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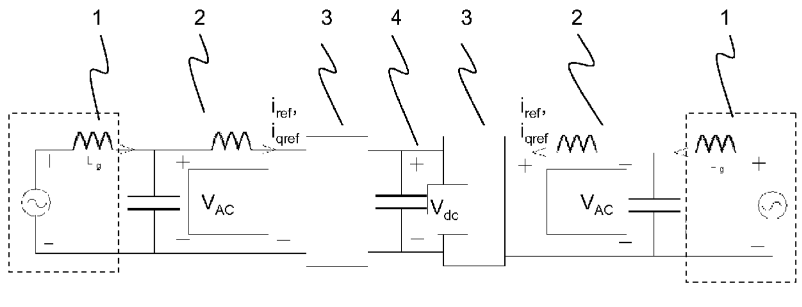
(54) Title: CONTROLLING A HIGH-VOLTAGE DIRECT-CURRENT (HVDC) LINK

Fig. 1



(57) Abstract: The present invention is directed to a High Voltage Direct Current HVDC link with Voltage Source Converters VSC (3) and interconnecting two power systems (1). A model-predictive control with a receding horizon policy is employed for controlling the outer loop of a two-loop or two-layer control scheme or setup for the HVDC link. The two-loop control scheme takes advantage of the difference in speed of the dynamics of the various system variables of the HVDC link and the interconnected power systems. Model-based prediction representative of the interconnected power systems' behaviour allows comparing the future effect of different control inputs applied within the control scheme, while taking into account any physical, safety and operating constraints. It is valid for a complete operating range, i.e. it avoids performance degradation when moving away from the nominal operating point of the control scheme for a HVDC link.

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DESCRIPTION

CONTROLLING A HIGH-VOLTAGE DIRECT-CURRENT (HVDC) LINK

FIELD OF THE INVENTION

The invention relates to the field of electric power transmission networks, and in particular to the control or operation of electric power systems interconnected by a High-Voltage Direct-Current (HVDC) link with Voltage-Source Converters (VSC).

BACKGROUND OF THE INVENTION

Voltage-Source Converters (VSC) for High-Voltage Direct-Current (HVDC) systems offer a cost-effective solution for interconnections in or between power networks, allowing for active and reactive power control in both directions, while preventing fault propagation and generally increasing low-frequency and voltage stability. The main control challenge for the operation of VSC-HVDC systems is achieving a stable and reliable operation over a wide range of operating conditions and system parameters. Moreover, suppression of transient over-voltages and over-currents is crucial for the operation of the system. State-of-the-art control solutions for VSC in HVDC applications are based on the design of controllers using locally linearized and/or averaged system models which are barely capable of predicting or analyzing the emergence of local power system instabilities, since the dynamics which cause the latter are not properly accounted for in the controller design.

The paper "Dynamic Model and Predictive Current Control of Voltage Source Converter Based HVDC" by Xiaoyan Wen et al., IEEE International Conference on Power System Technology 2006 (XP031053573), proposes a control method for a VSC-HVDC with a slow "external" and a fast "internal" control loop. The external or outer control loop controls the DC link voltage and/or the active and reactive power flows by determining the two converter current component references (i_α, i_β) in a rotating reference frame as input to the internal or inner control loop. The latter calculates the voltages required to track the requested currents, i.e. modulation voltages u_α, u_β are determined and ultimately fed into a Pulse Width Modulator (PWM) unit. The internal loop is designated "predictive current control" and assumes that the desired current reference will be attained with a simple one-step-ahead prediction. The external loop features a phase-locked loop (PLL) to transform (into the rotating reference frame) and decouple the state variables so that the adopted PI (Proportional-Integral) control scheme can operate correctly.

DESCRIPTION OF THE INVENTION

It is therefore an objective of the invention to enable a stable and reliable operation of power systems interconnected by a High-Voltage Direct-Current (HVDC) link with Voltage-Source Converters (VSC). This objective is achieved through a control method and a computer program according to the independent claims. Further preferred embodiments are evident from the dependent patent claims, wherein the claim dependency shall not be construed as excluding further meaningful claim combinations.

According to the invention, the initial state of the HVDC link and the interconnected power systems is determined at the beginning of an extended sampling period. A discrete-time prediction model including the HVDC link and the interconnected power systems is used to predict the effect of a particular sequence of converter current values as exemplary control inputs or decision variables over a desired prediction horizon comprising a plurality of time steps into the future. An optimum sequence of converter current values is identified as optimally approximating the target or desired behaviour of selected controlled variables by optimizing an objective function. Out of this optimum sequence, only the first converter current values are retained and provided to an inner loop of the control scheme for the HVDC link, all subsequent control inputs of the sequence being discarded. The inner loop, for the rest of the extended sampling period and based on the first optimized converter current values, repeatedly determines optimized pulse-width modulation voltage reference values. These voltage references are then forwarded and applied to the Pulse-Width Modulator (PWM) units in the VSCs of the HVDC link. At the beginning of the following extended sampling period the updated state of the HVDC link and the interconnected power systems is acquired, and the following first converter current values are determined and provided to the inner loop.

The sequence of optimal future control inputs is obtained by evaluating, and in particular minimizing, an objective, target or cost function. The objective function penalizes the deviation of the controlled variables from their references or control objectives. The controlled variables comprise at least one of an active or reactive power

P_{in}, Q_{in} transmitted across the HVDC link, a DC-link voltage V_{dc} of the HVDC link, or an AC filter voltage amplitude V_{ac} at the VSC of the HVDC link. The objective function in turn depends on future states or an anticipated behaviour as predicted by the prediction model of the HVDC link and the interconnected power system in conjunction with the future control inputs, and at the same time satisfies predetermined constraints. The latter include physical (voltage reference limits of the VSC), safety (current limitation in case of a fault) and operational constraints of the power system.

In a preferred embodiment the prediction model of the power system is Piecewise Affine (PWA). This provides for more modelling capabilities, and the prediction model can describe different modes of operation and incorporate discrete-valued states and inputs that are used for modelling logic components.

In an advantageous variant of the invention, the inner loop optimization problem is linear and pre-solved off-line for the whole operating range, leading to a look-up table of optimized pulse-width modulation voltage reference values or PWM control laws. The latter can later be evaluated continually given the converter current reference value at the beginning of an extended sampling period as well as updated system quantity values repeatedly sampled, at a system control frequency, during the extended sampling period. A pre-solution is particularly useful in case of limited computational capacity of a Digital Signal Processor (DSP) or a Field-Programmable Gate Array (FPGA) executing the inner loop.

The invention is most beneficially applied to power systems comprising a weak network with a grid impedance L_g exceeding 0.5. In this case, the AC filter voltage amplitude V_{ac} at the VSC of the HVDC link is the preferred controlled variable yielding the best optimization results.

In summary, a model-predictive control with a receding horizon policy is employed for controlling the outer loop of a two-loop or two-layer control scheme or setup for a HVDC link. The two-loop control scheme takes advantage of the difference in speed of the dynamics of the various system variables of the HVDC link and the interconnected power systems. Model-based prediction representative of the interconnected power systems' behaviour allows comparing the future effect of different control inputs applied within the control scheme, while taking into account any physical, safety and operating constraints. It is valid for a complete operating range, i.e. it avoids performance degradation when moving away from the nominal operating point of the control scheme for a HVDC link.

The present invention also relates to a computer program product including computer program code means for controlling one or more processors of a controller for an HVDC link with a VSC, particularly, a computer program product including a computer readable medium containing therein the computer program code means.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter of the invention will be explained in more detail in the following text with reference to preferred exemplary embodiments which are illustrated in the attached drawings, in which:

Fig.1 schematically shows an HVDC link interconnecting two power systems;

Fig.2 illustrates the main principles of a Model Predictive Control scheme; and

Fig.3 to 5 depicts an evolution of the controlled variables P_{in}, V_{DC} and V_{AC}, respectively.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Fig.1 shows a High-Voltage Direct-Current (HVDC) link connecting two power systems or electrical grids or (sub-) networks. Both power systems (1) are schematically represented through a series connection of a voltage source and a grid impedance L_g, and are connected to the HVDC link via an LC filter (2). The HVDC link comprises two Voltage-Source Converters (VSC) (3) and a DC line (4). The power systems (1) are representative of any number and arrangement of pieces of primary equipment, including generators, transformers, filters, AC transmission lines etc.

Fig.2 depicts the main principles of a Model Predictive Control (MPC) scheme. The evolution in time of the system state or of a particular physical system quantity is represented by a one- or multidimensional trajectory. A model taking into account its dynamics is used to predict output trajectories ($\underline{x}^i$) based on the current state at time t_0 and for several different potential candidate input sequences ($\Delta\underline{u}^i$). An objective or cost function is then defined based on the deviation of each predicted trajectory from a desired reference trajectory ($\underline{x}_{ref}$) over a window in time called the prediction interval (t_p). The effect of the various potential input sequences is evaluated, and the sequence for which the objective function is optimized is selected.

HVDC control ultimately sets modulation voltage references for Pulse-Width Modulator (PWM) units in the VSC in order to regulate the controlled variables i.e. the active or reactive power transmission across the DC-link (P_{in}, Q_{in}), the DC-link voltage (V_{dc}) and the AC filter voltage amplitudes (V_{ac}) at the interface between the converter station and the connected electric power grid (c.f. Fig.1). References for the aforementioned controlled variables serve as inputs to an outer or external control loop that conventionally operates with the aid of a PLL. The PLL is used to synchronize the reference frame of the d-q axes with the filter voltage in order to decouple the control objectives and variables, i.e. active power transmission/d axis variables and filter voltage amplitude/q axis variables respectively. The outer control loop determines converter current references (i_{dref}, i_{qref}) of the AC currents entering or leaving the VSCs (c.f. Fig.1), which are fed into an inner control loop. Tuning of the PLL may be demanding and the source of unstable behaviour of a closed loop system, and the resulting performance can be considerably dependent on the system parameters.

On the other hand, MPC is inherently a multi-objective/multi-variable methodology with a prediction model formulated in the time domain. It does not need any additional artifice such as variable decoupling via ad-hoc selected reference frame transformations to synchronize the control system with the grid frequency of the power network. In other words, the proposed MPC solution comprises a control structure that is intrinsically independent of the chosen angle of the d-q reference frame and that therefore does not require the use of a Phase Locked Loop PLL. The PLL may be retained solely to determine variations in the grid frequency but as this is a slowly changing quantity it does not significantly affect the dynamics of the HVDC control scheme.

The proposed solution is based on a two loop or layer structure, wherein the external or outer loop receives the specified control objectives as reference values for the active/reactive power (P_{in}, Q_{in}) and dc/ac voltage (V_{dc}, V_{ac}), and determines a sequence of converter current reference values $\{i_{dref}, i_{qref}\}$ as an optimum input sequence. Out of the latter, the first values i_{dref}^1, i_{qref}^1 are passed to the lower current control loop. The external loop includes an optimization on the basis of a nonlinear control model system including the HVDC link, the LC filters, and the power systems as defined above, with said converter currents as decision variables and the aforementioned active/reactive power and dc/ac voltage references as a control objective. Typically, an MPC prediction horizon is of the order of some 10 ms and spans a number of extended sampling periods of typically 1 ms each, corresponding to an external loop sampling period or sampling frequency at which systems states, controlled variables and constraints may be updated. The inner loop in turn is based on a linear control model of the HVDC link and the LC filters only, i.e. excluding the power systems being connected by the former, and determines, according to the converter currents requested by the outer loop, the actual modulation voltage references for the PWM units of the VSCs. The latter may be based on any converter topology (e.g. cascaded half-bridges "M^2LC" and cascaded full bridges "Chain-link"). The inner loop also takes into account updated system quantities of the linear control model of the HVDC link and the LC filters, which are provided at a system control, and/or sampling, frequency of e.g. 10 kHz. For the inner loop, MPC may be used as well, typically with a prediction horizon of a fraction of a millisecond (i.e. 0.1 to 0.3 ms). Alternatively, the inner loop may employ conventional, fast and proven PI (Proportional-Integral) control.

The proposed solution does not require any exchange of information between the two converter stations at the two ends of the HVDC-link, i.e. the two VSC operate independently. This is an important feature in that the high sampling rate of the control system (typically in the range of several kHz) does not allow for reliable information exchange between the two distant converter stations, especially in the face of possible outages in the communication channels.

Some simulation results are provided in the following to demonstrate the closed loop performance of the MPC controller in the outer loop of the control scheme. The proposed scheme is particularly effective when dealing with *weak* networks, i.e. when the short circuit ratio between AC and DC power of the system is small, typically below 2, which is equivalent to a grid impedance L_g in a range from 0.5 to 1 per unit values. Standard control schemes have considerable difficulty in dealing with such cases. Taking the extreme case when the above ratio and the grid impedance L_g are both equal to 1, Figs. 3 to 5 show, in per unit values and as a function of time (1 time unit = 0.1msec), the controlled variables, namely the active power transmitted by the VSCs (Fig.3), the DC voltage of the HVDC link (Fig.4) and the two filter voltages for the two stations (Fig.5). The reference value of the transmitted power is +/-0.5 whereas the DC and filter voltages should be steered to 1. The proposed MPC scheme clearly manages to steer the controlled variables to the requested values.

PATENT CLAIMS

1. A method of controlling a High-Voltage Direct-Current HVDC link with two Voltage-Source Converters VSC (3) and interconnecting two power systems (1), comprising
(a) determining, at the beginning t* of an extended sampling period, a present state of the HVDC link and the power systems (1),
(b) deriving a sequence of optimum converter current reference values $\{i_{dref}, i_{qref}\}$ by optimizing, over a prediction horizon t_p, an objective function based on a prediction model representing the HVDC link and the power systems (1),
(c) passing the first optimum value i_{dref}^1, i_{qref}^1 of said sequence to an inner control loop,
(d) deriving, by the inner control loop and based on said received first optimum value i_{dref}^1, i_{qref}^1, optimized pulse-width modulation voltage reference values,
(e) applying the optimized pulse-width modulation voltage reference values to a Pulse-Width Modulator (PWM) unit of a VSC (3),
(f) repeating steps (d) and (e) during the extended sampling period, and
(g) closing an outer control loop by returning to step (a) at the end of the extended sampling period.

2. The method according to claim 1, characterized in that step (b) comprises optimizing an objective function based on a piecewise affine prediction model.

3. The method according to claim 1, characterized in that step (d) comprises deriving the optimized pulse-width modulation voltage reference values by reverting to a look-up table.

4. The method according to claim 1, wherein at least one of the power systems (1) interconnected by the HVDC link comprises a weak network, characterized in that step (b) comprises optimizing an objective function that penalizes a deviation from a reference of an AC filter voltage amplitude V_{ac} at the VSC of the HVDC link.

5. A computer program for executing the method according to one of claims 1 to 4.

Fig. 1

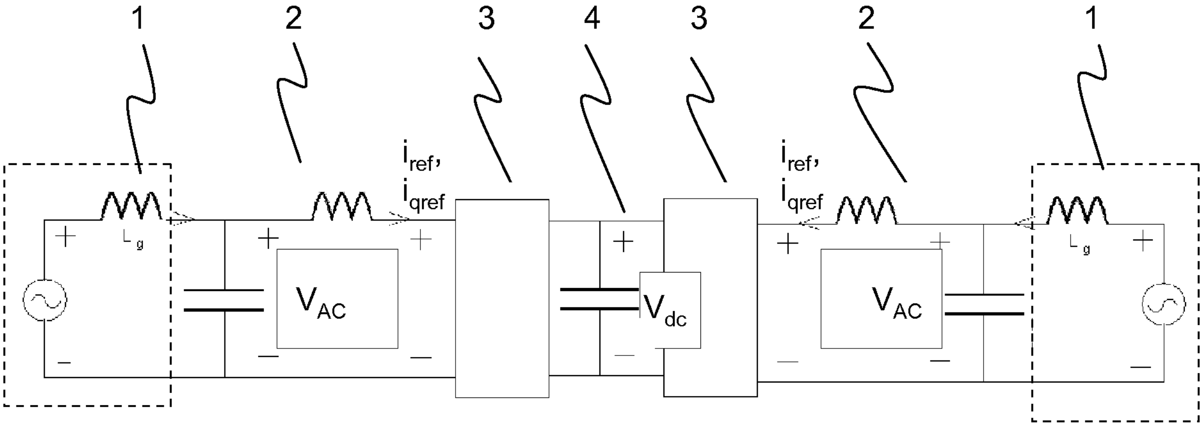

1
2
3
4
3
2
1
iref,
iqref
Lg
VAC
Vdc
+
−

Fig. 2

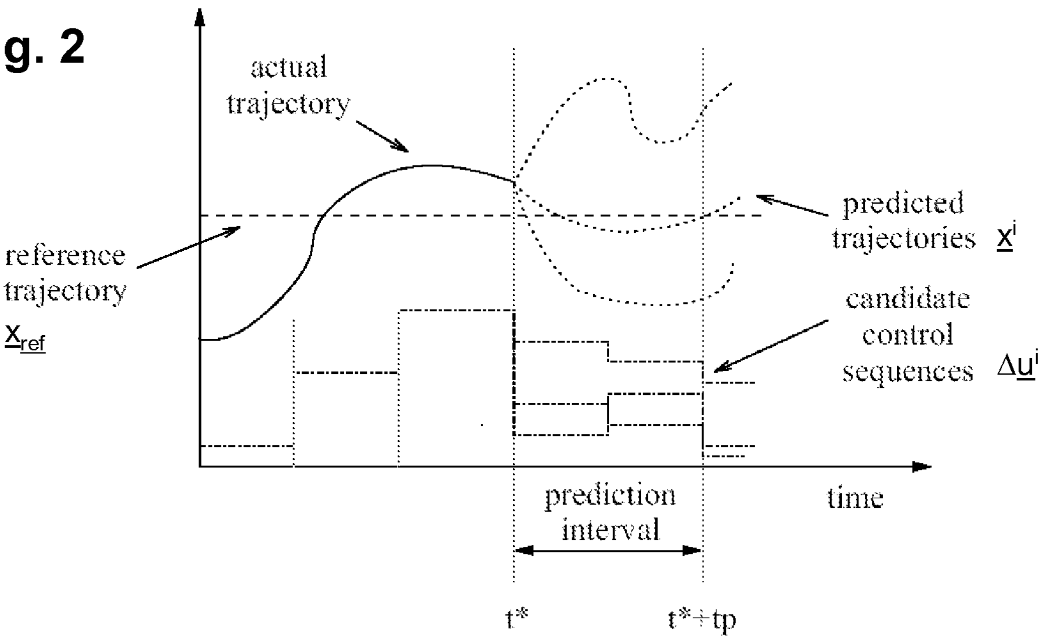

actual
trajectory
reference
trajectory
xref
predicted
trajectories xi
candidate
control
sequences Δui
prediction
interval
time
t*
t*+tp

Fig. 3

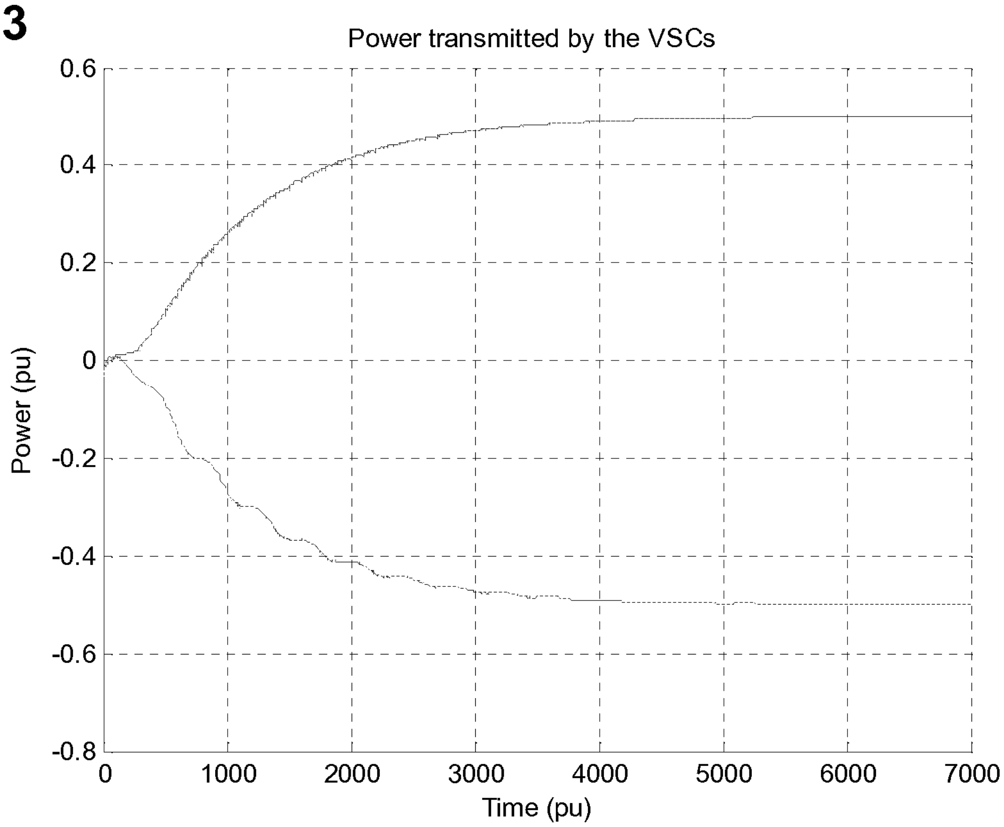

Power transmitted by the VSCs
Power (pu)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
1000
2000
3000
4000
5000
6000
7000
Time (pu)

Fig. 4

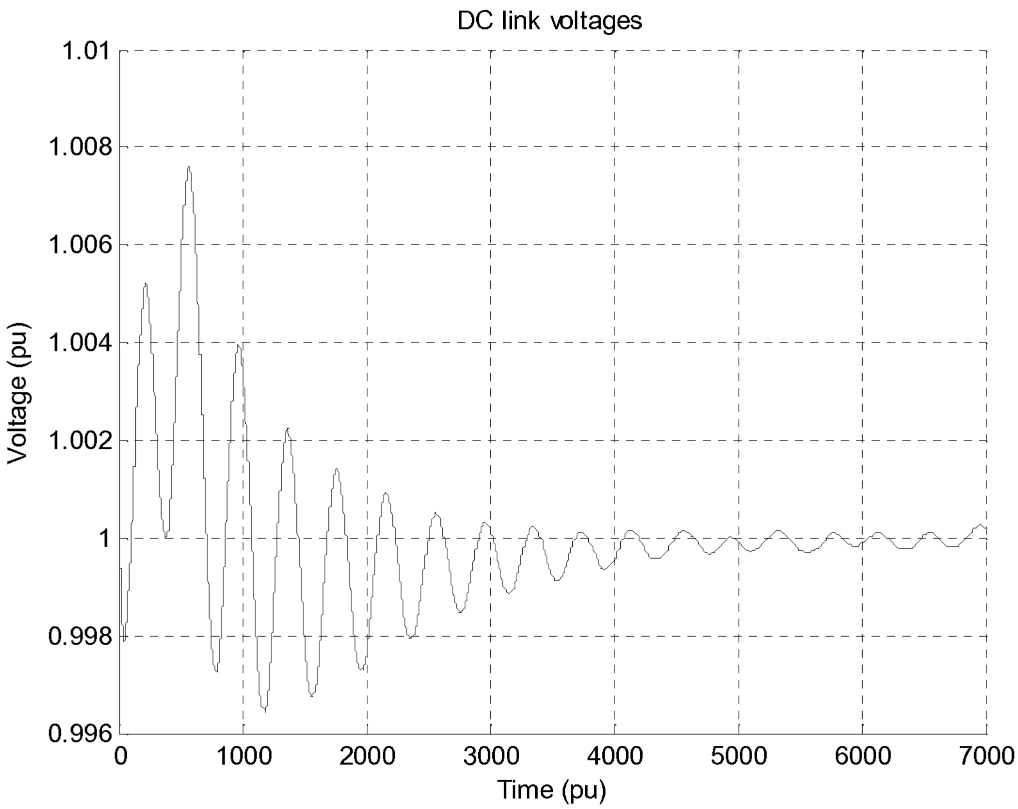
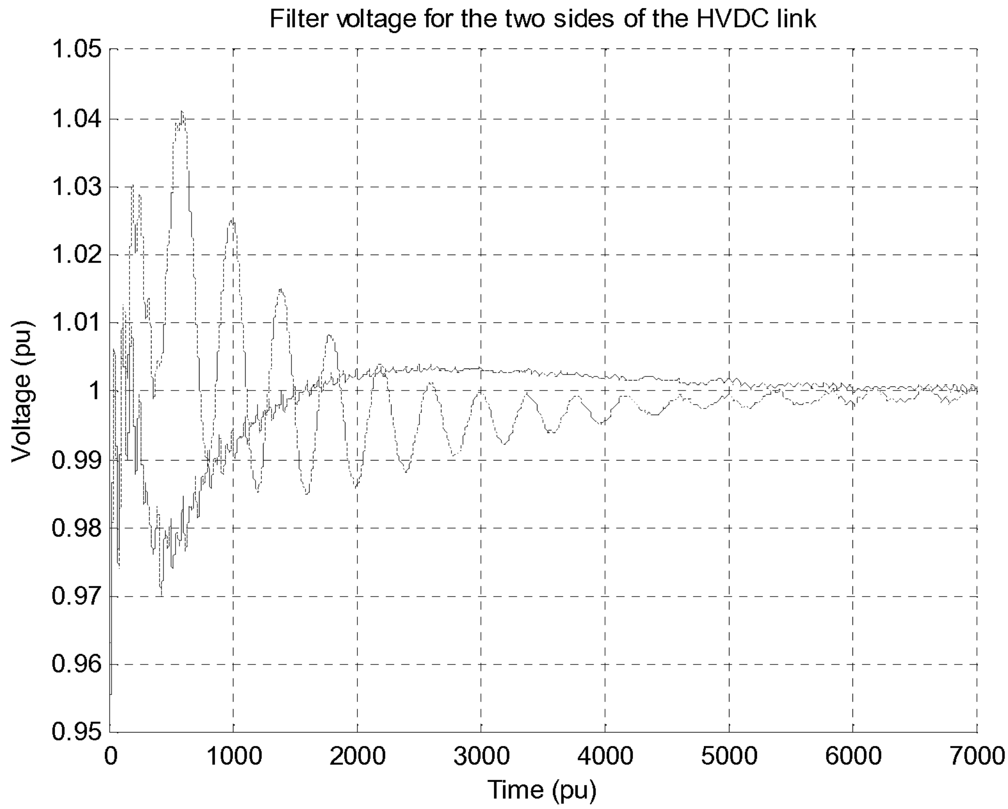

DC link voltages
Voltage (pu)
1.01
1.008
1.006
1.004
1.002
1
0.998
0.996
0
1000
2000
3000
4000
5000
6000
7000
Time (pu)

Fig. 5


Filter voltage for the two sides of the HVDC link
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
Voltage (pu)
0
1000
2000
3000
4000
5000
6000
7000
Time (pu)

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2009/067656

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 practical, 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.
X	XIAOYAN WEN ET AL: "Dynamic Model and Predictive Current Control of Voltage Source Converter Based HVDC" POWER SYSTEM TECHNOLOGY, 2006. POWERCON 2006. INTERNATIONAL CONFERENCE ON, IEEE, PI, 1 October 2006 (2006-10-01), pages 1-5, XP031053573 ISBN: 978-1-4244-0110-9 the whole document ----- -/--	1-5

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

[X] 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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
6 April 2010	16/04/2010

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	Zeng, Wenyan

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2009/067656

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CORREA P ET AL: "Predictive control of an indirect matrix converter" INDUSTRIAL ELECTRONICS, 2008. IECON 2008. 34TH ANNUAL CONFERENCE OF IEEE, IEEE, PISCATAWAY, NJ, USA, 10 November 2008 (2008-11-10), pages 1332-1336, XP031410635 ISBN: 978-1-4244-1767-4 page 1333, left-hand column, paragraph III - page 1334, right-hand column; figures 2,3	1-5
X,P	CORREA P ET AL: "Predictive Control of an Indirect Matrix Converter" IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, IEEE SERVICE CENTER, PISCATAWAY, NJ, USA, vol. 56, no. 6, 1 June 2009 (2009-06-01), pages 1847-1853, XP011250735 ISSN: 0278-0046 page 1848 - page 1850; figures 2,3	1-5
A,P	SÃ Â BASTIEN MARIETHOZ ET AL: "Explicit Model-Predictive Control of a PWM Inverter With an LCL Filter" IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, IEEE SERVICE CENTER, PISCATAWAY, NJ, USA LNKD- DOI:10.1109/TIE.2008.2008793, vol. 56, no. 2, 1 February 2009 (2009-02-01), pages 389-399, XP011237611 ISSN: 0278-0046 page 389 - page 393	1-5
A,P	WO 2009/016113 A1 (ABB RESEARCH LTD [CH]; PAPAFOTIOU GEORGIOS [CH]; HARNEFORS LENNART [SE) 5 February 2009 (2009-02-05) the whole document	1-5

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2009/067656

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2009016113 A1	05-02-2009	NONE	