DTU Library

Method to predetermine current/power flow change in a dc grid

Eriksson, Robert

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
11 May 2017 (11.05.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/077045 A1

(51) International Patent Classification:
H02J 3/36 (2006.01)

(21) International Application Number:
PCT/EP2016/076687

(22) International Filing Date:
4 November 2016 (04.11.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
15193490.8 6 November 2015 (06.11.2015) EP

(71) Applicant: **DANMARKS TEKNISKE UNIVERSITET** [DK/DK]; Anker Engelunds Vej 101 A, 2800 Kgs. Lyngby (DK).

(72) Inventor: **ERIKSSON, Klas Robert Erik**; Krakstigen 7, 125 33 Älvsjö (SE).

(74) Agent: **PLOUGMANN VINGTOFT A/S**; Rued Langgaards Vej 8, 2300 Copenhagen S (DK).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

(54) Title: METHOD TO PREDETERMINE CURRENT/POWER FLOW CHANGE IN A DC GRID

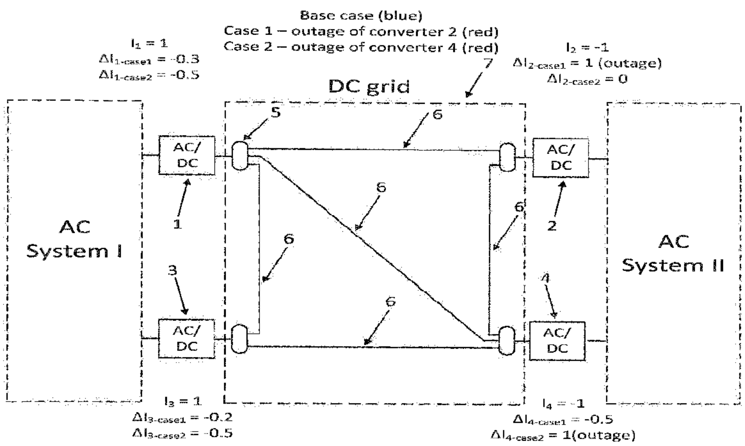

Figure 1

(57) Abstract: The invention relates to a method for controlling current/power flow within a power transmission system, comprising two or more interconnected converter stations. The method comprises the steps of: providing a DC admittance matrix given from the DC grid; providing a current distribution matrix for a number of, such as for all possible AC/DC converter outages; providing a DC bus voltage vector for the DC grid; the DC bus voltage vector being a vector containing the values of the voltage change at the AC/DC converters, measured at the AC/DC converters, before, during and after a forced current change occurs at one of the AC/DC converters; establishing a generalized droop feedback gain matrix G; controlling current/power flow within DC grid towards predefined setpoints, by use of control law. The invention presents an analytical approach to derive the generalized feedback gain allowing to differentiate the system response, i.e. current sharing, e.g. for different converter outages. The control approach aims at improving the DC voltage droop control by combining the local voltage signal available at the converter terminals, with remote voltage signals at different locations in the DC system, by means of communication. The local voltage feedback control is used for a fast, reliable system response. The invention also relates to a control device, implementing the method in the power transmission system.

WO 2017/077045 A1

METHOD TO PREDETERMINE CURRENT/POWER FLOW CHANGE IN A DC GRID

FIELD OF THE INVENTION

The present invention is related to the field of electric power systems, and in particular to techniques for controlling the current/power flow redistribution in a DC grid at converter outages with generalized feedback.

BACKGROUND OF THE INVENTION

In contrast with the more common AC systems, HVDC grid (High Voltage Direct Current) uses direct current for transmission of electrical power over long distances. In power transmission grids the AC power is converted to DC for transmission via overhead lines and cables. The advantages are: the frequency is eliminated, no need to compensate for the AC capacitive load, lower losses, power flow is controllable, cheaper per length and different systems can be connected with different frequencies.

The idea of building a super grid based on HVDC technology, has drawn attention in the power-engineering world, mainly because of the massive increase in volatile renewable energy sources. The super grid will increase reliability, transmission capacity, interconnect different regions with their own generation and consumption patterns and access for renewable resources such as wind farms, hydropower or solar panels.

The voltage source converter (VSC) is favourable to be used in the construction of the HVDC grid, however there are many challenges before such a grid can be realized.

One of the main challenges is the control of the DC voltage, where many methods have been proposed. The DC voltage is of the same importance as the frequency in AC systems. An unbalance in production and consumption cause a change in frequency, analogous an unbalance of injected and power drawn from the DC system is reflected in a deviation of the DC voltage. This dynamic process is several orders of magnitudes faster than the frequency. In AC systems the rotating masses have stored energy which is released in the case of unbalance deficit in production and the inertia is often measured in seconds. In DC systems most of the stored energy is located in the capacitor of the converters, as a sudden change of energy exchange with the AC system would need a countermeasure, with in tens of milliseconds as the capacitors only stores a fraction of the energy stored in the rotating masses.

Due to the fact that the time constant is much smaller in DC systems, it implicates fast control actions necessary to stabilize the grid.

When it comes to control of the DC voltage, conventionally in point-to-point connections, one of the converters is responsible maintaining the DC voltage. This is simply achieved by a PI-regulator taking the difference of the local DC voltage and the setpoint. This converter takes all burden and needs to keep some margin to be able to operate. Furthermore, in DC systems the power flow is determined by the voltage drop over the line, hence, there is a voltage variation in the DC system which directly relates to the power flow. This fact implicates that more than one converter cannot control the DC voltage to a certain setpoint as they would interfere.

Similar as in ac systems, droop-based control, using a proportional control action may be applied to distribute the control effort between different converter stations to share the burden of maintaining the balance. The majority of the control methods, presented in the literature in recent years, take this droop control as a starting point for the analysis and remarkable attention has been given to the design of the droop control itself and the determination of the droop values. However, there exists a trade-off between obtaining a predefined current sharing and limiting the voltage deviations after a contingency. The results rely on feedback of the local DC voltage and have limitations when it comes to a number of points.

WO 2013/020581 A1 discloses a DC power grid for use in high voltage direct current power transmission, comprising a plurality of terminals, each terminal being configured to import power from or export power to at least one other terminal and a plurality of control units; each control unit being operably associated with a respective one of the terminals and being configured to selectively control the respective terminal to increase its voltage in response to an increase in imported or exported current at the respective terminal and to decrease its voltage in response to a decrease in imported or exported current at the respective terminal.

FR 2997804 A1 relates to a method for controlling a multi-terminal HVDC network, comprising a primary control strategy to return to power-consumption power production balance and a secondary control strategy to reduce any voltage variation due to the first strategy.

OBJECT OF THE INVENTION

It is an object of the present invention to provide an alternative to the prior art, regarding DC voltage control in electrical power systems, such as High Voltage Direct Current grid (HVDC).
This invention presents an analytical approach to derive the generalized feedback gain allowing to differentiate the system response, i.e. current sharing, e.g. for different converter outages. The control approach presented aims at improving the DC voltage droop control by combining the local voltage signal available at the converter terminals, with remote voltage signals at different locations in the DC system, by means of communication. The local voltage feedback control is used for a fast, reliable system response.

SUMMARY OF THE INVENTION

The invention relates to a method for controlling current/power flow within a DC power grid, comprising two or more interconnected AC/DC converters. The method uses the approach of generalized feedback to develop a solid theoretical approach, to derive the feedback gain which differentiate system response originate from a forced current/power change in one converter station e.g. converter outage. Changing current in one converter, other converters keep the balance by alleviating their currents by pre-defined shares.

The method comprises the following steps:

- providing a DC admittance matrix given from the DC grid;

- providing a current distribution matrix for a number of, such as for all possible AC/DC converter outages;

- preferably, providing a DC bus voltage for the DC grid, the DC bus voltage vector preferably containing the values of the voltage change at the AC/DC converters, measured at the AC/DC converters, before, during and after a forced current change occurs at one of the AC/DC converters;

- establishing a generalized droop feedback gain matrix G;

- controlling current/power flow within DC grid towards predefined setpoints, by use of control law;

Preferably, the DC admittance matrix Y_{dc} is a matrix containing the values of the line admittances measured in the DC grid.

The current distribution matrix ΔI_{dc}^{*} is preferably a preselected current distribution matrix containing the values of the change in current injection at AC/DC converter j for a forced current change at AC/DC converter. ΔI_{dc}^{*} may be chosen by e.g. a system operator when a fault occurs at one or more AC/DC converter(s).

The generalized droop feedback gain matrix G, is preferably a matrix, establishing a relation between the established DC bus voltage vector ΔU_{dc} and a future current distribution in the grid, based on current distribution matrix ΔI_{dc}^{*} and DC admittance matrix Y_{dc}.

The control law $\Delta I_{dc} = -G \cdot \Delta U_{dc}$, preferably establishes a vector ΔI_{dc} being a current distribution vector for the AC/DC converters after a AC/DC converter outage in the DC grid.

A DC grid may comprise a processor configured to perform the method according to the present invention.

In the present context, a number of terms are used in a manner being ordinary to the skilled person. Some of these terms are detailed below:

Line is preferably used to mean/denote a connection between two AC/DC converters in a DC grid.

DC admittance matrix is preferably used to mean/denote a matrix containing the values of the line admittances in a DC power grid.

Current distribution matrix is preferably used to mean/denote a matrix containing the values of the change in current injection at AC/DC converter *j* for a forced current/power change e.g. outage of AC/DC converter *i*. The current distribution matrix is selected by the user e.g. system operator stating the current/power redistribution amongst the converters.

DC bus voltage vector is preferably used to mean/denote a vector containing the values of the voltage change at the AC/DC converters, before, during and after a forced current/power change occurs e.g. outage at one of the AC/DC converters.

Generalized droop feedback gain matrix G is preferably used to mean/denote a matrix, establishing a relation between the established DC bus voltage vector and future current distribution in the grid, based on current distribution matrix and DC admittance matrix.

Control law is preferably used to mean/denote an equation relating inputs to outputs, calculating a current change vector for the AC/DC converters.

Forced current change is preferably used to mean/denote a current change in one or more of the AC/DC converters, due to a converter outage e.g.

This aspect of the invention is particularly, but not exclusively, advantageous in that the present invention may be accomplished by a computer program product enabling a computer system to carry out the operations of the apparatus/system of the various aspects of the invention when down- or uploaded into the computer system. Such a computer program product may be provided on any kind of computer readable medium, or through a network.

The individual aspects of the present invention may each be combined with any of the other aspects. These and other aspects of the invention will be apparent from the following description with reference to the described embodiments.

The invention also relates to a control device, implementing the method in the power transmission system.

Further aspects and embodiments are presented in the following as well as in the accompanying claims.

BRIEF DESCRIPTION OF THE FIGURES

The figures show one way of implementing the present invention and is not to be construed as being limiting to other possible embodiments falling within the scope of the attached claim set.

Figure 1 illustrates schematically a grid composed of two AC systems I and II.
Figure 2 illustrates a DC grid connected to 3 different AC systems.
Figure 3 illustrates a flowchart of the method in the present invention.

DETAILED DESCRIPTION OF AN EMBODIMENT

Reference is made to fig. 1 showing schematically a DC grid connected through four AC/DC converters 1, 2, 3, 4 to two AC systems (I and II). The DC grid is made up from a number electrical connections 6 connected to connectors 5 at the DC side of the AC/CD converters. In the illustrative example of fig. 1, AC/DC converter 1 is connected to AC/DC converters 2, 3 and 4 through the electrical connections 6.

In a first mode of operation all AC/DC converters operates as designed, and the current written in as a vector $\boldsymbol{I_{dc}}=(I_1, I_2, I_3, I_4)$ where index refer to the specific number of the converter, the $\boldsymbol{I_{dc}}$ vector may have the components:

$$\boldsymbol{I_{dc}}=(1, -1, 1,-1)$$

If, as an example, AC/DC converter 2 suffers an outage, the method according to the present invention provides a pre-specified setpoint change to the current flow in the system. As will be disclosed in further details below, the method according to the present invention determines a change in current ΔI_i through each of the remaining AC/DC converters.

E.g. if convert 2 suffers an outage $\boldsymbol{\Delta I_{dc}}=(\Delta I_1,\Delta I_2,\Delta I_3, \Delta I_4)=(-0.3, 1, -0.2,-0.5)$ whereby the new current vector $\boldsymbol{I}_{outage\ 2}$ becomes $(\boldsymbol{I_{dc}}+ \boldsymbol{\Delta I_{dc}})$

$$\boldsymbol{I}_{outage\ 2}=(0.7, 0, 0.8, -1.5)$$

Thus, as will become clearer in the following, ΔI_{dc} is determined in generalized manner as

$$\boldsymbol{\Delta I_{dc}} = G \cdot \boldsymbol{\Delta U_{dc}}$$

where G is a generalized drop feedback gain matrix and $\boldsymbol{\Delta U_{dc}}$ is a DC bus voltage vector representing a generalized feedback signal for voltages at the AC/DC converter stations.

After an outage the current flowing through the converter facing an outage must be distributed to the other converters. The method does not, necessarily, determine the proportions but will distribute the current to any arbitrary pre-selected distribution to the other converters. The pre-selected distribution must ensure current balance thus sum to zero.
If, for instance, outage of AC/DC converter 4 occurs, the change in current ΔI_i through each of the remaining AC/DC converters $\boldsymbol{\Delta I_{dc}}=(\Delta I_1,\Delta I_2,\Delta I_3,\Delta I_4)=(-0.5,0,-0.5,1)$ whereby the new current vector $\boldsymbol{I}_{outage\ 4}$ becomes $(\boldsymbol{I_{dc}}+ \boldsymbol{\Delta I_{dc}})$

$$\boldsymbol{I}_{outage\ 4}=(0.5, -1, 0.5, 0)$$

The transfer level (which is the amount of electrical power flowing from one system to another) from AC system I to AC system II is the sum of the power flowing from I to II. After an outage the total transfer level between the two systems may be decreased, kept the same or be increased. The outcome depends on the generalized droop feedback gain matrix, *G,* (see below) which determines the new level. Preferably there is no direct relation between the currents after outage of converter 2 and 4, preferably, only that the sum of the current becomes zero (satisfying Kirchhoff's circuit law, which implies that the algebraic sum of currents in a network of conductors meeting at a point is zero) and that the converter that is facing an outage is transferring zero current.

The calculation of $\boldsymbol{\Delta I_{dc}}$ resides in the following equation, the control law:

$$\Delta \boldsymbol{I}_{dc} = -G \cdot \Delta \boldsymbol{U}_{dc} \quad (0)$$

$\Delta\mathbf{I}_{dc}$ being a current distribution vector for the AC/DC converters. The generalized droop feedback gain matrix, G, is determined by the method according to the invention such that the current change among the other remaining converters after a converter outage follows a predetermined scheme. The gain matrix only needs to be calculated once and handles all possible converter outages. Thus, the converter may share the current differently depending upon which converter faces an outage.

With the starting point of Kirchhoff’s current law the balancing of the DC grid takes place through control and feedback of the DC voltage implemented as current or power control. In the case of a converter outage implicating deficit or surplus of the injected current this must be compensated in order to stop the DC voltage to diverge resulting in damaged equipment and unstable operation. When using droop control, various converters jointly alleviate their current injection to meet the mismatch preventing the DC voltage to deviate from its initial value. The droop control is implemented based on current and extended by utilizing several measurements throughout the grid.

When relying on a local voltage signal in the droop control, the current-voltage relation at a droop controlled converter station can be written as:

$$I_{dc_i} = I_{dc,0_i} - \frac{1}{k_{dc_i}} (U_{dc_i} - U_{dc,0_i}) \qquad (1)$$

with I_{dc_i} and $I_{dc,0_i}$ respectively the actual and reference DC current at converter i and, k_{dc_i} is the DC droop constant.

The droop control current sharing after a converter outage is a function of the voltage droop constants in the different converters and the actual voltage drop. Using (1), an outage of converter i with a steady-state current injection of $I_{dc,0_i}$ gives rise to the current redistribution in the remaining converters described as

$$\Delta I_{dc_i} = -I_{dc,0_i} \qquad (2)$$

$$\Delta I_{dc_j} = I_{dc,0_i} \cdot g_j' \qquad (3)$$

where g_j' is the modified gain for converter j

$$g_j' = \frac{g_j \cdot \Delta U_{dc_j}}{\sum_{\substack{k=1 \\ k \neq i}}^{m} g_k \Delta U_{dc_k}} \qquad (4)$$

with $\Delta U_{dc_j} = (\Delta U_{dc_j} - \Delta U_{dc,0_j})$ and the converter gain g_j at converter j defined as the inverse of the DC droop constant k_{dc_j}. It can be observed from these equations that the actual redistribution of the current after the contingency depends on the DC grid voltage profile after the fault, which impedes a straightforward analysis.

The effect of the droop control can be seen as an integral part of the system response by rewriting the current flow equations. The DC system equations can be written as

$$Y_{dc} \cdot U_{dc} = I_{dc} \qquad (5)$$

with U_{dc} the DC bus voltage vector, I_{dc} containing the currents flowing into the DC system and Y_{dc} the DC admittance matrix.

Rewriting the voltage and current vectors

$$U_{dc} = U_{dc,0} + \Delta U_{dc} \quad (6)$$

$$I_{dc} = I_{dc,0} + \Delta I_{dc} \quad (7)$$

with the droop control law from (1),

$$\Delta I_{dc} = -G\Delta U_{dc} = Y_{dc}\,\Delta U_{dc} \quad (8)$$

In case of an outage of converter j, these equations can be combined and applying the superposition principle

$$(Y_{dc} + G_{out_j})\Delta U_{dc_j} = I_{dc,out_j} \quad (9)$$

with the modified gain matrix $G_{out\,j}$ and the current outage vector I_{dc,out_j} respectively defined as

$$G_{out_j} = diag([g_1 \ \cdot \ \cdot \ \cdot \ g_{j-1} \ 0 \ g_{j+1} \ \cdot \ \cdot \ \cdot \ g_n]) \quad (10)$$

$$I_{dc,out_j} = [0 \ \cdot \ \cdot \ \cdot \ 0 \ - \ I_{dc,0_j} \ 0 \ \cdot \ \cdot \ \cdot \ 0]^T \quad (11)$$

Rewriting the system equations this way, the droop control has been internalized as diagonal elements to the DC admittance matrix by a modified admittance matrix

$$Y'_{dc} = Y_{dc} + G_{out} \quad (12)$$

A trade-off exists between obtaining a predefined current redistribution and limiting the voltage deviations. Analyses show that a similar trade-off exists when striving towards a more general redistribution similar to the one in (14). In other words, one would still have to make a trade-off when aiming to minimize the influence of the DC grid layout. However, as long as the redistribution is along the lines of the control reaction dictated by the DC line resistances, there are still means to make the current distribution from (4) to approximate the ideal distribution from (14).

On the contrary, it can easily be seen that the droop control as such, either when based on a local control signal or other methods proposed in the literature, provides very little means to distinguish between different converter outages, i.e. to obtain a different current distributions depending on which converter faces an outage. Such a distinction could be beneficial from the AC system's point-of-view. As argued above, in the case of local droop control, there is an influence of the DC system layout, which makes that nearby converters tend to take a higher share than remote converters.

As an alternative, a common voltage feedback signal was proposed. This common signal consists of a single voltage measurement or a combination and using a common voltage feedback signal removes the voltage dependence of the current sharing after an outage.

The droop control law then simplifies to

$$I_{dc_i} = I_{dc,0_i} - \frac{1}{k_{dc_i}}\left(U_{dc}^{+} - U_{dc,0}^{+}\right) \quad (13)$$

with U_{dc}^{+} the common converter feedback signal and $U_{dc,0}^{+}$ its reference value. U_{dc}^{+} can be the voltage at one of the converter buses or a combination thereof. In case of a common voltage feedback signal used by all converters, as in (13), the relative current g_j' of converter j after a contingency can be written as

$$g_j' = \frac{g_j}{\sum_{\substack{k=1 \\ k \neq i}}^{m} g_k} \quad (14)$$

It can be seen that the droop control law becomes independent of the voltages in the system. A disadvantage compared to a local voltage based droop control, is the need for communication.

Instead generalized droop feedback is proposed using the generalized droop feedback gain matrix G in (8) defined as

$$G = \begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1n} \\ g_{21} & g_{22} & \cdots & g_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ g_{n1} & g_{n2} & \cdots & g_{nn} \end{bmatrix} \quad (15)$$

meaning that all converter voltages can be used for feedback in each droop controller.

In this multiple input generalized formulation, the modified gain matrix G_{out} for an outage replaces the corresponding to by zeros as the converter which is facing an outage cannot participate in the control. For example, an outage in converter 1 is followed by the gain matrix as follows

$$G_{out1} = \begin{bmatrix} 0 & 0 & \dots & 0 \\ g_{21} & g_{22} & \cdots & g_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ g_{n1} & g_{n2} & \cdots & g_{nn} \end{bmatrix} \quad (16)$$

The steady-state current change due to a converter outage can be derived from (8)-(17) and expressed as

$$\Delta I_{dc_j} = Y_{dc}\,(Y_{dc} + G_{outj})^{-1} \cdot I_{dc,outj} = M_j \cdot I_{dc,outj} \quad (17)$$

In the above equation not only the input direction, $I_{dc,outj}$, has an influence on the output also the outage which seems to modify the gain matrix M_j. With this formulation it can be realized that it is not straightforward to derive the feedback gains in order to achieve specific distribution of the currents followed by an outage.

When using local voltage feedback signals the voltages in the DC system influence the actual redistribution of the current after an outage. This influence cannot be eliminated without compromising the voltage deviations after an outage. The voltage dependency of the droop control makes that, when using similar droop settings at all the converters, a DC system has a tendency to solve deficits in the converters electrically closer.

The explanation to this is simply based on Ohm’s law as the voltage change is the most at the converter facing the outage, as it has the largest current change, therefor converters electrically closer also see larger voltage deviation compare to remote converters. This can be realized through superposition and converters located electrically remote tend to participate less in the balancing.

The use of a droop control scheme based on a common feedback signal, removes the voltage profile dependency as indicated in (14). This implies similar distribution among the operating converters independent of which converter that faces an outage. Thus the local effect, argued above is eliminated which can be seen as an unwanted consequence in some cases. From a transmission system operator (TSO) perspective, this can at a first glance be considered beneficial since, in this case, the droop values provide a direct and clear control variable to distribute the current in the case of an outage. Converter outages can give rise to different preferred current distributions seen from an AC grid point-of-view: a converter outage and the subsequent control actions undertaken by the converters give rise to a very fast change of the power flows in both the DC grid and the connected AC systems. The sudden change of power flows in the network can give rise to unstable system behaviour in the AC system. In this respect, it can be argued that the local aspects control action, which is inherently a part of the control when using a local voltage feedback, may be advantageous.

In the case of a DC grid is spread over a large area, the deficit or surplus caused by a converter outage will give rise to a control action in which mainly nearby converters in the DC system alleviate the contingency. This especially holds when similar droop control settings are used for all converters.

However, whether such a local control action is preferred from an AC system point of view largely depends on the internal structure of the underlying AC grids. This has been depicted conceptually in Fig. 2, where an overlay DC grid has been connected to an underlying AC system with 3 distinctive zones with weak interconnections, represented by the dashed lines. In case the converters are both electrically nearby in the AC as well as in the DC system (e.g. converters 1, 2 and 3), such a local control action can be beneficial as the outage and the control actions will largely influence local power flows and leave power flows between remote areas (around converters 4, 5 and 6) largely unchanged. This could be beneficial in this case, as the three areas are remotely connected both in the AC and in the DC system. A more thorough study would be needed in such a case to make sure that the sudden change of power flows locally does not give rise to other problems.

On the contrary, in case the AC and DC system topology have a completely different structure and the electrical distances in both grids cannot directly be related, this local effect of the control might be an unwanted consequence. For example, in Fig. 2 converters 5 and 6 are electrically close to converter 4 at the DC side, but are remote in the AC system. In this case, a predominantly local power distribution at the DC side could trigger inter-area oscillations between corresponding remote AC areas.

When it comes to security in interconnected AC/DC systems the N−1 criterion is often used to analyse transfer capability. The N-1 criterion is defined as:

> *For power transmission components delivering power to the same point, if one of the components goes out of service, the remaining components must be able to carry both the load they were carrying before the event, plus the load carried by the component that is out of service.*

To integrate the security of the DC grid thorough analysis is needed to look at contingencies e.g. power flow changes due to a converter outage to make sure the system withstand its effects.

This in turn may reduce the secure power flow limits in the DC system, as a consequence of possible security problems in the AC system, reducing its utilization. Even though the power flow in the DC system can rapidly be changed after an outage it might already be too late for the operator to react on such alert even if the action is handled automatically. As a consequence, a new innovative control method is proposed to control the system response of the DC converters followed by a converter outage according to predefined current setpoints.

As earlier explained, in hybrid AC/DC system interactions, the standard DC voltage control methods possess some clear drawbacks. Therefore, in this section, a generalized droop control is presented which differentiate the possible outages and distribute the current to predefined values. The aim is now to derive a new droop feedback which distributes the current/power sharing differently depending on which converter introduces a forced change in its current/power e.g. faces an outage.

Looking at an outage of each converter, one at a time, it corresponds to a disturbance applied to the input of the system in a certain direction expressed by (11). Using voltage deviation as feedback signal this was previously explained by (8) where the response directly depends on the voltage drop in the system related to the resistance. Another way to analyse the same problem is to use singular value decomposition (SVD) which can relate an input, converter outage, to an output, control action. To formulate the problem it needs to be put on a general form utilizing (17), however, it expresses the output for only one outage and the feedback matrix varies depending on the outage.

Followed by (16) to find the response followed by a converter outage the corresponding row in the feedback gain G was set to zero before multiplying it with the disturbance i.e., current vector. This was explained by the fact that the converter facing an outage cannot participate in the control, thus, the droop becomes $G_{out,j}$. On the other hand this can be seen differently and is here formulated in a better way. It is equivalent to keep the row while the voltage drop times this row adds up to the current change in the converter facing an outage. This can be expressed as follows

$$-I_{dc,0_j} = G_j \, \Delta U_{dc} \qquad (18)$$

with G_j being the j-th row in G. The generalized droop feedback gain matrix G is now independent of the converter outage and holds as long as (18) is fulfilled. Previously the problem was formulated for each converter outage as in (17) ended up with several equations which were to some extent related but the matrix M_j changed for each outage. The formulation of the general problem of (17) is instead expressed on a matrix form as follows

$$\Delta I_{dc}^{*} = Y_{dc} \, (Y_{dc} + G)^{-1} \, I_{dc,out} \quad (19)$$

where $I_{dc,out}$ contains all possible outages, corresponding to the columns, written on the matrix form as

$$I_{dc,out} = -\begin{bmatrix} I_{dc,0_1} & 0 & \dots & 0 \\ 0 & I_{dc,0_2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & \dots & I_{dc,0_n} \end{bmatrix} = \quad (20)$$

$$S^{rel} \cdot I_{dc,out}^{rel} = S^{rel} \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & \dots & 1 \end{bmatrix} \quad (21)$$

with ΔI_{dc}^{*} being the wanted current distribution, later defined as predefined setpoints. S^{rel} being an n x n matrix with the nonzero elements $-[\ \Delta I_{dc,0_1},\ \ldots,\ \Delta I_{dc,0_n}\ ]$ on the diagonal corresponding to the current operating point. However, the system is linear, consequently, any stabilizing controller brings the system to a stable operating point independently of the initial operating point.

For each outage the steady-state output are arranged in a matrix with each corresponding column being the output of the system. The output is now defined as the setpoints expressed as follows

$$\Delta I_{dc}^{*} = \begin{bmatrix} -I_{dc,0_1} & \Delta I_{dc_1}^{*2} & \dots & \Delta I_{dc_1}^{*n} \\ \Delta I_{dc_2}^{*1} & -I_{dc,0_2} & \dots & \Delta I_{dc_2}^{*n} \\ \vdots & \vdots & \ddots & \vdots \\ \Delta I_{dc_n}^{*1} & \dots & \dots & -I_{dc,0_n} \end{bmatrix} \quad (22)$$

with ΔI_{dc}^{*} being the current distribution matrix, the setpoint of the change in current injection at converter j for an outage of converter i. ΔI_{dc}^{*} is chosen by the user e.g. system operator when a fault occurs at one of the AC/DC converter stations and can be scaled similar to $\Delta I_{dc,out}^{rel}$, and then denoted as ΔI_{dc}^{*rel}. Since current balance must be reached each column sums to zero i.e.,

$$0 = -I_{dc,0_j} + \sum_{\substack{k=1\dots n \\ k \neq j}} \Delta I_{dc,k}^{*j} \quad for\ j = 1\ldots n \quad (23)$$

As the system is linear the size of the current of the converter facing an outage can be freely scaled by modifying S_{rel}.
The scaling does not necessarily relate to the actual operating point or to be normalized. This scaling has impacts on the feedback gain matrix hence dynamic response as well.

To find the general feedback gain singular value decomposition (SVD) will be used. The steady-state output after a forced current change $\Delta I_{dc,out}$ is given in (19).

The Y_{dc} can be decomposed, using SVD, as follows

$$Y_{dc} = U_{Y_{dc}} \cdot S_{Y_{dc}} \cdot V_{Y_{dc}}^T \quad (24)$$

Since Y_{dc} is symmetrical $U_{Y_{dc}} = V_{Y_{dc}}$ and Y_{dc} spans n — 1. Hence, one of the singular values in $S_{Y_{dc}}$ is zero. This originates from the property that the open loop system (uncontrolled) has no inherited property of achieving current balance. For instance, if the current is changed in one converter, the uncontrolled system becomes unstable since the other converters do not elevate their currents.
Applying droop control, or any control aiming at balancing the system, may stabilize the system.

Moreover, the steady-state output or setpoint matrix ΔI_{dc} can be expressed using SVD as follows

$$\Delta I_{dc}^{*rel} = U_I \cdot S_I \cdot V_I^T \qquad (25)$$

The rank of ΔI_{dc}^{*rel} is n — 1 since all feasible setpoints must be balanced, thus each column sums up to zero, therefor there exists a null direction. Hence, both sides in (19) have the same rank.

Using SVD (19) can now be rewritten as

$$\Delta I_{dc}^{*rel} = U_I \cdot S_I \cdot V_I^T =$$
$$U_{Y_{dc}} \cdot S_{Y_{dc}} \cdot V_{Y_{dc}}^T (U_{Y_{dc}} \cdot S_{Y_{dc}} \cdot V_{Y_{dc}}^T + G)^{-1} \cdot I_{dc,out} =$$

$$U_{Y_{dc}} \cdot S_{Y_{dc}} \cdot V_{Y_{dc}}^T (U_{Y_{dc}} \cdot S_{Y_{dc}} \cdot V_{Y_{dc}}^T + G)^{-1} \cdot S_{rel} \cdot I_{dc,out}^{rel} \quad (26)$$

Next both sides are multiplied with its inverse resulting in the following

$$(U_I \cdot S_I \cdot V_I^T)^{-1} =$$

$$= (U_{Y_{dc}} \cdot S_{Y_{dc}} \cdot V_{Y_{dc}}^T (U_{Y_{dc}} \cdot S_{Y_{dc}} \cdot V_{Y_{dc}}^T + G)^{-1} \cdot S_{rel})^{-1} \quad (27)$$

Solving to find G gives

$$G = (S_{rel} \cdot V_{Y_{dc}} \cdot S_{Y_{dc-mod}}^{-1} \cdot V_{Y_{dc}} U_I \cdot S_{MOD-1} \cdot V_I^T)^{-1} - Y_{dc} \quad (28)$$

which simplifies to

$$G = S_{rel} \cdot V_I \cdot S_{inv-1} \cdot U_I^T \cdot U_{Y_{dc}} \cdot S_{Y_{dc-mod}} \cdot U_{Y_{dc}}^T - Y_{dc} \quad (29)$$

where S_{inv-1} being the inverse of S_1 with the inverse of the last singular value replaced by nonzero and $S_{Y_{dc-mod}}$ being $S_{Y_{dc}}$ with the last element replace by nonzero.

The eigenvector that spans the null direction, the last eigenvector, is the same in both U_I^T and $U_{Y_{dc}}$. This comes from the fact that the sum of the injected currents is zero and that the self-admittance is equal to the sum of all connecting lines as there is no load in the DC grid. The orthonormal vector is $\sqrt{\frac{1}{n}}\,[-1,\ldots,-1]$ and is therefore also orthogonal to all other eigenvectors in U_I^T and $U_{Y_{dc}}$.

Consequently, by multiplication of U_I^T and $U_{Y_{dc}}$, the last row and column becomes a unit vector with one in the last position.

Once again SVD is applied to (29) resulting in

$$G = G' - Y_{dc} = S_{rel} \cdot U_{G'} \cdot S_{G'} \cdot V_{G'}^T - Y_{dc}. \quad (30)$$

The diagonal element in $S_G{}'$ at the affectable position, through the last element in $S_{Y_{dc}}$, is denoted $\sigma_{G'-n}$.

To stabilize the system, the feedback gain in the null direction must be larger than zero. This means that any change of the current injection must be compensated. Increasing the gain in the null direction implies that the converters together respond to any increase or decrease of the voltage by elevating their current. This can be seen as the converters act like an impedance load which current changes as the voltage changes. This moreover means that any change of this gain does not influence the steady-state output current as it is defined by the values of the other singular values. However, the gain in the null direction has a major impact on the dynamic response.

To see the impact of the variable parameters, $\sigma_{G'-n}$ and S_{rel}, of the feedback gain (30) is expressed as

$$G' = \begin{bmatrix} S_{rel,1}[b_{11} + \sigma_{G'-n} \cdot c_{11}] & \cdots & S_{rel,1}[b_{1n} + \sigma_{G'-n} \cdot c_{1n}] \\ \vdots & \ddots & \vdots \\ S_{rel,1}[b_{n1} + \sigma_{G'-n} \cdot c_{n1}] & \cdots & S_{rel,1}[b_{nn} + \sigma_{G'-n} \cdot c_{nn}] \end{bmatrix}$$

$$= S_{rel}\,(B + \sigma_{G'-n} \cdot C) \qquad (31)$$

where $\sigma_{G'-n} > 0$ and the diagonal elements in S_{rel} can be set to any positive real number.

$$B = \begin{bmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{n1} & \cdots & b_{nn} \end{bmatrix} = U_{G'} \cdot S_{G'} \cdot V_{G'}^{T} \qquad (32)$$

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1n} \\ \vdots & \ddots & \vdots \\ c_{n1} & \cdots & c_{nn} \end{bmatrix} = U_{G'-n} \cdot V_{G'-n}^{T} =$$

$$= U_{G'-n} \cdot \frac{1}{\sqrt{n}} \cdot \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}^T =$$

$$= \frac{1}{\sqrt{n}} \cdot \begin{bmatrix} | & \cdots & | \\ U_{G'-n} & & U_{G'-n} \\ | & \cdots & | \end{bmatrix} \qquad (33)$$

The general feedback gain can be changed by the scaling of the diagonal elements in S_{rel} and $\sigma_{G'-n}$. The direction of how the gains can be changed depends on the DC admittance matrix and setpoints. This implies there is a possibility to adjust the gains to achieve proper dynamic response meanwhile the steady-state distribution of the current remains.

Compared to D1, the method according to the present invention differs, among others, in the sense of using local and global measurements in each converter. In D1 only local measurements are used.

Comparing to D2, the method according to the present invention would be categorized as primary control and focuses on predefined setpoints, with possibility to reduce voltage deviation from initial values.

The invention can be implemented by means of hardware, software, firmware or any combination of these. The invention or some of the features thereof can also be implemented as software running on one or more data processors and/or digital signal processors.

The individual elements of an embodiment of the invention may be physically, functionally and logically implemented in any suitable way such as in a single unit, in a plurality of units or as part of separate functional units. The invention may be implemented in a single unit, or be both physically and functionally distributed between different units and processors.

Although the present invention has been described in connection with the specified embodiments, it should not be construed as being in any way limited to the presented examples. The scope of the present invention is to be interpreted in the light of the accompanying claim set. In the context of the claims, the terms "comprising" or "comprises" do not exclude other possible elements or steps. Also, the mentioning of references such as "a" or "an" etc. should not be construed as excluding a plurality. The use of reference signs in the claims with respect to elements indicated in the figures shall also not be construed as limiting the scope of the invention. Furthermore, individual features mentioned in different claims, may possibly be advantageously combined, and the mentioning of these features in different claims does not exclude that a combination of features is not possible and advantageous.

List of reference symbols used

1	AC/DC converter
2	AC/DC converter
3	AC/DC converter
4	AC/DC converter
5	connector
6	electrical connection
7	DC grid

CLAIMS

1. A method for controlling current/power flow within a DC grid (7) comprising two or more interconnected AC/DC converters (1, 2, 3, 4), said method comprising the steps of:

- providing a DC admittance matrix Y_{dc} for said DC grid

- providing a current distribution matrix ΔI_{dc}^{*} for a number of possible outages of AC/DC converter(s)

- providing a DC bus voltage vector ΔU_{dc} for said DC grid, wherein said DC bus voltage vector ΔU_{dc} is a vector containing the values of the voltage change at the AC/DC converters, measured at the said AC/DC converters, before, during and after a forced current change occurs at one of the AC/DC converters

- establishing, by use of a control unit, a generalized droop feedback gain matrix G

- controlling current/power flow within said DC grid, towards predefined operating points, by use of control law $\Delta I_{dc} = -G \cdot \Delta U_{dc}$

2. The method as claimed in claim 1, wherein said DC admittance matrix Y_{dc} is a matrix containing the values of the line admittances measured in said DC grid (7).

3. The method as claimed in claim 1, wherein said current distribution matrix ΔI_{dc}^{*} is a preselected current distribution matrix containing the values of the change in current injection at AC/DC converter j for a forced current change at AC/DC converter , said ΔI_{dc}^{*} being chosen by e.g. a system operator when a fault occurs at one or more AC/DC converter(s).

4. The method as claimed in claim 1, wherein said generalized droop feedback gain matrix G, is a matrix, establishing a relation between the established DC bus

voltage vector ΔU_{dc} and a future current distribution in the grid, based on current distribution matrix ΔI_{dc}^{*} and DC admittance matrix Y_{dc}.

5. The method as claimed in claim 1, wherein said control law $\Delta I_{dc} = -G \cdot \Delta U_{dc}$, establishes a vector ΔI_{dc} being a current distribution vector for said AC/DC converters after a AC/DC converter outage in the said DC grid.

6. A DC grid comprising a processor configured to perform the method according to any of the preceding claims.

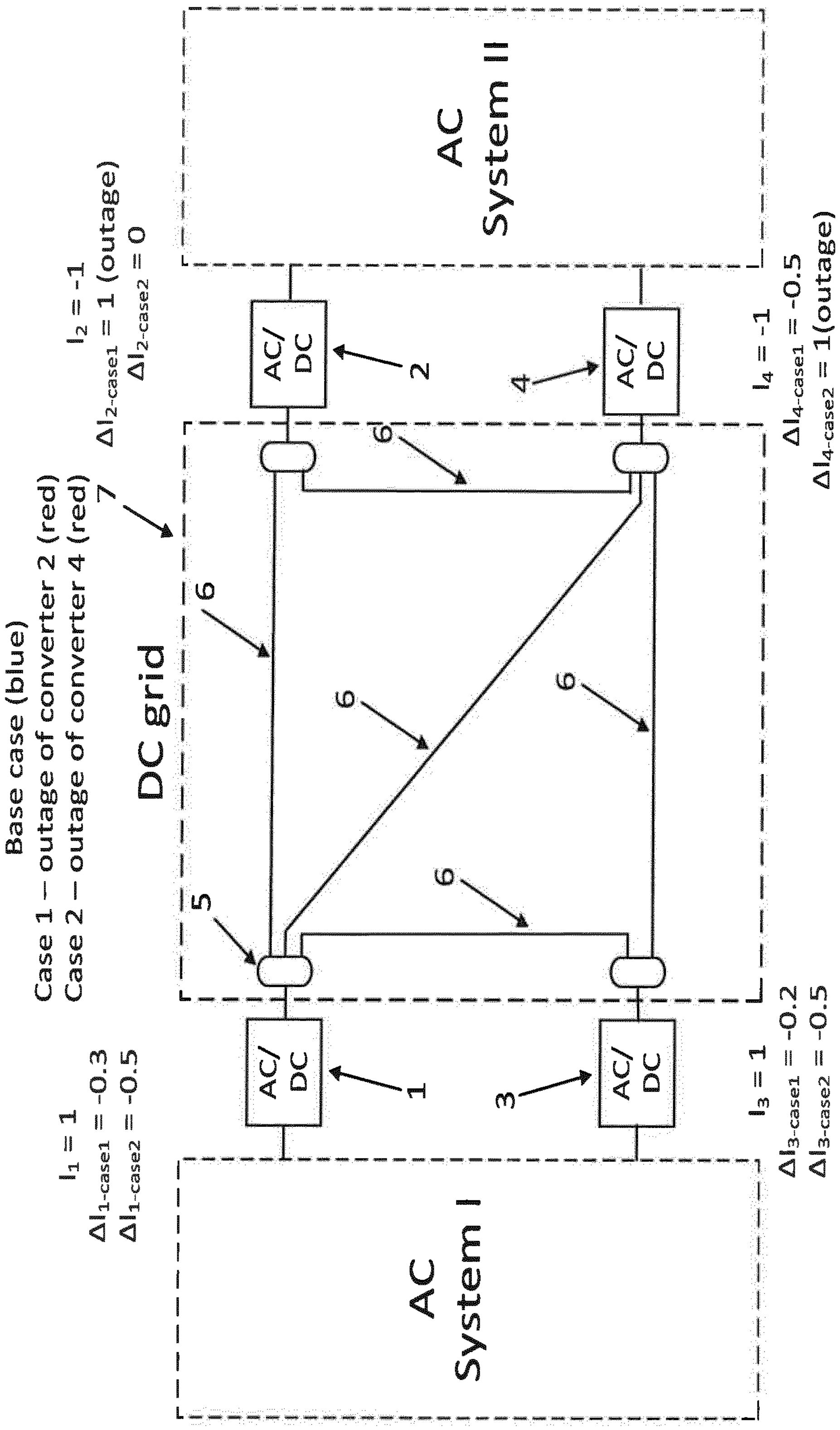
Base case (blue)
Case 1 – outage of converter 2 (red)
Case 2 – outage of converter 4 (red)
DC grid
AC System I
AC System II
AC/DC
AC/DC
AC/DC
AC/DC
$I_1 = 1$
$\Delta I_{1\text{-case1}} = -0.3$
$\Delta I_{1\text{-case2}} = -0.5$
$I_2 = -1$
$\Delta I_{2\text{-case1}} = 1$ (outage)
$\Delta I_{2\text{-case2}} = 0$
$I_3 = 1$
$\Delta I_{3\text{-case1}} = -0.2$
$\Delta I_{3\text{-case2}} = -0.5$
$I_4 = -1$
$\Delta I_{4\text{-case1}} = -0.5$
$\Delta I_{4\text{-case2}} = 1$(outage)
1
2
3
4
5
6
6
6
6
6
6
7

Figure 1

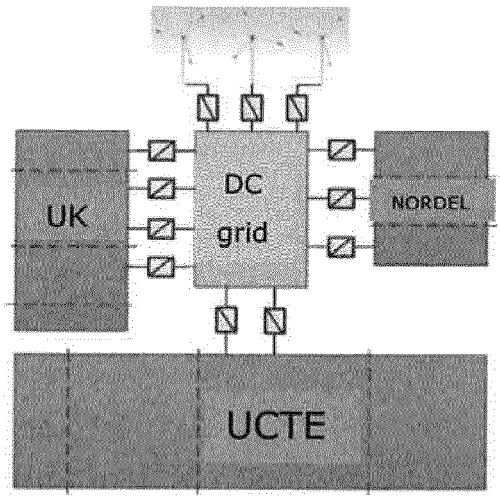

Figure 2

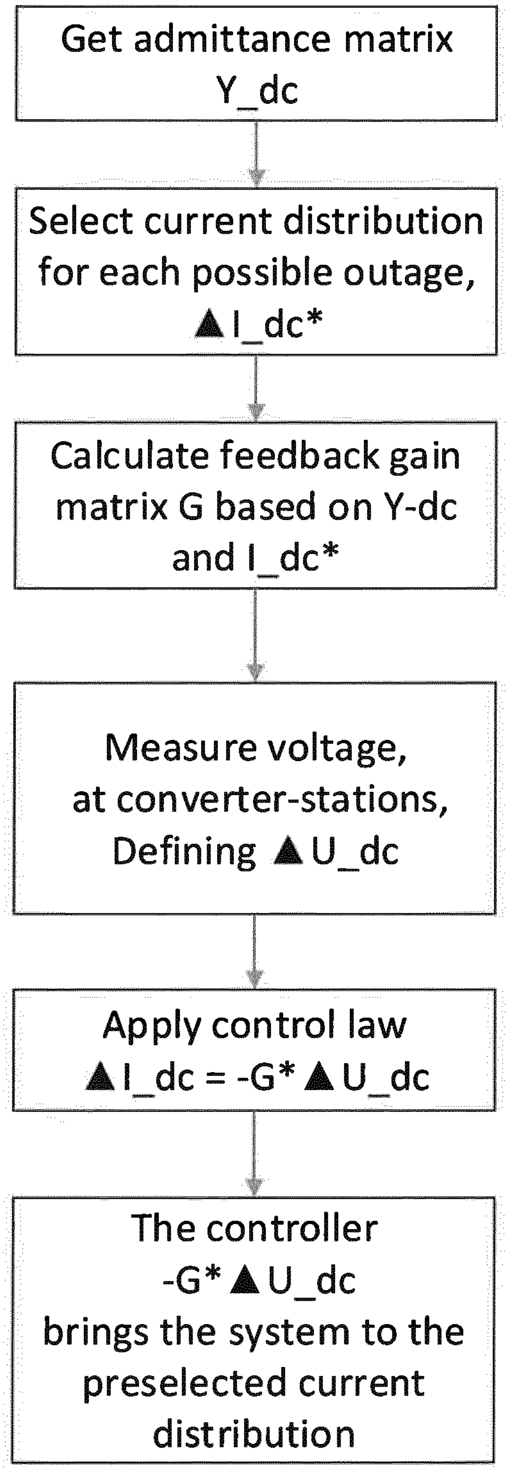
Get admittance matrix Y_dc
Select current distribution for each possible outage, ▲I_dc*
Calculate feedback gain matrix G based on Y-dc and I_dc*
Measure voltage, at converter-stations, Defining ▲U_dc
Apply control law ▲I_dc = -G*▲U_dc
The controller -G*▲U_dc brings the system to the preselected current distribution

Figure 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/076687

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02J3/36
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

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, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2013/020581 A1 (ALSTOM TECHNOLOGY LTD [CH]; CHUKALURI ESWAR KUMAR [GB]) 14 February 2013 (2013-02-14) page 6, line 1 - page 13, line 20; figures 1,3	1-6
X	FR 2 997 804 A1 (ALSTOM TECHNOLOGY LTD [CH]) 9 May 2014 (2014-05-09) page 8, line 1 - page 11, line 28; figures 1,8-11	1-6

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

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"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
2 February 2017	10/02/2017

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	Bergler, Christian

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2016/076687

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
WO 2013020581	A1	14-02-2013	NONE			
FR 2997804	A1	09-05-2014	EP	2917992	A1	16-09-2015
			FR	2997804	A1	09-05-2014
			WO	2014072246	A1	15-05-2014