # 1 (Measured from left axis)
PFAPR profile # 2 (Measured from left axis)
V_{PCC} profile (Measured from right axis)
601
602
0
0,2
0,4
0,6
0,8
1
1,2
1,4
$V_{PCC_{A(pu)}}$

Fig. 6

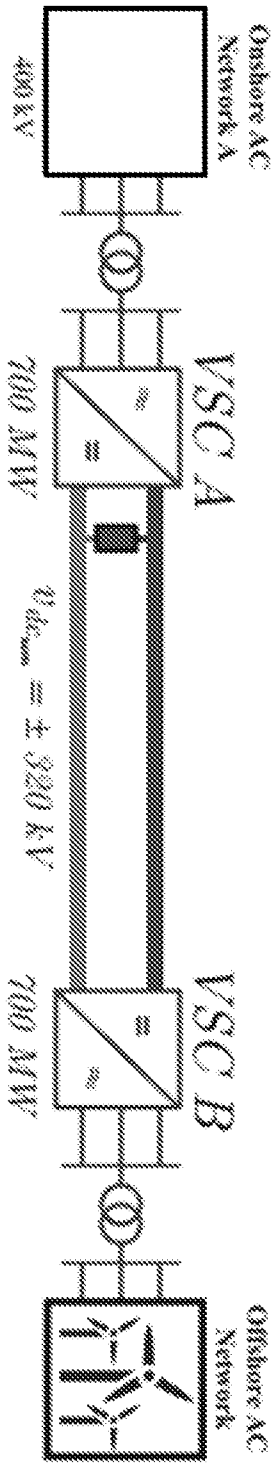

400 kV
Onshore AC Network A
700 MW
VSC A
± 320 kV
700 MW
VSC B
Offshore AC Network

Fig. 7

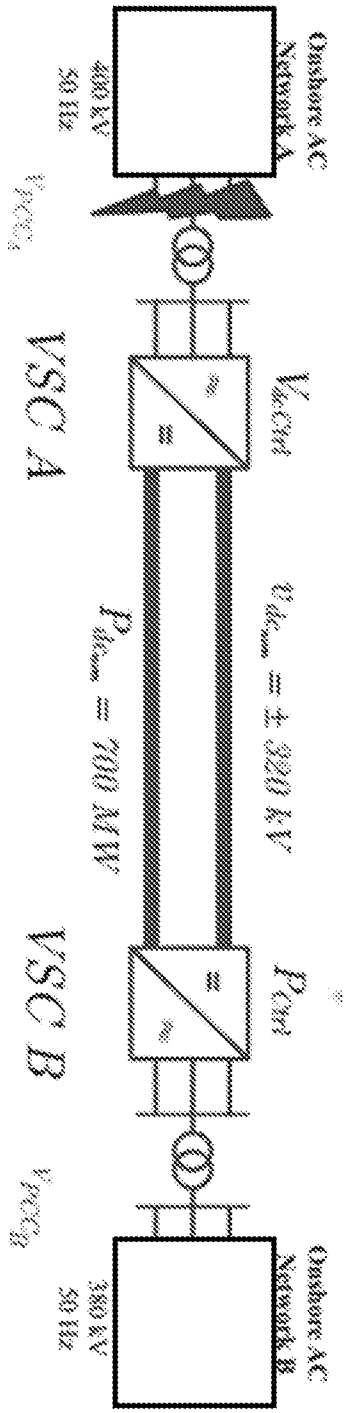

Onshore AC Network A
400 kV 50 Hz
V_{PCC_A}
VSC A
V_{conv}
$P_{dc_} = 700$ MW
$V_{dc_} = \pm 320$ kV
VSC B
P_{conv}
V_{PCC_B}
Onshore AC Network B
380 kV 50 Hz

Fig. 8

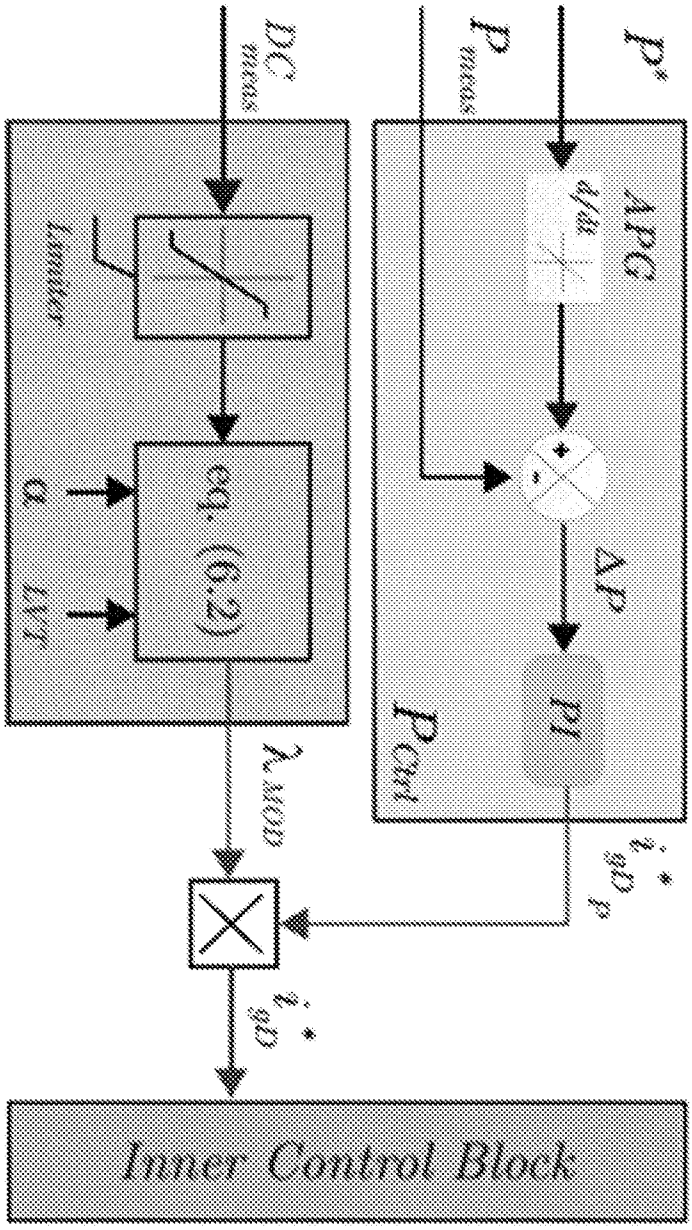

DC meas
Limiter
eq. (6.2)
a
LVT
λ_{mod}
i_{qs}^*
P_{Out}
PI
ΔP
ΔP_C
P_{meas}
P^*
Inner Control Block

Fig. 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2024/050357

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02J3/36 H02M1/00
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)
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 practicable, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2022/156681 A1 (NR ELECTRIC CO LTD [CN]; NR ENGINEERING CO LTD [CN]) 28 July 2022 (2022-07-28) figures 1,2,4,5,6 & EP 4 283 816 A1 (NR ELECTRIC CO LTD [CN]; NR ENGINEERING CO LTD [CN]) 29 November 2023 (2023-11-29) figures 1,4,5,6 paragraphs [0001], [0002], [0004], [0013] - [0017], [0049], [0050], [0062], [0137] claims 8-12	1-10
A	EP 2 495 864 A1 (CONVERTEAM TECHNOLOGY LTD [GB]) 5 September 2012 (2012-09-05) figures 1a,1b,2,3 paragraphs [0007] - [0027]	1-10

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 September 2024	10/10/2024

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Zettler, Karl-Rudolf

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/NL2024/050357

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		EP 2495864 A1	05-09-2012
		US 2013334889 A1	19-12-2013
		WO 2012117026 A2	07-09-2012