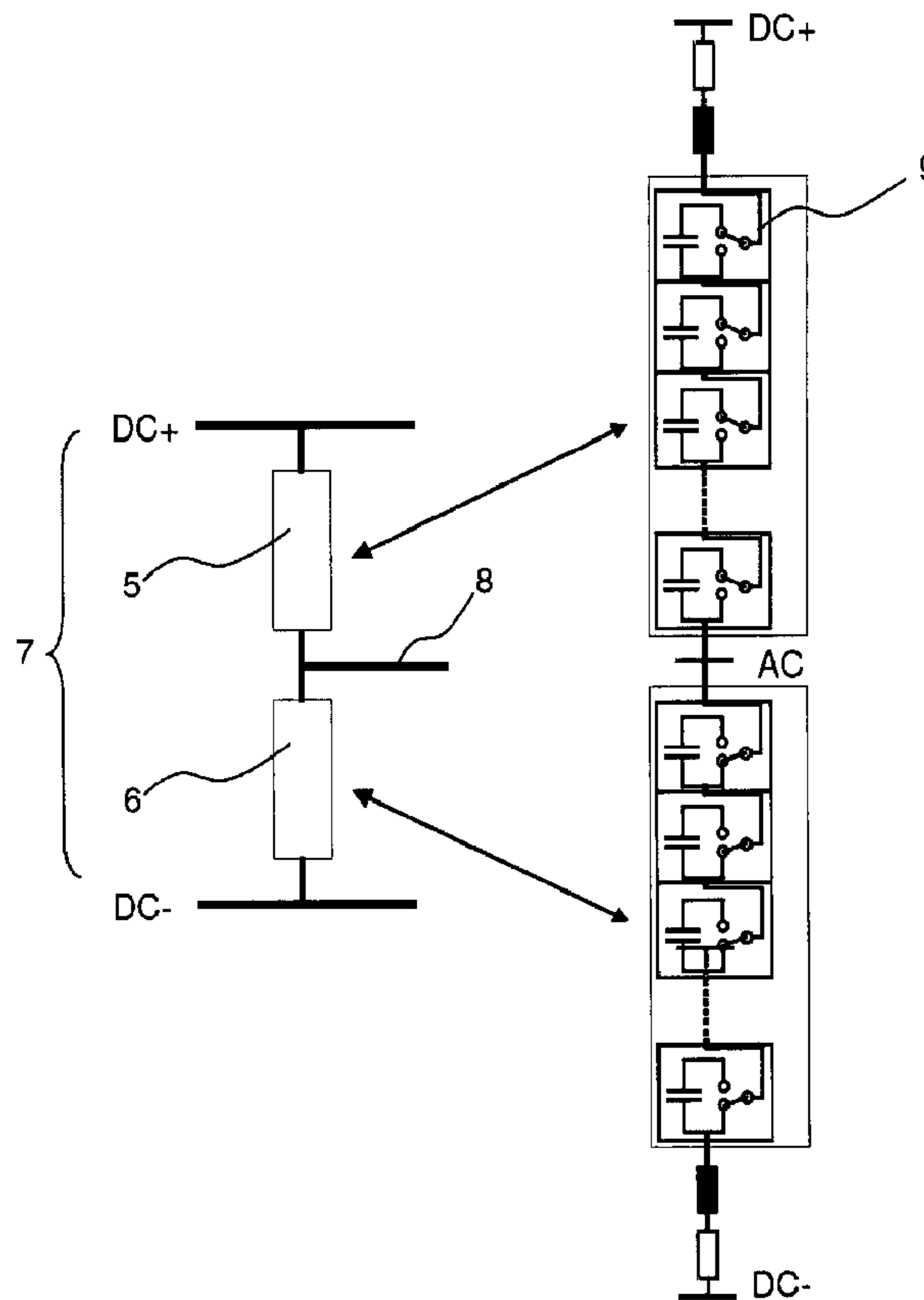




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(72) **Inventeur/Inventor:**
ANGQUIST, LENNART, SE
(73) **Propriétaire/Owner:**
ABB SCHWEIZ AG, CH
(74) **Agent:** GOWLING WLG (CANADA) LLP

(54) **Titre : PROCEDE ET APPAREIL DESTINES A CALCULER DES INDICES D'INSERTION POUR UN CONVERTISSEUR
MODULAIRE A NIVEAUX MULTIPLES**
(54) **Title: A METHOD AND APPARATUS FOR CALCULATING INSERTION INDECS FOR A MODULAR MULTILEVEL CONVERTER**



(57) **Abrégé/Abstract:**

It is presented a method for calculating insertion indices for a phase leg of a DC to AC modular multilevel converter. Each phase leg comprises two serially connected arms, wherein each arm comprises a number of submodules, wherein each submodule can be

(57) Abrégé(suite)/Abstract(continued):

in a bypass state or a voltage insert mode. The insertion index comprises data representing the portion of available submodules that should be in the voltage insert mode. The method comprises the steps of : calculating a desired arm voltage for an upper arm connected to the upper DC source common bar and a lower arm connected to the lower DC source common bar, obtaining values representing actual total arm voltages in the upper arm and lower arm, respectively, and calculating modulation indices for the upper and lower arm, respectively, using the respective desired arm voltage and the respective value representing the total actual arm voltage. A corresponding apparatus is also presented.

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(71) Applicant (for all designated States except US): **ABB TECHNOLOGY AG** [CH/CH]; Affolternstrasse 44, CH-8050 Zürich (CH).

(72) Inventor; and

(75) Inventor/Applicant (for US only): **ÄNGQUIST, Lennart** [SE/SE]; Åsundavägen 26, S-745 71 Enköping (SE).(74) Agent: **AHRENGART, Kenneth**; ABB AB, Intellectual Property, Ingenjör Bååths gata 11, Mimer T2, Floor E, S-721 83 Västerås (SE).

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(54) Title: A METHOD AND APPARATUS FOR CALCULATING INSERTION INDICES FOR A MODULAR MULTI-LEVEL CONVERTER

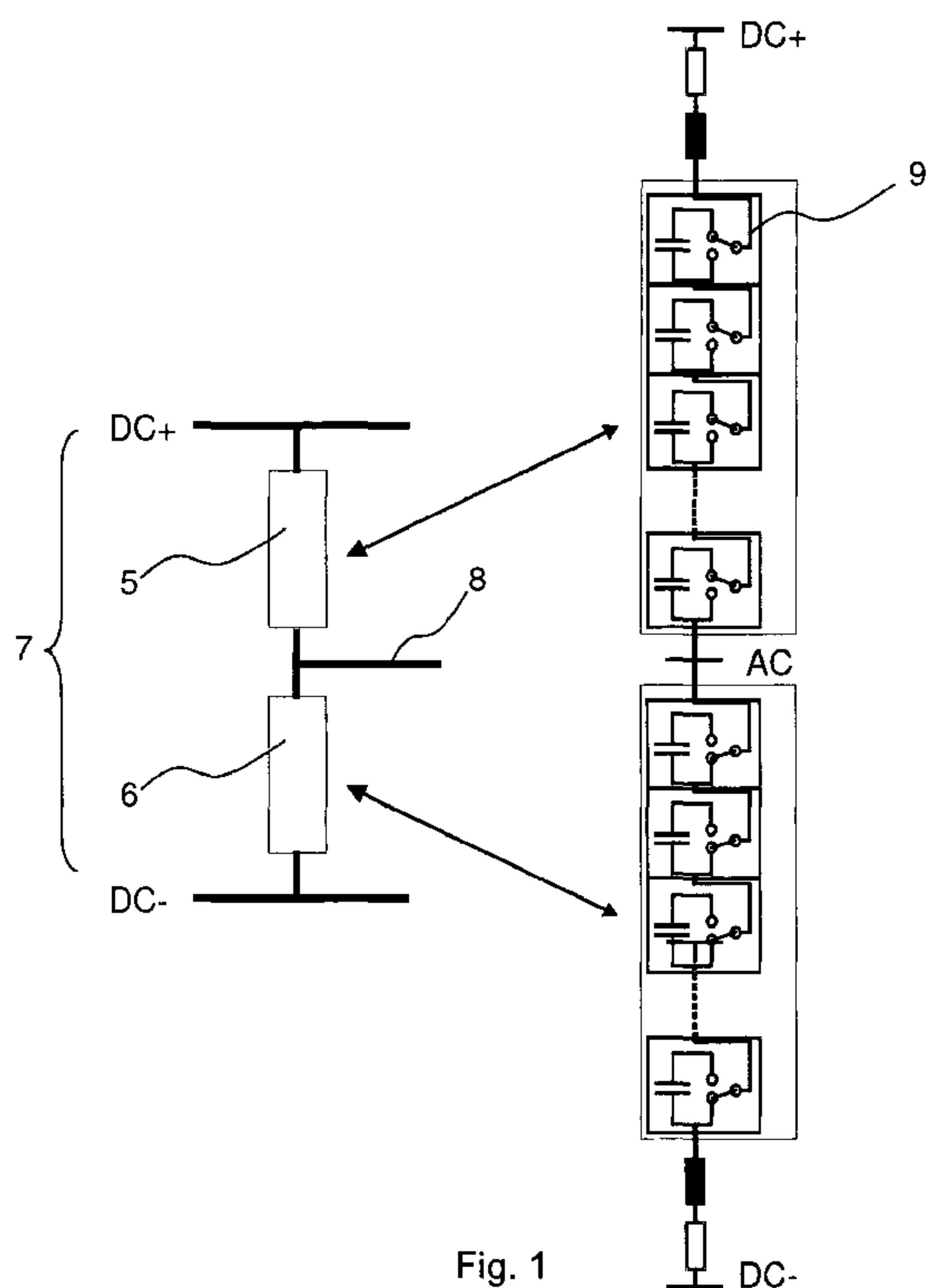


Fig. 1

(57) Abstract: It is presented a method for calculating insertion indices for a phase leg of a DC to AC modular multilevel converter. Each phase leg comprises two serially connected arms, wherein each arm comprises a number of submodules, wherein each submodule can be in a bypass state or a voltage insert mode. The insertion index comprises data representing the portion of available submodules that should be in the voltage insert mode. The method comprises the steps of: calculating a desired arm voltage for an upper arm connected to the upper DC source common bar and a lower arm connected to the lower DC source common bar, obtaining values representing actual total arm voltages in the upper arm and lower arm, respectively, and calculating modulation indices for the upper and lower arm, respectively, using the respective desired arm voltage and the respective value representing the total actual arm voltage. A corresponding apparatus is also presented.

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**A METHOD AND APPARATUS FOR CALCULATING INSERTION INDECES
FOR A MODULAR MULTILEVEL CONVERTER**

TECHNICAL FIELD

The invention relates to the calculation of insertion
5 indices comprising data representing the portion of
available submodules of a modular multilevel converter
that should be in voltage insert mode.

BACKGROUND

The concept Modular Multilevel Converter (M2C) denotes a
10 class of Voltage Source Converter (VSC). It has one or
several phase legs connected in parallel between two DC
bars, a positive DC+ and a negative DC-. Each phase leg
consists of two series-connected converter arms. The
connection point between the converter arms constitutes
15 an AC terminal for the leg.

Each arm consists of a number (N) of submodules. Each
submodule has two terminals. Using these terminals the
submodules in each arm are series-connected so that they
form a string. The end terminals of the string constitute
20 the connection terminals of the arm. By controlling
individual modules in each arm, a voltage corresponding
to the accumulation of insertion voltages can be provided
on the AC terminal.

Such a converter is known from DE10103031. In this
25 document, a method to equalize the voltages in the
submodule capacitors within the arm is briefly described.
For each arm, a modulator determines when the number of
inserted submodules shall change. The principle for
equalizing is that, at each instant when a change of the
30 number of inserted submodules is commanded, a selection

mechanism chooses the submodule to be inserted or bypassed depending on the actual current direction in the arm (charging or discharging) and the corresponding available submodules in the arm (bypassed highest voltage/bypassed lowest voltage/inserted highest voltage/inserted lowest voltage). Such a selection mechanism aims to achieve that the DC voltage across the DC capacitors in the submodules are equal, $u_{c,sm}(t)$.

A problem with the prior art is the presence of a circulation current going through the legs between the DC terminals.

SUMMARY

An object of the invention is to reduce circulation currents going through the legs between the DC terminals.

15 In accordance with an aspect of the present invention there is provided a method for calculating insertion indices for a phase leg of a DC to AC modular multilevel converter, the converter via a control apparatus, said control apparatus having at least one controller, comprising one
20 phase leg between upper and lower DC source common bars for each phase, each phase leg comprising two serially connected arms, wherein an AC output for each phase leg is connected between the two serially connected arms, wherein each arm comprises a number of submodules, wherein each
25 submodule can be in a bypass state or a voltage insert mode, the insertion index comprising data representing a portion of available submodules that should be in the voltage insert mode for a particular arm, the method comprising the steps of: calculating, in said controller,
30 a desired arm voltage $u_{cu}(t)$ for an upper arm connected to the upper DC source common bar and a desired arm voltage

$u_{CL}(t)$ for a lower arm connected to the lower DC source common bar, obtaining, in said controller, values representing actual total arm voltages $u_{CU}^{\Sigma}(t)$ and $u_{CL}^{\Sigma}(t)$ in the upper arm and lower arm, respectively, by measuring
 5 the sum of capacitor voltages in each arm using sensors in the submodules, and calculating, in said controller, the insertion indices $n_U(t)$ and $n_L(t)$ for the upper and lower arm, respectively, using the respective desired arm voltage and the respective value representing the total
 10 actual arm voltage, as

$$n_U(t) = \frac{u_{CU}(t)}{u_{CU}^{\Sigma}(t)} \quad n_L(t) = \frac{u_{CL}(t)}{u_{CL}^{\Sigma}(t)};$$

wherein the step of calculating desired arm voltages for a phase leg comprises calculating

$$u_{CU}(t) = u_D/2 - e_v(t) - u_{diff}(t)$$

15 for the upper arm, and calculating

$$u_{CL}(t) = u_D/2 + e_v(t) - u_{diff}(t)$$

for the lower arm, where $u_{CU}(t)$ represents desired upper arm voltage where $u_{CL}(t)$ represents desired lower arm voltage, u_D represents a voltage between the upper and
 20 lower DC source common bars, $e_v(t)$ represents a reference inner AC output voltage and $u_{diff}(t)$ represents a control voltage to control a current passing through the whole phase leg, and calculating

$$u_{diff}(t) = u_{diff1}(t) + u_{diff2}(t)$$

25 where $u_{diff1}(t)$ represents a voltage obtained by summing energy in the arms of the leg and $u_{diff2}(t)$ represents a

voltage obtained by calculating a difference in energy between the arms of the leg.

The step of obtaining a value representing actual arm voltage may comprise calculating

$$5 \quad u_{diff2}(t) = \hat{u}_{diff2} \cos(\omega_1 t + \psi)$$

where $\hat{u}_{diff2}$ represents an error between total upper arm energy and total lower arm energy, ω_1 represents the angular velocity of the network frequency and ψ represents the angle given by $\psi = \angle(R + j\omega_1 L)$ where R
 10 represents the resistance of the converter arm and L represents the inductance of the converter arm.

The step of obtaining values representing actual arm voltages may comprise: calculating $u_{cu}^\Sigma(t)$, actual voltage for the upper arm, using C_{arm} , capacitance for the arm,
 15 $\hat{i}_{diff0}$, DC current passing through the two serially connected arms of the phase leg, $W_{cu}^\Sigma(t)$, desired average energy in the upper arm, $\hat{e}_v$, amplitude of reference for the inner AC output voltage, $\hat{i}_v$, amplitude of AC output current, ϕ , a phase difference between $i_v(t)$ and $e_v(t)$,
 20 DC current circulating through the two series-connected arms, and calculating $u_{cl}^\Sigma(t)$, actual voltage for the lower arm, using C_{arm} , capacitance for the arm, $\hat{i}_{diff0}$, DC current passing through the two serially connected arms of the phase leg, $W_{cl}^\Sigma(t)$, desired average energy in the
 25 lower arm, $\hat{e}_v$, amplitude of reference for inner AC output voltage, $\hat{i}_v$, amplitude of AC output current ϕ , a phase difference between $i_v(t)$ and $e_v(t)$, $\hat{i}_{diff0}$, DC current circulating through the two series-connected arms.

The step of obtaining a value representing actual arm voltage may comprise calculating

$$\hat{i}_{\text{diff0}} = \frac{\hat{e}_v \hat{i}_v \cos \varphi}{u_D + \sqrt{u_D^2 - 4 R \hat{e}_v \hat{i}_v \cos \varphi}}$$

where φ represents a phase difference between $i_v(t)$ and $e_v(t)$, u_D represents a voltage between the upper and lower DC source common bars and R represents the resistance of the converter arm.

The step of obtaining a value representing actual arm voltage may comprise calculating

$$10 \quad u_{cu}^{\Sigma}(t) = \sqrt{\frac{2W_{cu}^{\Sigma}(t)}{C_{\text{arm}}}}$$

where $W_{cu}^{\Sigma}(t)$ represents instantaneous energy in the upper arm and is calculated as follows:

$$\begin{aligned} W_{cu}^{\Sigma}(t) = & W_{cu0}^{\Sigma} - \frac{\hat{e}_v \hat{i}_{\text{diff0}}}{\omega_1} \sin \omega_1 t + \\ & \left(\frac{u_F}{2} - R \hat{i}_{\text{diff0}} \right) \frac{\hat{i}_v}{2\omega_1} \sin(\omega_1 t + \varphi) - \frac{\hat{e}_v \hat{i}_v}{8\omega_1} \sin(2\omega_1 t + \varphi) \end{aligned}$$

and calculating

$$15 \quad u_{cl}^{\Sigma}(t) = \sqrt{\frac{2W_{cl}^{\Sigma}(t)}{C_{\text{arm}}}}$$

where $W_{cl}^{\Sigma}(t)$ represents instantaneous energy in the lower arm and is calculated as follows:

$$W_{CL}^{\Sigma}(t) = W_{CL0}^{\Sigma} + \frac{\hat{e}_v \hat{i}_{diff0}}{\omega_1} \sin \omega_1 t -$$

$$\left(\frac{u_D}{2} - R \hat{i}_{diff0} \right) \frac{\hat{i}_v}{2\omega_1} \sin(\omega_1 t + \varphi) - \frac{\hat{e}_v \hat{i}_v}{8\omega_1} \sin(2\omega_1 t + \varphi)$$

where ω_1 represents the angular velocity of the network frequency, u_D represents a voltage between the upper and lower DC source common bars, R represents the resistance
 5 of the converter arm.

The step of obtaining a value representing actual arm voltage may comprise measuring voltages of the submodules of the arm and summing these measured voltages.

The insertion index may comprise data representing a
 10 direction of the inserted voltage.

In accordance with another aspect of the present invention there is provided A method for calculating insertion indices for a phase leg of a DC to AC modular multilevel converter, via a control apparatus, said
 15 control apparatus having at least one controller, the converter comprising one phase leg between upper and lower DC source common bars for each phase, each phase leg comprising two serially connected arms, wherein an AC output for each phase leg is connected between the two
 20 serially connected arms, wherein each arm comprises a number of submodules, wherein each submodule can be in a bypass state or a voltage insert mode, the insertion index comprising data representing a portion of available submodules that should be in the voltage insert mode for
 25 a particular arm, the method comprising the steps of: calculating, in said controller, a desired arm voltage $u_{cu}(t)$ for an upper arm connected to the upper DC source

common bar and a desired arm voltage $u_{CL}(t)$ for a lower arm connected to the lower DC source common bar, obtaining, in said controller, values representing actual total arm voltages $u_{CU}^{\Sigma}(t)$ and $u_{CL}^{\Sigma}(t)$ in the upper arm and
 5 lower arm, respectively, and calculating, in said controller, the insertion indices $n_U(t)$ and $n_L(t)$ for the upper and lower arm, respectively, using the respective desired arm voltage and the respective value representing the total actual arm voltage, as

$$10 \quad n_U(t) = \frac{u_{CU}(t)}{u_{CU}^{\Sigma}(t)} \quad n_L(t) = \frac{u_{CL}(t)}{u_{CL}^{\Sigma}(t)};$$

wherein the step of calculating desired arm voltages for a phase leg comprises calculating

$$u_{CU}(t) = u_D/2 - e_v(t) - u_{diff}(t)$$

for the upper arm, and calculating

$$15 \quad u_{CL}(t) = u_D/2 + e_v(t) - u_{diff}(t)$$

for the lower arm, where $u_{CU}(t)$ represents desired upper arm voltage where $u_{CL}(t)$ represents desired lower arm voltage, u_D represents a voltage between the upper and lower DC source common bars, $e_v(t)$ represents a reference
 20 inner AC output voltage and $u_{diff}(t)$ represents a control voltage to control a current passing through the whole phase leg, wherein the step of obtaining values representing actual arm voltages comprises: calculating $u_{CU}^{\Sigma}(t)$, actual total voltage for the upper arm, using C_{arm} ,
 25 capacitance for the arm, i_{diff0} , DC current passing through the two serially connected arms of the phase leg, $W_{CU}^{\Sigma}(t)$, desired average energy in the upper arm, $\hat{e}_v$, amplitude of reference for the inner AC output voltage, $\hat{i}_v$, amplitude

of AC output current, ϕ , a phase difference between $i_v(t)$ and $e_v(t)$, DC current circulating through the two series-connected arms, and calculating $u_{CL}^\Sigma(t)$, actual total voltage for the lower arm, using C_{arm} , capacitance for the arm, $\hat{i}_{diff0}$, DC current
 5 passing through the two serially connected arms of the phase leg, $W_{CL}^\Sigma(t)$, desired average energy in the lower arm, $\hat{e}_v$, amplitude of reference for inner AC output voltage, $\hat{i}_v$, amplitude of AC output current ϕ , a phase difference between $i_v(t)$ and $e_v(t)$, $\hat{i}_{diff0}$, DC current circulating through the two series-connected
 10 arms.

In a further aspect of the present invention there is provided An apparatus for calculating insertion indices for a phase leg of a DC to AC modular multilevel converter, the converter comprising one phase leg between upper and lower DC source common
 15 bars for each phase, each phase leg comprising two serially connected arms, wherein an AC output for each phase leg is connected between the two serially connected arms, wherein each arm comprises a number of submodules, wherein each submodule can be in a bypass state or a voltage insert mode, the insertion
 20 index comprising data representing a portion of available submodules that should be in the voltage insert mode for a particular arm, the apparatus comprises:

a controller arranged to calculate a desired arm voltage $u_{CU}(t)$ for an upper arm connected to the upper DC source common bar and
 25 a desired arm voltage $u_{CL}(t)$ for a lower arm connected to the lower DC source common bar, to obtain values representing actual total arm voltages $u_{CU}^\Sigma(t)$ and $u_{CL}^\Sigma(t)$ in the upper arm and lower arm, respectively, by measuring the sum of capacitor voltages in each arm using sensors in the submodules, and to

calculate the insertion indices $n_U(t)$ and $n_L(t)$ for the upper and lower arm, respectively, using the respective desired arm voltage and the respective value representing the total actual arm voltage, as

$$5 \quad n_U(t) = \frac{u_{CU}(t)}{u_{CU}^*(t)} \quad n_L(t) = \frac{u_{CL}(t)}{u_{CL}^*(t)};$$

wherein the calculating of desired arm voltages for a phase leg comprises calculating

$$u_{CU}(t) = u_D/2 - e_v(t) - u_{diff}(t)$$

for the upper arm, and calculating

$$10 \quad u_{CL}(t) = u_D/2 + e_v(t) - u_{diff}(t)$$

for the lower arm, where $u_{CU}(t)$ represents desired upper arm voltage, $u_{CL}(t)$ represents desired lower arm voltage, u_D represents a voltage between the upper and lower DC source common bars, $e_v(t)$ represents a reference inner AC
 15 output voltage and $u_{diff}(t)$ represents a control voltage to control a current passing through the whole phase leg, and calculating

$$u_{diff}(t) = u_{diff1}(t) + u_{diff2}(t)$$

where $u_{diff1}(t)$ represents a voltage obtained by summing
 20 energy in the arms of the leg and $u_{diff2}(t)$ represents a voltage obtained by calculating a difference in energy between the arms of the leg.

In accordance with another aspect of the present invention there is provided An apparatus for calculating insertion
 25 indices for a phase leg of a DC to AC modular multilevel converter, the converter comprising one phase leg between upper and lower DC source common bars for each phase, each

phase leg comprising two serially connected arms, wherein an AC output for each phase leg is connected between the two serially connected arms, wherein each arm comprises a number of submodules, wherein each submodule can be in a
 5 bypass state or a voltage insert mode, the insertion index comprising data representing a portion of available submodules that should be in the voltage insert mode for a particular arm, the apparatus comprises: a controller arranged to calculate a desired arm voltage $u_{CU}(t)$ for an
 10 upper arm connected to the upper DC source common bar and a desired arm voltage $u_{CL}(t)$ for a lower arm connected to the lower DC source common bar, to obtain values representing actual total arm voltages $u_{CU}^{\Sigma}(t)$ and $u_{CL}^{\Sigma}(t)$ in the upper arm and lower arm, respectively, and to calculate
 15 insertion indices for the upper and lower arm, respectively, using the respective desired arm voltage and the respective value representing the total actual arm voltage, as

$$n_U(t) = \frac{u_{CU}(t)}{u_{CU}^{\Sigma}(t)} \quad n_L(t) = \frac{u_{CL}(t)}{u_{CL}^{\Sigma}(t)};$$

20 wherein the calculating of desired arm voltages for a phase leg comprises calculating

$$u_{CU}(t) = u_D/2 - e_v(t) - u_{diff}(t)$$

for the upper arm, and calculating

$$u_{CL}(t) = u_D/2 + e_v(t) - u_{diff}(t)$$

25 for the lower arm, where $u_{CU}(t)$ represents desired upper arm voltage, $u_{CL}(t)$ represents desired lower arm voltage, u_D represents a voltage between the upper and lower DC source common bars, $e_v(t)$ represents a reference inner AC

output voltage and $u_{diff}(t)$ represents a control voltage to control a current passing through the whole phase leg, wherein the step of obtaining values representing actual

5 arm voltages comprises: calculating $u_{cu}^{\Sigma}(t)$, actual total voltage for the upper arm, using C_{arm} , capacitance for the arm, i_{diff0} , DC current passing through the two serially connected arms of the phase leg, $W_{cu}^{\Sigma}(t)$, desired average energy in the upper arm, $\hat{e}_v$, amplitude of reference for

10 the inner AC output voltage, $\hat{i}_v$, amplitude of AC output current, ϕ , a phase difference between $i_v(t)$ and $e_v(t)$, DC current circulating through the two series-connected arms, and calculating $u_{cl}^{\Sigma}(t)$, actual total voltage for the lower arm, using C_{arm} , capacitance for the arm, i_{diff0} , DC current

15 passing through the two serially connected arms of the phase leg, $W_{cl}^{\Sigma}(t)$, desired average energy in the lower arm, $\hat{e}_v$, amplitude of reference for inner AC output voltage, $\hat{i}_v$, amplitude of AC output current ϕ , a phase difference between $i_v(t)$ and $e_v(t)$, i_{diff0} , DC current circulating

20 through the two series-connected arms.

Generally, all terms used in the application are to be interpreted according to their ordinary meaning in the technical field, unless explicitly defined otherwise herein. All references to "a/an/the element, apparatus,

25 component, means, step, etc." are to be interpreted

openly as referring to at least one instance of the element, apparatus, component, means, step, etc., unless explicitly stated otherwise. The steps of any method disclosed herein do not have to be performed in the exact
5 order disclosed, unless explicitly stated.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is now described, by way of example, with reference to the accompanying drawings, in which:

Fig 1 is a schematic diagram of phase legs and arms,

10 Fig 2 is a schematic circuit model of a phase leg of Fig 1,

Fig 3 is a Nichols plot for an open loop transfer function,

15 Fig 4 is a Nichols plot for an open loop transfer function when a PID controller is used,

Fig 5 is a Nichols plot for an open loop transfer function when a PID controller, time delay and notch filter is used,

20 Fig 6 is a graph showing a simulation result at a step in the reference for the total energy in the converter leg,

Fig 7 is a graph showing the simulation result when the current changes from 0.1 pu to 1.0 pu in the converter leg,

25 Fig 8 shows a Nichols plot for a balance controller according to another embodiment.

DETAILED DESCRIPTION

The invention will now be described more fully hereinafter with reference to the accompanying drawings, in which certain embodiments of the invention are shown.

5 This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided by way of example so that this disclosure will be thorough and complete, and will fully
10 convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout the description.

In the description in the following, continuous variables are used, corresponding to the simplifying assumption
15 that the arms have infinite number of submodules that are switched with infinite switching frequency.

Fig 1 shows an M2C (Modular Multilevel Converter) having a phase leg 7 that comprising an upper arm 5 and a lower arm 6. Each arm 5, 6 comprising a number of serially
20 connected submodules 9. Each submodule 9 comprises a switchable capacitor. An AC output 8 is connected between the upper and lower arms 5, 6. Although only one phase leg 7 is shown here, the M2C comprises one phase leg 7 for each phase, i.e. three phase legs 7 for a three phase
25 system, where each phase leg 7 comprises upper and lower arms 5, 6 comprising submodules 9.

An upper DC source common bar (in this case DC+) and a lower DC source common bar (in this case DC-) for each phase is provided. It is to be noted that the upper and
30 lower DC source common bars can switch polarity.

Ideally the capacitors keep a constant DC voltage and the AC terminal voltage is controlled by varying the number of inserted modules in the upper and lower arms. If the voltage between the DC bars is constant this obviously
 5 requires that, in average, the total number of inserted modules in the two arms remain constant. The arm inductors however will limit the rate of change of the arm currents, making it possible to accept minor short deviations from this condition.

10 Now once the context is presented, define the insertion index, $n_x(t)$, for the arm x to be the ratio between the inserted number of submodules and the total number of available submodules in the arm. The arm voltage then becomes

15 (1) $u_{Cx}(t) = n_x(t) u_{C,SM}(t)$

In a simple approach the number of inserted modules in each arm can be generated by the modulator much in the same way as in PWM modulation for conventional VSCs. Then, in order to generate an inner AC voltage with
 20 amplitude $\hat{e}_v$ the insertion indices for the upper and the lower arms become

$$\begin{aligned} u_{CU}(t) &= n_U(t) u_D & u_{CL}(t) &= n_L(t) u_D \\ n_U(t) &= \frac{1 - \hat{m} \cos \omega t}{2} & n_L(t) &= \frac{1 + \hat{m} \cos \omega t}{2} \\ \hat{m} &= \frac{\hat{e}_v}{\frac{u_D}{2}} \end{aligned}$$

(2)

When the simple modulation approached described above is used and the converter is loaded on its AC side the
 25 desired waveform will be distorted due to the ripple in the capacitor voltages that will be created when the load

current passes through the converter arms. Specifically a strong second harmonic current will circulate through the converter leg and the DC side and/or the neighbor phases. This undesired second harmonic current increases the peak
 5 of the arms currents and causes extra losses in the converter arms.

The problem can be solved by generating the insertion indices for the arms, n_U and n_L , in other ways. Such methods would aim to:

- 10 • eliminate and/or control the harmonic current in the converter arms
- for each arm control the total energy stored in all capacitors in that arm which is equivalent to control the total voltage of all capacitors in the arm
- 15 • thereby control the total energy stored in the phase leg as well as the balance between the upper and the lower arms in the phase leg

According to the invention the insertion indices $n_U(t)$ and $n_L(t)$ for the converter arms are being derived in
 20 real-time according to the following procedure

- the reference for the converter inner voltage relative the midpoint of the DC link is given in the form $e_v(t) = \hat{e}_v \cos \omega_1 t$; this reference typically is delivered by an AC side controller operating on AC quantities like output
 25 voltage, current or flux; the converter circuit parameters like arm resistance and inductance may be used by the controller
- the desired arm voltages $u_{CU}(t)$ and $u_{CL}(t)$ are calculated as

$$(3) \quad u_{CU}(t) = \frac{u_D}{2} - e_V(t) - u_{diff}(t) \quad u_{CL}(t) = \frac{u_D}{2} + e_V(t) - u_{diff}(t)$$

where u_D is the voltage between the DC rails and $u_{diff}(t)$ is a control voltage that is created by the control system that will be described later in the this memo

- 5 • the total capacitor voltages, $u_{CU}^\Sigma(t)$ and $u_{CL}^\Sigma(t)$, of all capacitors in the upper and lower arms respectively, are measured or estimated as will be described later in this memo

- the insertion indices are calculated as

$$10 \quad (4) \quad n_U(t) = \frac{u_{CU}(t)}{u_{CU}^\Sigma(t)} \quad n_L(t) = \frac{u_{CL}(t)}{u_{CL}^\Sigma(t)}$$

According to the invention there are two different ways to create the variables $u_{diff}(t)$, $u_{CU}^\Sigma(t)$ and $u_{CL}^\Sigma(t)$.

First approach, feedback control

15 In this approach the sum of the capacitor voltages in each arm, $u_{CU}^\Sigma(t)$ and $u_{CL}^\Sigma(t)$, are measured using sensors in the submodules. If the voltage sharing between the modules is assumed to be even the total energies in each arm can be calculated as

$$(5) \quad W_{CU}^\Sigma(t) = \frac{C_{arm}}{2} u_{CU}^\Sigma(t)^2 \quad W_{CL}^\Sigma(t) = \frac{C_{arm}}{2} u_{CL}^\Sigma(t)^2$$

20 where $C_{arm} = C_{submod}/N$. Alternatively the energy in each arm capacitor can be calculated individually and the total energy for each arm then can be created by summing the energies in all submodules in each arm. The voltage reference component $u_{diff}(t)$ is created as the sum of the

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output signals from two independent controllers

$$u_{diff}(t) = u_{diff1}(t) + u_{diff2}(t).$$

The first controller has a reference for the total energy in both arms of the phase leg. The response signal is the
 5 measured total energy $W_{Cu}^2(t) + W_{Cd}^2(t)$, which may be filtered using e.g. a notch filter tuned to the frequency $2\omega_1$ (ω_1 is the network frequency) or any other filter suppressing the same frequency. The error, i.e. the difference
 10 between the reference and the response signals, is connected to a controller (normally of type PID) that has the output signal $u_{diff1}(t)$.

The second controller has a reference for the difference between the energies in the arms in the phase leg. This reference typically is zero, meaning that the energy in
 15 the arms in the phase leg shall be balanced. The response signal is created as the measured $W_{Cu}^2(t) - W_{Cd}^2(t)$, filtered by a notch filter tuned to ω_1 or any other filter suppressing the same frequency. The error is brought to a controller (typically of P type), which has an output
 20 signal $\hat{u}_{diff2}$. The contribution to the total voltage reference $u_{diff}(t)$ is obtained by multiplying $\hat{u}_{diff2}$ by a sinusoidal time function $\cos(\omega_1 t + \psi)$, which is phase-shifted relative the inner voltage reference by the angle ψ given by $\psi = \angle(R + j\omega_1 L)$, where R and L are the
 25 resistance and inductance respectively in the converter arm. Thus:

$$(6) \quad u_{diff}(t) = u_{ref}(t) + \hat{u}_{diff2} \cos(\omega_1 t + \psi)$$

The first approach to stabilisation of the converter according to the procedure described in this section is
 30 described in more detail in Appendix 1.

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Remark 1: The reference for the AC side inner voltage may comprise a minor third harmonic voltage component, which is used to increase the available output voltage level in a 3-phase converter. This does not impact significantly
5 on the behaviour described.

Remark 2: A third reference component may be added to the control voltage $u_{diff}(t)$. This component has the purpose of intentionally creating a second harmonic current in the arms in order to increase the available output
10 voltage for loads with certain power factors.

Second approach, open-loop control

In this approach the AC side current $i_v(t)$ is measured. Its fundamental frequency component is extracted with amplitude and phase relative the reference inner voltage
15 $e_v(t)$ for the converter. Thus the AC side current can be written as

$$(7) \quad i_v(t) = \hat{i}_v \cos(\omega_1 t + \varphi)$$

Assuming that the converter shall operate ideally in steady-state, i.e. it shall produce undisturbed AC output
20 voltage and the upper and lower arms shall carry half the AC output current each, it is possible to calculate the ideal derivative of the energies in each arm. The result is

$$(8) \quad \frac{dW_{CU}^*}{dt} = -\hat{e}_v \hat{i}_{avg} \cos \omega_1 t + \left(\frac{\mu_D}{2} - R \hat{i}_{avg} \right) \frac{\hat{i}_v}{2} \cos(\omega_1 t + \varphi) - \frac{\hat{e}_v \hat{i}_v}{4} \cos(2\omega_1 t + \varphi)$$

$$25 \quad (9) \quad \frac{dW_{CL}^*}{dt} = +\hat{e}_v \hat{i}_{avg} \cos \omega_1 t - \left(\frac{\mu_D}{2} - R \hat{i}_{avg} \right) \frac{\hat{i}_v}{2} \cos(\omega_1 t + \varphi) - \frac{\hat{e}_v \hat{i}_v}{4} \cos(2\omega_1 t + \varphi)$$

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where $\hat{i}_{diff0}$ is a DC current circulating through the two series-connected arms and the DC supply

$$(10) \quad \hat{i}_{diff0} = \frac{\hat{e}_r \hat{i}_r \cos \varphi}{u_D + \sqrt{u_D^2 - 4 R \hat{e}_r \hat{i}_r \cos \varphi}}$$

When there is only a DC circulating current $\hat{i}_{diff0}$ then also
 5 the control voltage $u_{diff}(t)$ becomes a DC voltage with the value $u_{diff}(t) = R \hat{i}_{diff0}$ so that (3) becomes

$$(11) \quad u_{cu}(t) = \frac{u_D}{2} - e_r(t) - R \hat{i}_{diff0} \quad u_{cl}(t) = \frac{u_D}{2} + e_r(t) - R \hat{i}_{diff0}$$

Moreover, equations (8) and (9) can be integrated, each with a freely selected integration constant, so that

$$10 \quad (12) \quad W_{cu}^x(t) = W_{cu}^x - \frac{\hat{e}_r \hat{i}_{diff0}}{\omega_1} \sin \omega_1 t + \left(\frac{u_D}{2} - R \hat{i}_{diff0} \right) \frac{\hat{i}_r}{2 \omega_1} \sin(\omega_1 t + \varphi) - \frac{\hat{e}_r \hat{i}_r}{8 \omega_1} \sin(2 \omega_1 t + \varphi)$$

$$(13) \quad W_{cl}^x(t) = W_{cl}^x + \frac{\hat{e}_r \hat{i}_{diff0}}{\omega_1} \sin \omega_1 t - \left(\frac{u_D}{2} - R \hat{i}_{diff0} \right) \frac{\hat{i}_r}{2 \omega_1} \sin(\omega_1 t + \varphi) - \frac{\hat{e}_r \hat{i}_r}{4 \omega_1} \sin(2 \omega_1 t + \varphi)$$

Thus the instantaneous energies in each arm can be calculated in real-time knowing only the references for the inner converter voltage and the actual AC current.

15 The integration constants are the references for the desired average energy in each arm in the phase leg.

But if the energies are known then also the total capacitor voltage in the arms are known due to the connection equations

$$20 \quad (14) \quad u_{cu}^x(t) = \sqrt{\frac{2 W_{cu}^x(t)}{C_{arm}}} \quad u_{cl}^x(t) = \sqrt{\frac{2 W_{cl}^x(t)}{C_{arm}}}$$

Now the insertion indices valid for the desired steady-state operation can be calculated using equation (4). Given these insertion indices the energies in the upper and lower arms converges to the reference values given as
5 free integration constants in (12) and (13). Normally these values are selected equal for both arms so that balanced operation is obtained. The value of the energy reference is selected to give the desired total capacitor voltage in each converter arm.

10 The second approach to stabilisation of the converter according to the procedure presented in this section is described in more detail in Appendix 2.

Remark 1: If a third harmonic voltage component (to increase the available voltage in a 3-phase converter) is
15 added the formulas for the energies in the upper and lower arm will change somewhat. However the principle described in this paper still can be applied.

Remark 2: If even order harmonics are intentionally added to the circulating current the formulas for the energies
20 in the upper and lower arms will change somewhat. The principle described above however still applies.

APPENDIX 1: Description of feedback control system

A purpose of this appendix is to disclose in more details the control mechanisms (modulation) that can be utilized.
25 The targets are

- to derive a control strategy that provides main circuit stability
- to produce as high AC output voltage as possible with very low harmonic distortion

- to control the DC voltages of the capacitors in the modules

Continuous model

It is of course possible to investigate the M2C converter
5 by simulation. This approach however seems to be quite
cumbersome in the sense that it involves detailed models
of the arms (with tens of semiconductor devices in each).
A lot of data will be generated making it more difficult
to extract useful results.

- 10 Another approach, which will be followed here, makes use
of a modulation principle that has been proposed by in
DE10103031, in which a selection mechanism is used to
determine which individual module that shall be inserted
or bypassed when the number of devices in an arm shall be
15 changed. The selection is made in dependence of the
direction of the arm current (or phase current) and a
comparison of the DC voltages in the congregation of
modules in each arm, from which the modules having the
highest and lowest voltages are identified.
- 20 Simulation has shown that this mechanism successfully
keeps the DC voltages of the module capacitors quite
close to each other, even for low number of modules in
each arm (say e.g. five per arm). This functionality
seems to remain even if the total switching frequency is
25 low (a few hundred switchings per second for each
semiconductor device).

Now it is assumed that this mechanism is in use and that
accordingly there is no need to look at the DC voltages
in the individual modules any more. The modulation
30 process then can be described in terms of the total

collective energy in each arm. As the total switching frequency (for all modules in each arm) becomes quite high continuous modelling can be used. The continuous model is a lot simpler to grasp than the detailed model
 5 and it is an ideal base for understanding the principles for the function of the M2C converter and to formulate control laws for different control aspects.

Due to the assumptions static relations exist between the total capacitor energy in the upper and lower arm, W_{cu}^Σ and
 10 W_{cl}^Σ , and the corresponding total voltage of all capacitor modules in the arm, u_{cu}^Σ and u_{cl}^Σ . Namely, if it is assumed that the energy is evenly shared between the modules, this relation becomes

$$\begin{aligned} W_{cu}^\Sigma &= N \left(\frac{C}{2} \left(\frac{u_{cu}^\Sigma}{N} \right)^2 \right) = \frac{C}{2N} u_{cu}^{\Sigma^2} & u_{cu}^\Sigma &= \sqrt{\frac{2N}{C} W_{cu}^\Sigma} \\ W_{cl}^\Sigma &= N \left(\frac{C}{2} \left(\frac{u_{cl}^\Sigma}{N} \right)^2 \right) = \frac{C}{2N} u_{cl}^{\Sigma^2} & u_{cl}^\Sigma &= \sqrt{\frac{2N}{C} W_{cl}^\Sigma} \end{aligned} \quad (A1)$$

15 where N is the number of modules per arm and C is the capacitance per module. In the following we will use the quantity 'arm capacitance' C_{arm} defined as follows

$$(A2) \quad C_{arm} = \frac{C}{N}$$

20 Then

$$\begin{aligned} W_{cu}^\Sigma &= \frac{C_{arm}}{2} (u_{cu}^\Sigma)^2 & u_{cu}^\Sigma &= \sqrt{\frac{2 W_{cu}^\Sigma}{C_{arm}}} \\ W_{cl}^\Sigma &= \frac{C_{arm}}{2} (u_{cl}^\Sigma)^2 & u_{cl}^\Sigma &= \sqrt{\frac{2 W_{cl}^\Sigma}{C_{arm}}} \end{aligned} \quad (A3) \quad \Leftrightarrow$$

Derivation of the continuous model

The electrical circuit representing the phase leg of the M2C converter is depicted in Fig 2. The inserted capacitor voltages, U_{CU} and U_{CL} , are created from the
 5 total capacitor voltages, u_{CU}^{Σ} and u_{CL}^{Σ} , respectively, by applying the insertion indices, n_U and n_L , which are controlled by the control system.

$$\begin{aligned} n_U &= \frac{u_{CU}}{u_{CU}^{\Sigma}} & 0 \leq n_U \leq 1 \\ n_L &= \frac{u_{CL}}{u_{CL}^{\Sigma}} & 0 \leq n_L \leq 1 \end{aligned}$$

(A4)

In the following, however, the main circuit model will be
 10 formulated using the real voltages as variables. If the total capacitor voltages, u_{CU}^{Σ} and u_{CL}^{Σ} , are measured, the corresponding insertion indices can always be obtained from (A4).

The capacitor modules serve as controlled electromotive
 15 forces in the circuit. Let the total energy in the capacitors be W_{CU}^{Σ} and W_{CL}^{Σ} in the upper and lower arms respectively. Inspection of the circuit model in Fig 2 immediately yields

$$\begin{aligned} \frac{dW_{CU}^{\Sigma}}{dt} &= i_U u_{CU} \\ \frac{dW_{CL}^{\Sigma}}{dt} &= -i_L u_{CL} \end{aligned}$$

(A5)

20 In order to gain some more insight it is helpful separate the arms currents in two parts. One part emerges from the AC current, which naturally separates into two halves, one passing through the upper and one passing through the lower arm. The deviation from this "ideal" condition is

described by a difference current i_{diff} which passes through the series-connected arms and the DC source. Define

$$(A6) \quad \begin{aligned} i_U &= \frac{i_V}{2} + i_{diff} \\ i_L &= \frac{i_V}{2} - i_{diff} \end{aligned} \quad \Leftrightarrow \quad i_{diff} = \frac{i_U - i_L}{2}$$

5 The circuit in Fig 2 now gives the equations

$$(A7) \quad \begin{aligned} \frac{u_D}{2} - R \left(\frac{i_V}{2} + i_{diff} \right) - L \left(\frac{1}{2} \frac{di_V}{dt} + \frac{di_{diff}}{dt} \right) - u_{CU} - u_V &= 0 \\ -\frac{u_D}{2} - R \left(\frac{i_V}{2} - i_{diff} \right) - L \left(\frac{1}{2} \frac{di_V}{dt} - \frac{di_{diff}}{dt} \right) + u_{CL} - u_V &= 0 \end{aligned}$$

Adding and subtracting the equations give the results

$$(A8) \quad \begin{aligned} u_V &= \frac{u_{CL} - u_{CU}}{2} - \frac{R}{2} i_V - \frac{L}{2} \frac{di_V}{dt} \\ L \frac{di_{diff}}{dt} + R i_{diff} &= \frac{u_D}{2} - \frac{u_{CL} + u_{CU}}{2} \end{aligned}$$

These equations show that

- 10 - the AC voltage only depends on the AC current i_V and the difference between the arm voltages u_{CL} and u_{CU}
- the arm voltage difference acts as an inner AC voltage in the converter and the inductance L and resistance R form a fix, passive inner impedance for the AC current
- 15 - the difference current i_{diff} only depends on the DC link voltage and the sum of the arm voltages
- the difference current i_{diff} can be controlled independently of the AC side quantities by subtracting the same voltage contributions to both arms

Define

$$(A9) \quad \begin{aligned} e_V &= \frac{u_{CL} - u_{CU}}{2} & u_{CU} &= \frac{u_D}{2} - e_V - u_{diff} \\ u_{diff} &= \frac{u_D - u_{CL} - u_{CU}}{2} & u_{CL} &= \frac{u_D}{2} + e_V - u_{diff} \end{aligned} \Leftrightarrow$$

where e_V is the desired inner voltage in the AC voltage source and u_{diff} is a voltage that controls the difference
5 current i_{diff} .

Then (8) becomes

$$(A10) \quad \begin{aligned} u_V &= e_V - \frac{R}{2} i_V - \frac{L}{2} \frac{di_V}{dt} \\ L \frac{di_{diff}}{dt} + Ri_{diff} &= u_{diff} \end{aligned}$$

Inserting equations (A6) and (A9) in (A5) yields

$$(A11) \quad \begin{aligned} \frac{dW_{CU}^\Sigma}{dt} &= \left(\frac{i_V}{2} + i_{diff} \right) \left(\frac{u_D}{2} - e_V - u_{diff} \right) \\ \frac{dW_{CL}^\Sigma}{dt} &= \left(-\frac{i_V}{2} + i_{diff} \right) \left(\frac{u_D}{2} + e_V - u_{diff} \right) \end{aligned}$$

10 It makes sense to investigate the total energy stored in all capacitor banks in the whole leg and to examine the balance between the energy in the upper and the lower arm. Define

$$(A12) \quad \begin{aligned} W_C^\Sigma &= W_{CU}^\Sigma + W_{CL}^\Sigma & W_{CU}^\Sigma &= \frac{W_C^\Sigma + W_C^\Delta}{2} \\ W_C^\Delta &= W_{CU}^\Sigma - W_{CL}^\Sigma & W_{CL}^\Sigma &= \frac{W_C^\Sigma - W_C^\Delta}{2} \end{aligned} \Leftrightarrow$$

15 The result is

$$(A13) \quad \begin{aligned} \frac{dW_C^\Sigma}{dt} &= (u_D - 2u_{diff}) i_{diff} - e_V i_V \\ \frac{dW_C^\Delta}{dt} &= -2e_V i_{diff} + \left(\frac{u_D}{2} - u_{diff} \right) i_V \end{aligned}$$

Equation (A13) indicates that the total energy in both arms as well as the energy balance between the upper and lower arms can be controlled primarily by i_{diff} , which is in its turn controlled by u_{diff} through (A10).

- 5 The term in the upper equation in (A13) is recognized as the instantaneous power delivered to the AC side.

$$(A14) \quad p_v = e_v i_v$$

Steady state solution

We shall look at the special case where the AC emf and
10 current is given. Thus let

$$(A15) \quad \begin{aligned} e_v &= \hat{e}_v \cos \omega t \\ i_v &= \hat{i}_v \cos(\omega t + \varphi) \end{aligned}$$

Assume that there is a solution where the difference current i_{diff} is a pure dc component. Thus

$$(A16) \quad i_{diff}(t) = \hat{i}_{diff}$$

- 15 Then, according to (A10)

$$(A17) \quad u_{diff}(t) = R \hat{i}_{diff}$$

The derivative of the total and difference energies the according to (A13) become

$$(A18) \quad \begin{aligned} \frac{dW_c^\Sigma}{dt} &= (u_D - 2R\hat{i}_{diff})\hat{i}_{diff} - \frac{\hat{e}_v\hat{i}_v}{2} [\cos\varphi + \cos(2\omega t + \varphi)] \\ \frac{dW_c^\Delta}{dt} &= -2\hat{e}_v\hat{i}_{diff} \cos\omega t + \left(\frac{u_D}{2} - R\hat{i}_{diff}\right)\hat{i}_v \cos(\omega t + \varphi) \end{aligned}$$

- 20 From (A18) some observations can immediately be made

- the derivative of the total energy contains only a constant and a component having double network frequency
- the derivative of the difference energy only contains components having network frequency

5 Steady-state condition requires that the constant component of the total energy derivative disappears so that

$$(A19) \quad \begin{aligned} (u_D - 2R\hat{i}_{diff})\hat{i}_{diff} - \frac{\hat{e}_V\hat{i}_V}{2}\cos\varphi &= 0 \\ \hat{i}_{diff} &= \frac{\hat{e}_V\hat{i}_V\cos\varphi}{u_D + \sqrt{u_D^2 - 4R\hat{e}_V\hat{i}_V\cos\varphi}} \end{aligned}$$

With this difference current the remaining term becomes

$$10 \quad (A20) \quad \frac{dW_C^\Sigma}{dt} = -\frac{\hat{e}_V\hat{i}_V}{2}\cos(2\omega t + \varphi)$$

The steady-state average energy can be freely selected so that the total energy in steady-state becomes

$$(A21) \quad W_C^\Sigma(t) = W_{C0}^\Sigma - \frac{\hat{e}_V\hat{i}_V}{4\omega}\sin(2\omega t + \varphi)$$

15 The expression for the difference energy In (A18) can be directly integrated, also with a freely selectable integration constant (which normally shall be zero)

$$(A22) \quad W_C^\Delta(t) = W_{C0}^\Delta - \frac{2\hat{e}_V\hat{i}_{diff}}{\omega}\sin\omega t + \frac{\left(\frac{u_D}{2} - R\hat{i}_{diff}\right)\hat{i}_V}{\omega}\sin(\omega t + \varphi)$$

The investigation shows that

- solutions of the desired type, i.e. with a difference component having only a DC component, exist with freely selectable energy levels in each arm
- the steady state solutions for the energy time functions contain only a double frequency component in the total energy and a fundamental frequency component in the difference energy

Linearised model for control studies

Let us go back and linearise the equations (A13) around a steady state point as described in the preceding section. Assume that the DC link voltage is constant. The

$$\begin{aligned}
 \frac{d\Delta W_C^\Sigma}{dt} &= (u_D - 2R\hat{i}_{diff})\Delta i_{diff} - 2\hat{i}_{diff}\Delta u_{diff} - \Delta p_V \\
 \frac{d\Delta W_C^\Delta}{dt} &= -2e_V\Delta i_{diff} - i_V\Delta u_{diff} - 2\hat{i}_{diff}\Delta e_V + \left(\frac{u_D}{2} - R\hat{i}_{diff}\right)\Delta i_V
 \end{aligned}
 \tag{A23}$$

Further the differential equation that governs i_{diff} as function of u_{diff} applies so that

$$L\frac{d\Delta i_{diff}}{dt} + R\Delta i_{diff} = \Delta u_{diff}
 \tag{A24}$$

Stability requirements

When the AC side current is stiff (A23) reduces to

$$\begin{aligned}
 \frac{d\Delta W_C^\Sigma}{dt} &= (u_D - 2R\hat{i}_{diff})\Delta i_{diff} - 2\hat{i}_{diff}\Delta u_{diff} \\
 \frac{d\Delta W_C^\Delta}{dt} &= -2e_V\Delta i_{diff} - i_V\Delta u_{diff}
 \end{aligned}
 \tag{A25}$$

The linearized equations (A25) show that any control system, which makes the sum of the inserted voltages, u_{CL} and u_{CU} , perfectly match the voltage u_D on the DC side,

i.e. makes $u_{diff} \equiv 0$, also makes the difference current become zero causing the derivatives of the energies in the arms to vanish. The main circuit in the converter then is marginally stable. Thus is not sufficient to
 5 select the inserted voltages in (A9) according to the desired e_v , but an u_{diff} that creates stability must also be provided.

Control law for the total capacitor energy

The equation for the total energy equation can be
 10 formulated in the Laplace domain

$$\begin{aligned} \Delta W_c^\Sigma(s) &= \frac{1}{s} \left\{ \frac{(u_D - 2R\hat{i}_{diff})}{R + sL} - 2\hat{i}_{diff} \right\} \Delta u_{diff}(s) - \frac{\Delta p_v(s)}{s} = \\ &= \frac{u_D - 4R\hat{i}_{diff} - 2L\hat{i}_{diff}s}{(R + sL)s} \Delta u_{diff}(s) - \frac{\Delta p_v(s)}{s} \end{aligned} \quad (A26)$$

Applying a proportional gain in an energy controller

$$(A27) \quad \Delta u_{diff}(s) = K_p \{ \Delta W_c^{\Sigma ref}(s) - \Delta W_c^\Sigma(s) \}$$

yields

$$\begin{aligned} \Delta W_c^\Sigma(s) &= \frac{[u_D - 4R\hat{i}_{diff} - 2L\hat{i}_{diff}s]K_p}{(R + sL)s + [u_D - 4R\hat{i}_{diff} - 2L\hat{i}_{diff}s]K_p} \Delta W_c^{\Sigma ref}(s) - \\ &\quad - \frac{R + sL}{(R + sL)s + [u_D - 4R\hat{i}_{diff} - 2L\hat{i}_{diff}s]K_p} \Delta p_v(s) \end{aligned} \quad (A28)$$

The poles in the above transfer functions are mainly determined by

$$(A29) \quad s_{1,2}^2 L + u_D K_p = 0 \quad \Leftrightarrow \quad s_{1,2} = \pm j \sqrt{\frac{u_D K_p}{L}}$$

The control system is investigated for a converter leg in an example converter with the main parameters given in Table 1.

3-ph rated power	30 MVA
rated frequency	50 Hz
line-line voltage	13.8 kV rms
rated phase current	1255 A rms
arm capacitance	500 μ F/arm
arm inductance	3 mH
arm resistance	100 m Ω

Table 1: Example converter main data

5

Fig 3 shows the Nichols plot for the open loop transfer function in (A26) with the proportional gain $K_p=0.001$ V/J. The curve is almost independent of the active load.

As expected is the phase margin at 90 rad/s quite small,
 10 which means that the response will be quite oscillatory. In Fig 4 the Nichols plot is shown when a PID controller is used.

The selected transfer function is given by

$$(A30) \quad F^\Sigma(s) = K_p \left(1 + \frac{K_I}{s} + \frac{sT_D}{1+sT_F} \right)$$

15 with $K_p=0.002$ V/J, $K_I=20$ s⁻¹, $T_D=10$ ms, $T_F=2$ ms

It has been shown that the total energy response signal contains a frequency component with twice the network

frequency. This component can be removed from the controller response using a notch filter. Further it is advisable to assume that a delay occurs in the measured total energy (total capacitor voltage). Fig 5 shows the
 5 corresponding Nicols's diagram where the notch filter and the time delay have been included.

The transfer function in Fig 5 is

$$(A31) \quad F^{\Sigma}(s) = K_p \left(1 + \frac{K_I}{s} + \frac{sT_D}{1+sT_F} \right) e^{-sT_{del}} \frac{s^2 + (2\omega_l)^2}{s^2 + 2\zeta(2\omega_l)s + (2\omega_l)^2}$$

with $K_p=0.002$ V/J, $K_I=20$ s⁻¹, $T_D=10$ ms, $T_F=2$ ms, $T_{del}=1$ ms,
 10 $\zeta=0.05$

Fig 6 shows the simulation result at a step in the reference for the total energy in the converter leg.

Equation (A28) shows that the energy control system having only a proportional feedback will have a static
 15 error

$$(A32) \quad \frac{\Delta W_C^{\Sigma}}{\Delta p_V} = \frac{-R}{K_p(u_D - 4R\hat{i}_{diff})}$$

For the values in Table 1 together with $K_p=0.002$ V/J this energy dependence becomes approximately 0.002 J/W. Each leg of the converter handles about 10 MW causing the
 20 energy drop to be about 20 kJ (out of about 312 kJ) per leg.

Fig 7 shows the simulation result when the current changes from 0.1 pu to 1.0 pu in the converter leg.

Control law for balancing the capacitor energies in the
 25 arms

The general differential equation governing the balance between the energies in the upper and the lower arm was derived in (A13)

$$(A33) \quad \frac{dW_C^\Delta}{dt} = -2e_v i_{diff} + \left(\frac{u_D}{2} - u_{diff} \right) i_v$$

5 It was linearised in (A23)

$$(A34) \quad \frac{d\Delta W_C^\Delta}{dt} = -2e_v \Delta i_{diff} - i_v \Delta u_{diff} - 2\hat{i}_{diff} \Delta e_v + \left(\frac{u_D}{2} - R\hat{i}_{diff} \right) \Delta i_v$$

If we consider linearising around the steady state solution defined by (A15) the linearised equation becomes

$$(A35) \quad \frac{d\Delta W_C^\Delta}{dt} = -2\hat{e}_v \cos \omega t \Delta i_{diff} - \hat{i}_v \cos(\omega t + \varphi) \Delta u_{diff} - 2\hat{i}_{diff} \Delta e_v + \left(\frac{u_D}{2} - R\hat{i}_{diff} \right) \Delta i_v$$

10 Assume first that the AC side quantities are constant.
Then

$$(A36) \quad \frac{d\Delta W_C^\Delta}{dt} = -2\hat{e}_v \cos \omega t \Delta i_{diff} - \hat{i}_v \cos(\omega t + \varphi) \Delta u_{diff}$$

Further assume that the controller produces a fundamental frequency sinusoidal signal with phase ζ relative the
15 inner emf in the converter leg

$$(A37) \quad u_{diff}(t) = \hat{u}_{diff}(t) \cos(\omega t + \xi)$$

Using the quasi-stationary solution to (A10) yields

$$(A38) \quad \hat{i}_{diff}(t) = \frac{\hat{u}_{diff}}{\sqrt{R^2 + (\omega L)^2}} \cos(\omega t + \xi - \eta)$$

$$\eta = \arg(R + j\omega L)$$

Inserting in (A36) we get

$$(A39) \quad \frac{d\Delta W_c^\Delta}{dt} = \left\{ -\frac{2\hat{e}_v}{\sqrt{R^2 + (\omega L)^2}} \cos(\omega t) \cos(\omega t + \xi - \eta) - \hat{i}_v \cos(\omega t + \varphi) \cos(\omega t + \xi) \right\} \Delta \hat{u}_{diff}$$

The products of the cosine functions in (A39) are DC quantities and terms with the double network frequency. These components are

$$(A40) \quad \begin{aligned} a^{dc} &= \frac{-\hat{e}_v}{\sqrt{R^2 + (\omega L)^2}} \cos(\xi - \eta) - \frac{\hat{i}_v}{2} \cos(\xi - \varphi) \\ a^{2\omega} &= \frac{-\hat{e}_v}{\sqrt{R^2 + (\omega L)^2}} \cos(2\omega t + \xi - \eta) - \frac{\hat{i}_v}{2} \cos(2\omega t + \xi + \varphi) \end{aligned}$$

The relation between the two terms at various frequencies has been found to show that the first term dominates completely even for operating frequencies down to 5 Hz. Therefore it is sufficient to consider the first term.

10 The maximum DC component then is obtained when

$$(A41) \quad \xi = \eta = \arg(R + j\omega L)$$

With this selection of the argument for the inserted difference voltage we get the simplified formula

$$(A42) \quad \frac{d\Delta W_c^\Delta}{dt} = -\frac{\hat{e}_v}{\sqrt{R^2 + (\omega L)^2}} \Delta \hat{u}_{diff}$$

15 A proportional controller is sufficient to control the balance between the energies as the function is indeed just an integrator. However, the measured difference energy has a strong fundamental frequency component, which should be eliminated in the response to the

20 regulator. Thus the transfer function in the balancing controller is given by

$$(A43) \quad F^{\Delta}(s) = K_{P\Delta} \frac{s^2 + \omega_1^2}{s^2 + 2\zeta\omega_1 s + \omega_1^2}$$

Fig 8 shows the Nichols plot for the balance controller with parameters according to Table 1 and with control parameters $K_{P\Delta} = -0.005$ V/J, $t_{Del} = 1$ ms, $\zeta = 0.1$.

- 5 Fig 5 shows that the closed loop for the energy controller has unity gain up to about 300 rad/s and that it amplifies frequencies in the range 100 - 200 rad/s with more than 3 dB. Therefore the gain in the balance controller has been kept low for these frequencies in
10 order to avoid interaction between the two controllers.

Appendix 2: Description of open loop control system

The aim of the investigation is to describe an M2C system where the modulation operates in open-loop mode. The meaning of the name "open-loop" in this context is that
15 the modulation system does not measure the total voltage of the capacitors in the phase leg arms. Rather these total voltages are estimated in run-time using the desired AC emf and the measured AC current. The reference for the inserted arm voltages are obtained assuming that
20 the instantaneous AC emf and AC current are steady state values. Further it is assumed that a voltage sharing system is provided to distribute the total arm voltage in each arm evenly between all modules that constitute the arm.

25 Steady state analysis

The starting point is that the converter produces a sinusoidal emf

$$(B1) \quad e_V = \hat{e}_V \cos \omega_1 t$$

and is loaded with a sinusoidal phase current

$$(B2) \quad i_V = \hat{i}_V \cos(\omega_1 t + \varphi)$$

Under ideal conditions the arm currents only contains a
5 DC component $\hat{i}_{diff0}$ so that the arm currents become

$$(B3) \quad i_U = \frac{\hat{i}_V}{2} \cos(\omega_1 t + \varphi) + \hat{i}_{diff0} \quad i_L = \frac{\hat{i}_V}{2} \cos(\omega_1 t + \varphi) - \hat{i}_{diff0}$$

When the difference current is $\hat{i}_{diff0}$ the difference
voltage becomes $u_{diff} = R \hat{i}_{diff0}$ so that the arm voltages become

$$(B4) \quad u_{CU} = \frac{u_D}{2} - \hat{e}_V \cos \omega_1 t - R \hat{i}_{diff0} \quad u_{CL} = \frac{u_D}{2} + \hat{e}_V \cos \omega_1 t - R \hat{i}_{diff0}$$

10 The derivatives of the arm energies are

$$(B5) \quad \frac{dW_{CU}^2}{dt} = u_{CU} i_U \quad \frac{dW_{CL}^2}{dt} = -u_{CL} i_L$$

Inserting the expressions in (B3) and (B4) yields

$$(B6) \quad \begin{aligned} \frac{dW_{CU}^2}{dt} = & \left(\frac{u_D}{2} - R \hat{i}_{diff0} \right) \hat{i}_{diff0} - \frac{\hat{e}_V \hat{i}_V \cos \varphi}{4} - \\ & - \hat{e}_V \hat{i}_{diff0} \cos \omega_1 t + \left(\frac{u_D}{2} - R \hat{i}_{diff0} \right) \frac{\hat{i}_V}{2} \cos(\omega_1 t + \varphi) - \frac{\hat{e}_V \hat{i}_V}{4} \cos(2\omega_1 t + \varphi) \end{aligned}$$

$$(B7) \quad \begin{aligned} \frac{dW_{CL}^2}{dt} = & \left(\frac{u_D}{2} - R \hat{i}_{diff0} \right) \hat{i}_{diff0} - \frac{\hat{e}_V \hat{i}_V \cos \varphi}{4} - \\ & + \hat{e}_V \hat{i}_{diff0} \cos \omega_1 t - \left(\frac{u_D}{2} - R \hat{i}_{diff0} \right) \frac{\hat{i}_V}{2} \cos(\omega_1 t + \varphi) - \frac{\hat{e}_V \hat{i}_V}{4} \cos(2\omega_1 t + \varphi) \end{aligned}$$

15 In steady state the DC term must be zero. This condition
allows us to determine the DC component to

$$(B8) \quad \hat{i}_{diff0} = \frac{\hat{e}_V \hat{i}_V \cos \varphi}{u_D + \sqrt{u_D^2 - 4R\hat{e}_V \hat{i}_V \cos \varphi}}$$

Thus, in steady state, the energy variations are

$$(B9) \quad \frac{dW_{CU}^z}{dt} = -\hat{e}_V \hat{i}_{diff0} \cos \omega_1 t + \left(\frac{u_D}{2} - R\hat{i}_{diff0}\right) \frac{\hat{i}_V}{2} \cos(\omega_1 t + \varphi) - \frac{\hat{e}_V \hat{i}_V}{4} \cos(2\omega_1 t + \varphi)$$

$$(B10) \quad \frac{dW_{CL}^z}{dt} = +\hat{e}_V \hat{i}_{diff0} \cos \omega_1 t - \left(\frac{u_D}{2} - R\hat{i}_{diff0}\right) \frac{\hat{i}_V}{2} \cos(\omega_1 t + \varphi) - \frac{\hat{e}_V \hat{i}_V}{4} \cos(2\omega_1 t + \varphi)$$

- 5 These formulas can immediately be integrated to obtain the instantaneous energy variations. Note that a freely selectable integration constant appears in each expression. Thus

$$(B11) \quad W_{CU}^z(t) = W_{CU0}^z - \frac{\hat{e}_V \hat{i}_{diff0}}{\omega_1} \sin \omega_1 t + \left(\frac{u_D}{2} - R\hat{i}_{diff0}\right) \frac{\hat{i}_V}{2\omega_1} \sin(\omega_1 t + \varphi) - \frac{\hat{e}_V \hat{i}_V}{8\omega_1} \sin(2\omega_1 t + \varphi)$$

$$10 \quad (B12) \quad W_{CL}^z(t) = W_{CL0}^z + \frac{\hat{e}_V \hat{i}_{diff0}}{\omega_1} \sin \omega_1 t - \left(\frac{u_D}{2} - R\hat{i}_{diff0}\right) \frac{\hat{i}_V}{2\omega_1} \sin(\omega_1 t + \varphi) - \frac{\hat{e}_V \hat{i}_V}{4\omega_1} \sin(2\omega_1 t + \varphi)$$

The total capacitor voltages now are given by

$$(B13) \quad u_{CU}^z(t) = \sqrt{\frac{2W_{CU}^z(t)}{C_{arm}}} \quad u_{CL}^z(t) = \sqrt{\frac{2W_{CL}^z(t)}{C_{arm}}}$$

and they can be used to determine the insertion indices in run-time according to

$$15 \quad (B14) \quad n_U(t) = \frac{u_{CU}(t)}{u_{CU}^z(t)} \quad n_L(t) = \frac{u_{CL}(t)}{u_{CL}^z(t)}$$

Open-loop control

The idea of the open-loop control mode is to

- measure the AC terminal current

- extract the amplitude and phase relative the created emf in the converter as in (B2)
- perform the calculation as described above
- utilize the so obtained insertion indices according to
5 (B14) in the converter

The invention has mainly been described above with reference to a few embodiments. However, as is readily appreciated by a person skilled in the art, other embodiments than the ones disclosed above are equally
10 possible within the scope of the invention, as defined by the appended patent claims.

CLAIMS

1. A method for calculating insertion indices for a phase leg of a DC to AC modular multilevel converter, the converter via a control apparatus, said control apparatus
 5 having at least one controller, comprising one phase leg between upper and lower DC source common bars for each phase, each phase leg comprising two serially connected arms, wherein an AC output for each phase leg is connected between the two serially connected arms, wherein each arm
 10 comprises a number of submodules, wherein each submodule can be in a bypass state or a voltage insert mode, the insertion index comprising data representing a portion of available submodules that should be in the voltage insert mode for a particular arm, the method comprising the steps
 15 of:

calculating, in said controller, a desired arm voltage $u_{CU}(t)$ for an upper arm connected to the upper DC source common bar and a desired arm voltage $u_{CL}(t)$ for a lower arm connected to the lower DC source common bar,

20 obtaining, in said controller, values representing actual total arm voltages $u_{CU}^{\Sigma}(t)$ and $u_{CL}^{\Sigma}(t)$ in the upper arm and lower arm, respectively, by measuring the sum of capacitor voltages in each arm using sensors in the submodules, and

25 calculating, in said controller, the insertion indices $n_U(t)$ and $n_L(t)$ for the upper and lower arm, respectively, using the respective desired arm voltage and

the respective value representing the total actual arm voltage, as

$$n_U(t) = \frac{u_{CU}(t)}{u_{CU}^{\Sigma}(t)} \quad n_L(t) = \frac{u_{CL}(t)}{u_{CL}^{\Sigma}(t)};$$

wherein the step of calculating desired arm voltages for
5 a phase leg comprises calculating

$$u_{CU}(t) = u_D/2 - e_v(t) - u_{diff}(t)$$

for the upper arm, and calculating

$$u_{CL}(t) = u_D/2 + e_v(t) - u_{diff}(t)$$

for the lower arm, where $u_{CU}(t)$ represents desired upper
10 arm voltage where $u_{CL}(t)$ represents desired lower arm
voltage, u_D represents a voltage between the upper and
lower DC source common bars, $e_v(t)$ represents a reference
inner AC output voltage and $u_{diff}(t)$ represents a control
voltage to control a current passing through the whole
15 phase leg, and calculating

$$u_{diff}(t) = u_{diff1}(t) + u_{diff2}(t)$$

where $u_{diff1}(t)$ represents a voltage obtained by summing
energy in the arms of the leg and $u_{diff2}(t)$ represents a
voltage obtained by calculating a difference in energy
20 between the arms of the leg.

2. The method according to claim 3, wherein the step of
obtaining a value representing actual arm voltage
comprises calculating

$$u_{diff2}(t) = \hat{u}_{diff2} \cos(\omega_1 t + \psi)$$

where $\hat{u}_{diff2}$ represents a difference between total upper arm energy and total lower arm energy, ω_1 represents the angular velocity of the network frequency and ψ represents
 5 the angle given by $\psi = \angle(R + j\omega_1 L)$ where R represents the resistance of the converter arm and L represents the inductance of the converter arm.

3. A method for calculating insertion indices for a phase leg of a DC to AC modular multilevel converter, via
 10 a control apparatus, said control apparatus having at least one controller, the converter comprising one phase leg between upper and lower DC source common bars for each phase, each phase leg comprising two serially connected arms, wherein an AC output for each phase leg is connected
 15 between the two serially connected arms, wherein each arm comprises a number of submodules, wherein each submodule can be in a bypass state or a voltage insert mode, the insertion index comprising data representing a portion of available submodules that should be in the voltage insert
 20 mode for a particular arm, the method comprising the steps of:

calculating, in said controller, a desired arm voltage $u_{cu}(t)$ for an upper arm connected to the upper DC source common bar and a desired arm voltage $u_{cl}(t)$ for a
 25 lower arm connected to the lower DC source common bar,
 obtaining, in said controller, values representing

actual total arm voltages $u_{CU}^{\Sigma}(t)$ and $u_{CL}^{\Sigma}(t)$ in the upper arm and lower arm, respectively, and

calculating, in said controller, the insertion indices $n_U(t)$ and $n_L(t)$ for the upper and lower arm, respectively, using the respective desired arm voltage and the respective value representing the total actual arm voltage, as

$$n_U(t) = \frac{u_{CU}(t)}{u_{CU}^{\Sigma}(t)} \quad n_L(t) = \frac{u_{CL}(t)}{u_{CL}^{\Sigma}(t)};$$

wherein the step of calculating desired arm voltages for a phase leg comprises calculating

$$u_{CU}(t) = u_D/2 - e_v(t) - u_{diff}(t)$$

for the upper arm, and calculating

$$u_{CL}(t) = u_D/2 + e_v(t) - u_{diff}(t)$$

for the lower arm, where $u_{CU}(t)$ represents desired upper arm voltage where $u_{CL}(t)$ represents desired lower arm voltage, u_D represents a voltage between the upper and lower DC source common bars, $e_v(t)$ represents a reference inner AC output voltage and $u_{diff}(t)$ represents a control voltage to control a current passing through the whole phase leg,

wherein the step of obtaining values representing actual arm voltages comprises:

calculating $u_{CU}^{\Sigma}(t)$, actual total voltage for the upper arm, using C_{arm} , capacitance for the arm, $\hat{i}_{diff0}$, DC current passing through the two serially connected arms of the phase leg, $W_{CU}^{\Sigma}(t)$, desired average energy in the upper arm,
 5 $\hat{e}_v$, amplitude of reference for the inner AC output voltage, $\hat{i}_v$, amplitude of AC output current, φ , a phase difference between $i_v(t)$ and $e_v(t)$, DC current circulating through the two series-connected arms, and

calculating $u_{CL}^{\Sigma}(t)$, actual total voltage for the lower
 10 arm, using C_{arm} , capacitance for the arm, $\hat{i}_{diff0}$, DC current passing through the two serially connected arms of the phase leg, $W_{CL}^{\Sigma}(t)$, desired average energy in the lower arm, $\hat{e}_v$, amplitude of reference for inner AC output voltage, $\hat{i}_v$, amplitude of AC output current φ , a phase difference
 15 between $i_v(t)$ and $e_v(t)$, $\hat{i}_{diff0}$, DC current circulating through the two series-connected arms.

4. The method according to claim 3, wherein the step of obtaining a value representing actual arm voltage comprises calculating

20
$$\hat{i}_{diff0} = \frac{\hat{e}_v \hat{i}_v \cos \varphi}{u_D + \sqrt{u_D^2 - 4 R \hat{e}_v \hat{i}_v \cos \varphi}}$$

where φ represents a phase difference between $i_v(t)$ and $e_v(t)$, u_D represents a voltage between the upper and lower DC source common bars and R represents the resistance of the converter arm.

5. The method according to any one of claims 1 or 2, wherein the step of obtaining a value representing actual total arm voltage comprises measuring voltages of the submodules of the arm and summing these measured voltages.

5 6. The method according to any one of claims 1 to 5, wherein the insertion index comprises data representing a direction of the inserted voltage.

7. An apparatus for calculating insertion indices for a phase leg of a DC to AC modular multilevel converter, the
 10 converter comprising one phase leg between upper and lower DC source common bars for each phase, each phase leg comprising two serially connected arms, wherein an AC output for each phase leg is connected between the two serially connected arms, wherein each arm comprises a
 15 number of submodules, wherein each submodule can be in a bypass state or a voltage insert mode, the insertion index comprising data representing a portion of available submodules that should be in the voltage insert mode for a particular arm, the apparatus comprises:
 20 a controller arranged to calculate a desired arm voltage $u_{CU}(t)$ for an upper arm connected to the upper DC source common bar and a desired arm voltage $u_{CL}(t)$ for a lower arm connected to the lower DC source common bar, to obtain values representing actual total arm voltages $u_{CU}^{\Sigma}(t)$
 25 and $u_{CL}^{\Sigma}(t)$ in the upper arm and lower arm, respectively, by measuring the sum of capacitor voltages in each arm using sensors in the submodules, and to calculate the insertion indices $n_U(t)$ and $n_L(t)$ for the upper and lower arm,

respectively, using the respective desired arm voltage and the respective value representing the total actual arm voltage, as

$$n_U(t) = \frac{u_{CU}(t)}{u_{CU}^{\Sigma}(t)} \quad n_L(t) = \frac{u_{CL}(t)}{u_{CL}^{\Sigma}(t)};$$

- 5 wherein the calculating of desired arm voltages for a phase leg comprises calculating

$$u_{CU}(t) = u_D/2 - e_v(t) - u_{diff}(t)$$

for the upper arm, and calculating

$$u_{CL}(t) = u_D/2 + e_v(t) - u_{diff}(t)$$

- 10 for the lower arm, where $u_{CU}(t)$ represents desired upper arm voltage, $u_{CL}(t)$ represents desired lower arm voltage, u_D represents a voltage between the upper and lower DC source common bars, $e_v(t)$ represents a reference inner AC output voltage and $u_{diff}(t)$ represents a control voltage to
15 control a current passing through the whole phase leg, and calculating

$$u_{diff}(t) = u_{diff1}(t) + u_{diff2}(t)$$

- where $u_{diff1}(t)$ represents a voltage obtained by summing energy in the arms of the leg and $u_{diff2}(t)$ represents a
20 voltage obtained by calculating a difference in energy between the arms of the leg.

8. An apparatus for calculating insertion indices for a phase leg of a DC to AC modular multilevel converter, the

converter comprising one phase leg between upper and lower DC source common bars for each phase, each phase leg comprising two serially connected arms, wherein an AC output for each phase leg is connected between the two
 5 serially connected arms, wherein each arm comprises a number of submodules, wherein each submodule can be in a bypass state or a voltage insert mode, the insertion index comprising data representing a portion of available submodules that should be in the voltage insert mode for
 10 a particular arm, the apparatus comprises:

a controller arranged to calculate a desired arm voltage $u_{CU}(t)$ for an upper arm connected to the upper DC source common bar and a desired arm voltage $u_{CL}(t)$ for a lower arm connected to the lower DC source common bar, to
 15 obtain values representing actual total arm voltages $u_{CU}^{\Sigma}(t)$ and $u_{CL}^{\Sigma}(t)$ in the upper arm and lower arm, respectively, and to calculate insertion indices for the upper and lower arm, respectively, using the respective desired arm voltage and the respective value representing the total
 20 actual arm voltage, as

$$n_U(t) = \frac{u_{CU}(t)}{u_{CU}^{\Sigma}(t)} \quad n_L(t) = \frac{u_{CL}(t)}{u_{CL}^{\Sigma}(t)};$$

wherein the calculating of desired arm voltages for a phase leg comprises calculating

$$u_{CU}(t) = u_D/2 - e_v(t) - u_{diff}(t)$$

25 for the upper arm, and calculating

$$u_{CL}(t) = u_D/2 + e_v(t) - u_{diff}(t)$$

for the lower arm, where $u_{CU}(t)$ represents desired upper arm voltage, $u_{CL}(t)$ represents desired lower arm voltage, u_D represents a voltage between the upper and lower DC source common bars, $e_v(t)$ represents a reference inner AC output voltage and $u_{diff}(t)$ represents a control voltage to control a current passing through the whole phase leg,

wherein the step of obtaining values representing actual arm voltages comprises:

10 calculating $u_{CU}^\Sigma(t)$, actual total voltage for the upper arm, using C_{arm} , capacitance for the arm, $\hat{i}_{diff0}$, DC current passing through the two serially connected arms of the phase leg, $W_{CU}^\Sigma(t)$, desired average energy in the upper arm, $\hat{e}_v$, amplitude of reference for the inner AC output voltage, $\hat{i}_v$, amplitude of AC output current, ϕ , a phase difference between $i_v(t)$ and $e_v(t)$, DC current circulating through the two series-connected arms, and

20 calculating $u_{CL}^\Sigma(t)$, actual total voltage for the lower arm, using C_{arm} , capacitance for the arm, $\hat{i}_{diff0}$, DC current passing through the two serially connected arms of the phase leg, $W_{CL}^\Sigma(t)$, desired average energy in the lower arm, $\hat{e}_v$, amplitude of reference for inner AC output voltage, $\hat{i}_v$, amplitude of AC output current ϕ , a phase difference between $i_v(t)$ and $e_v(t)$, $\hat{i}_{diff0}$, DC current circulating through the two series-connected arms.

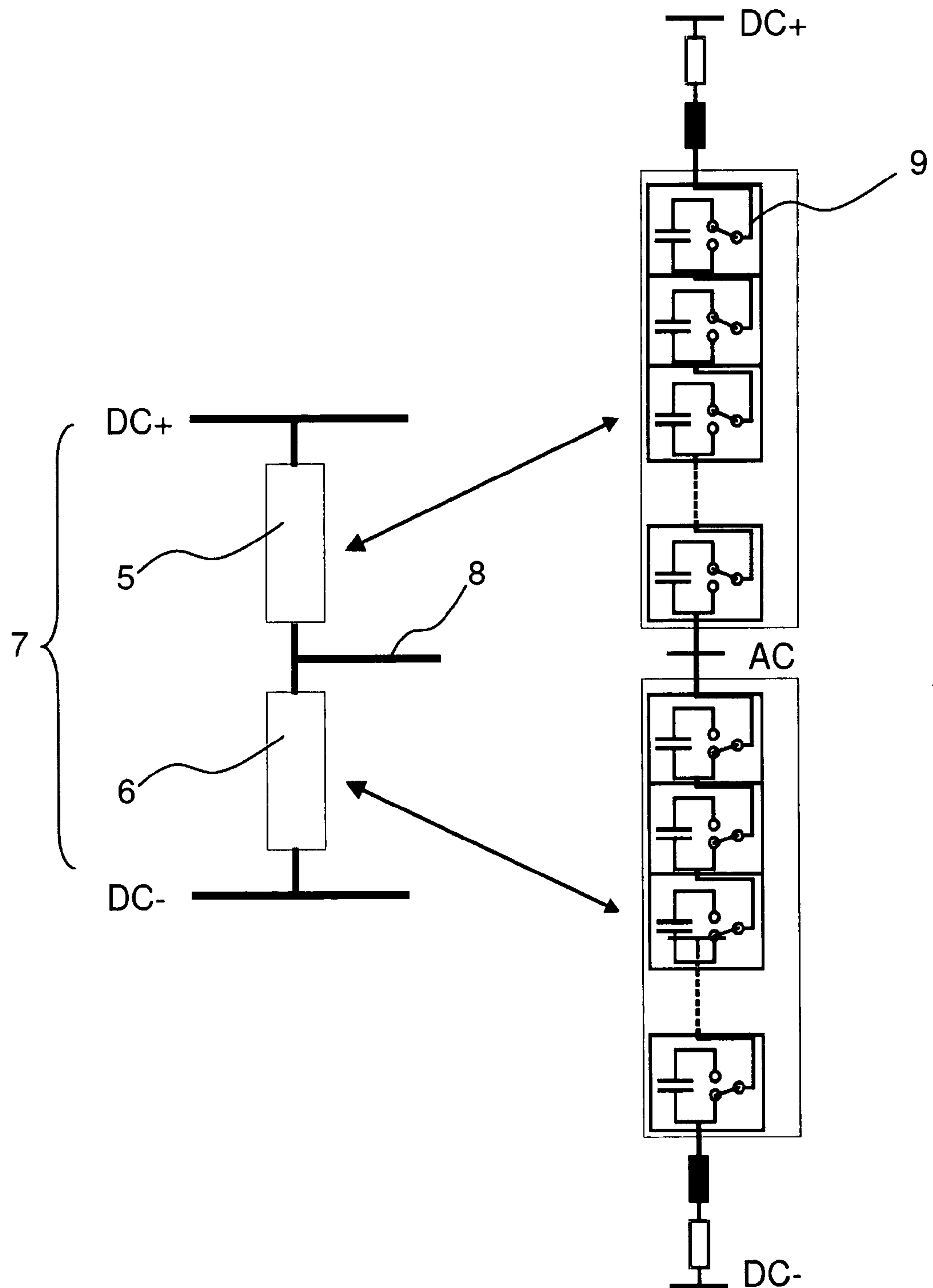


Fig. 1

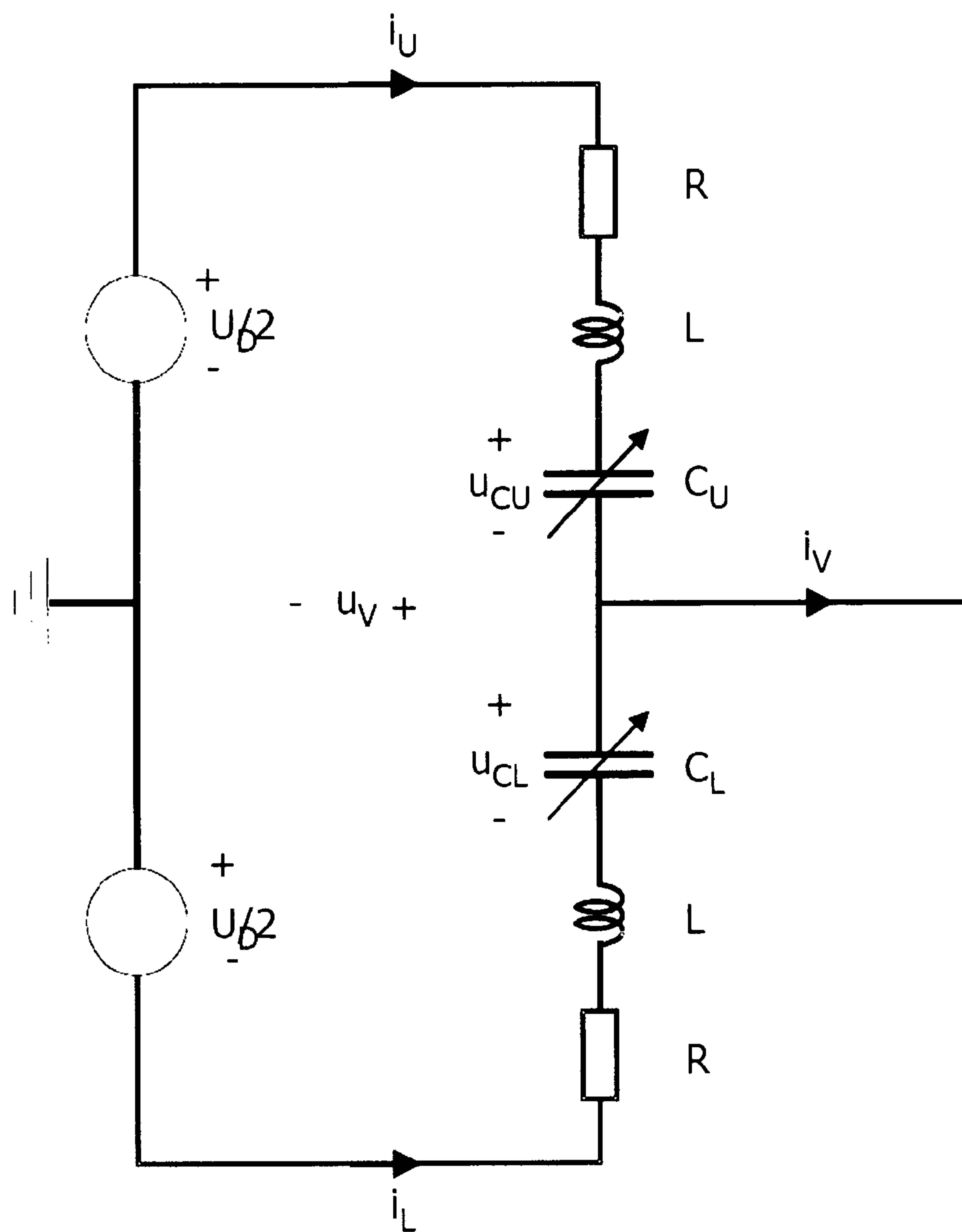


Fig. 2

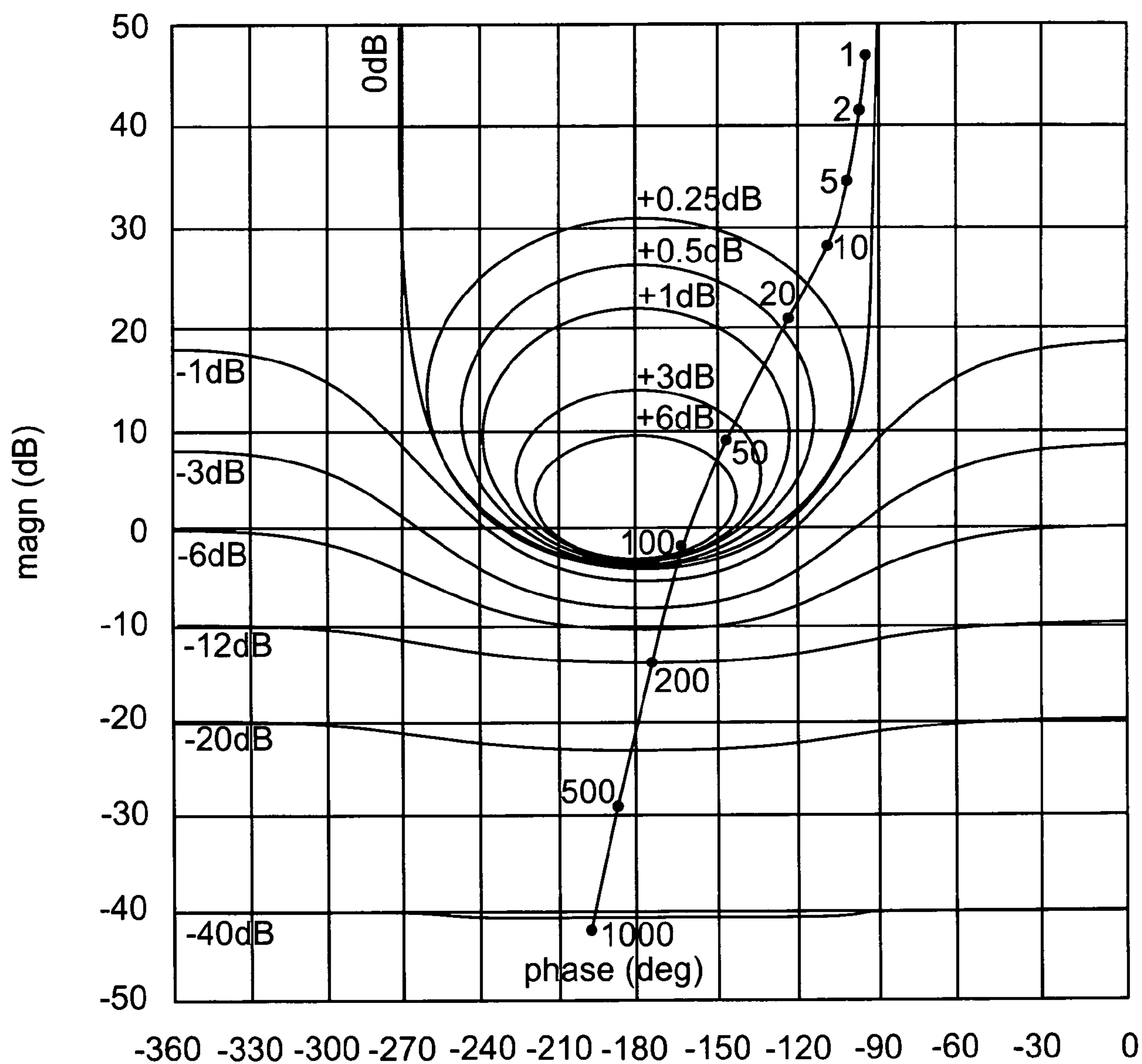


Fig. 3

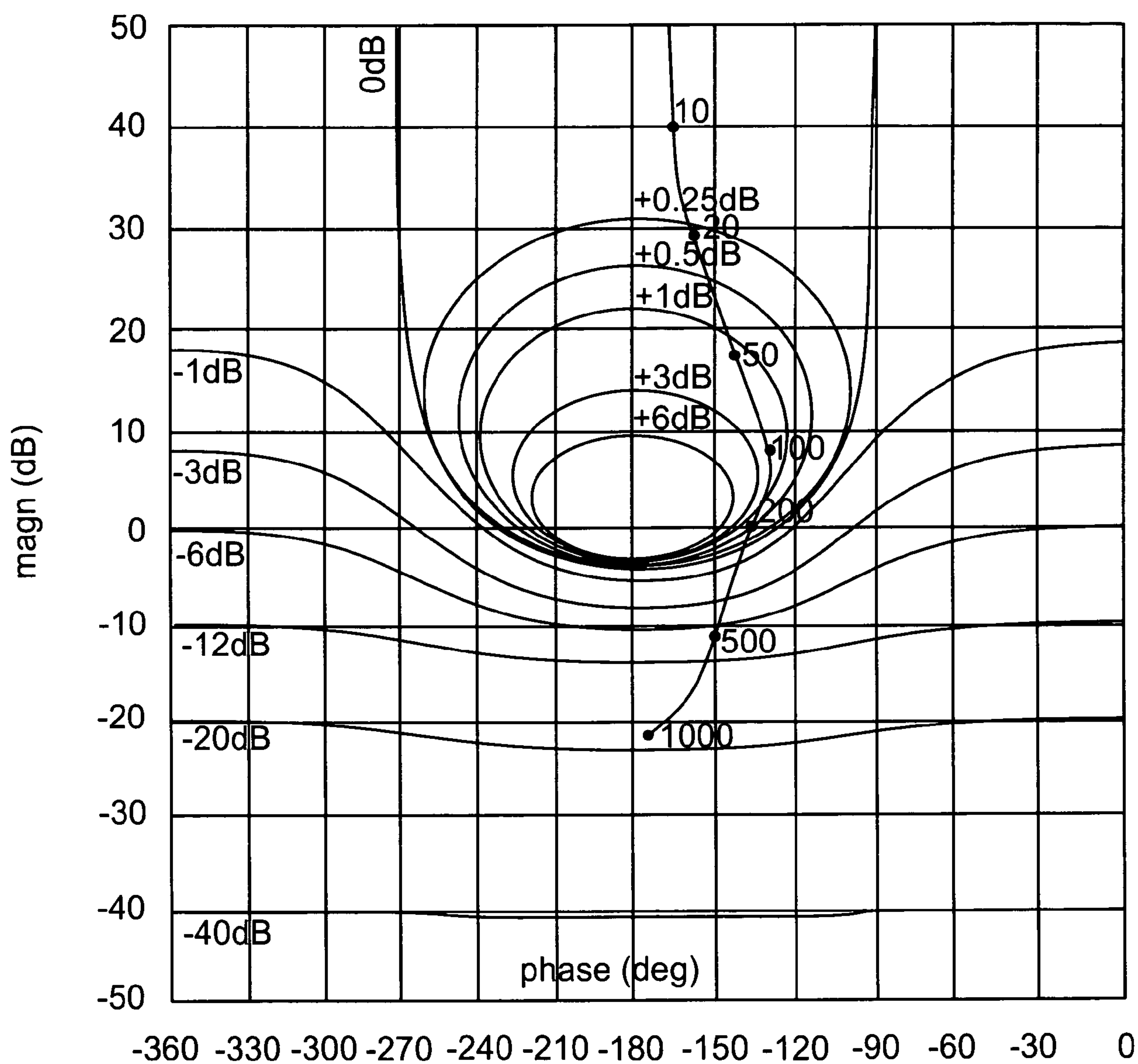


Fig. 4

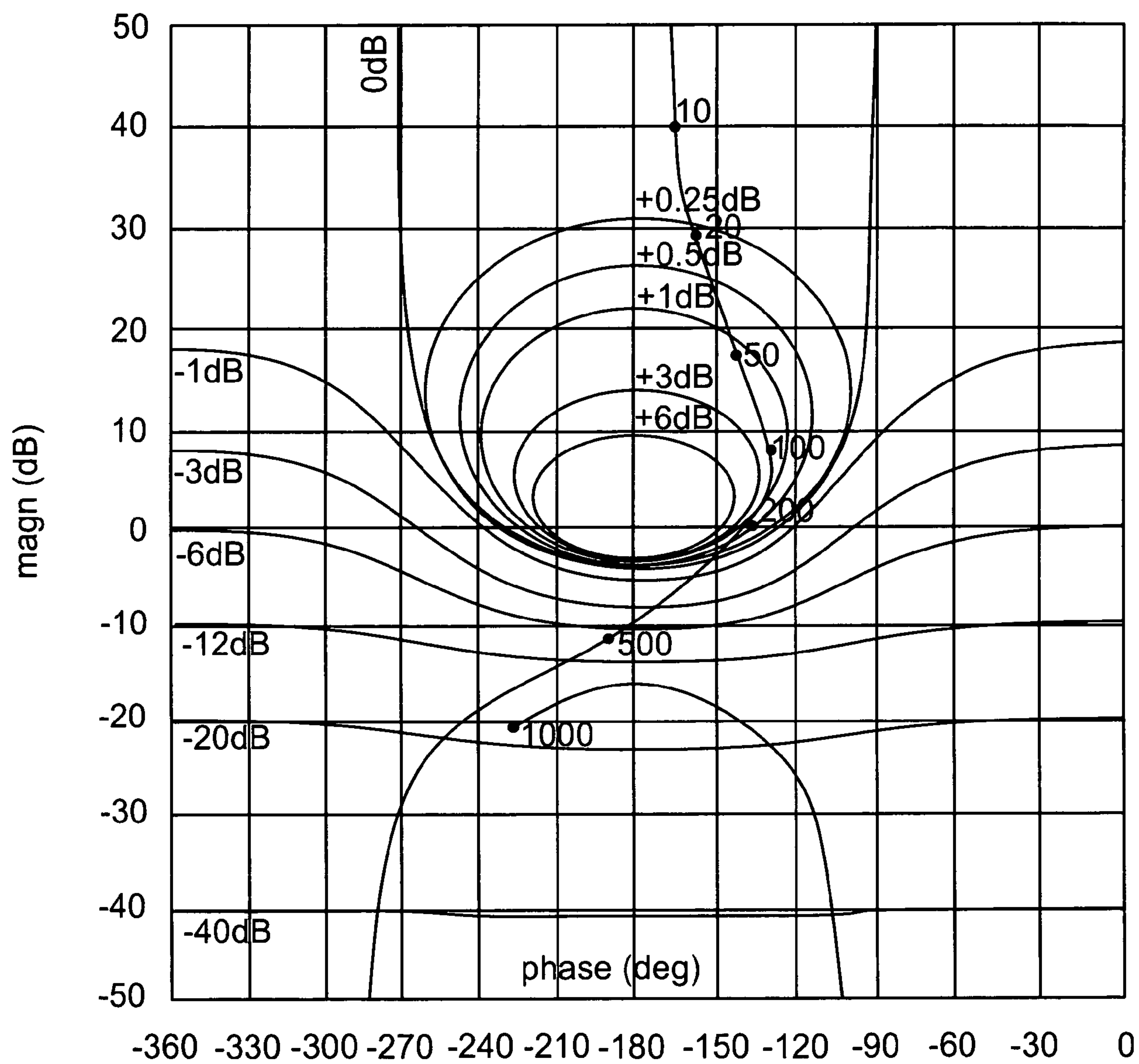


Fig. 5

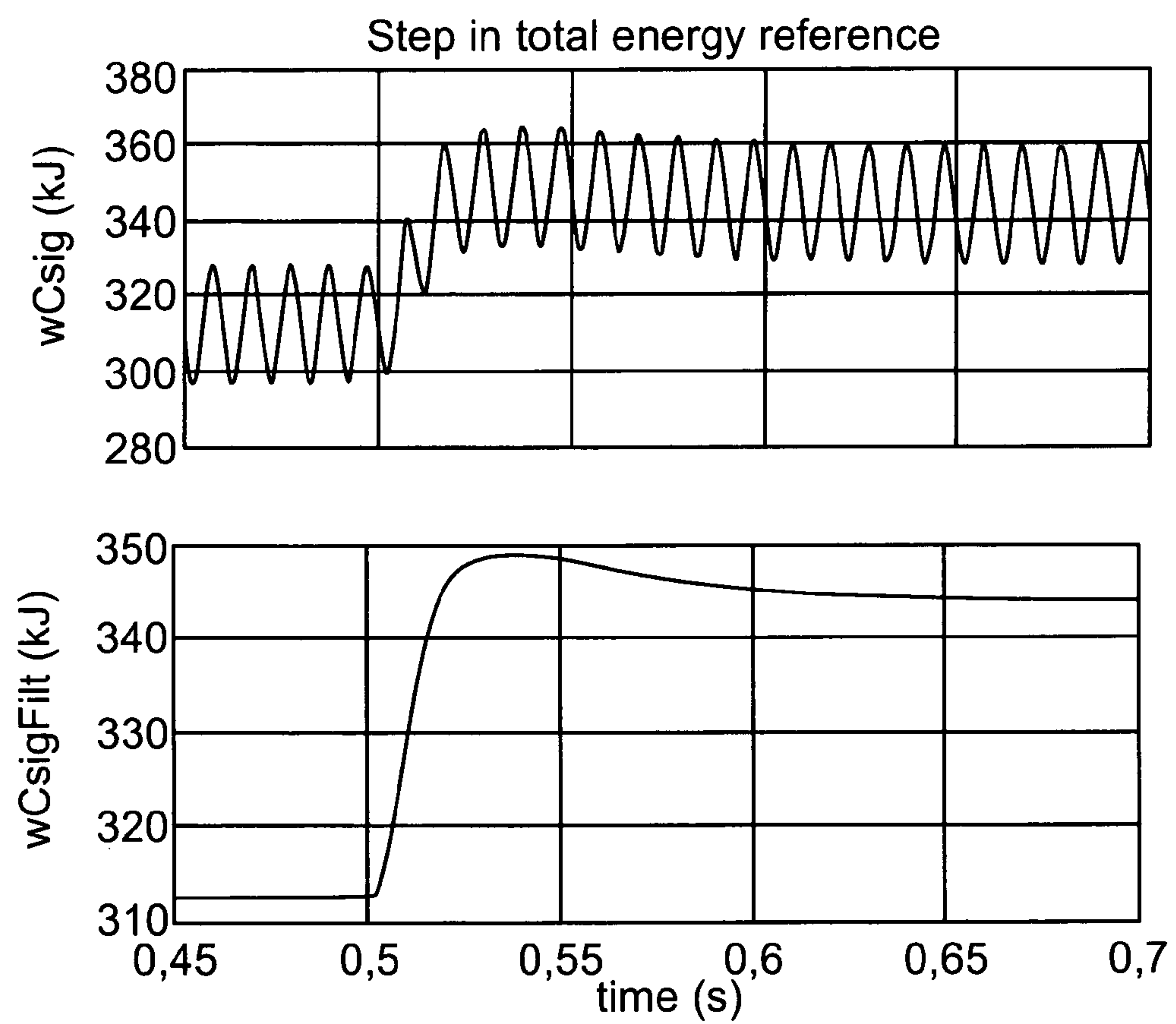


Fig. 6

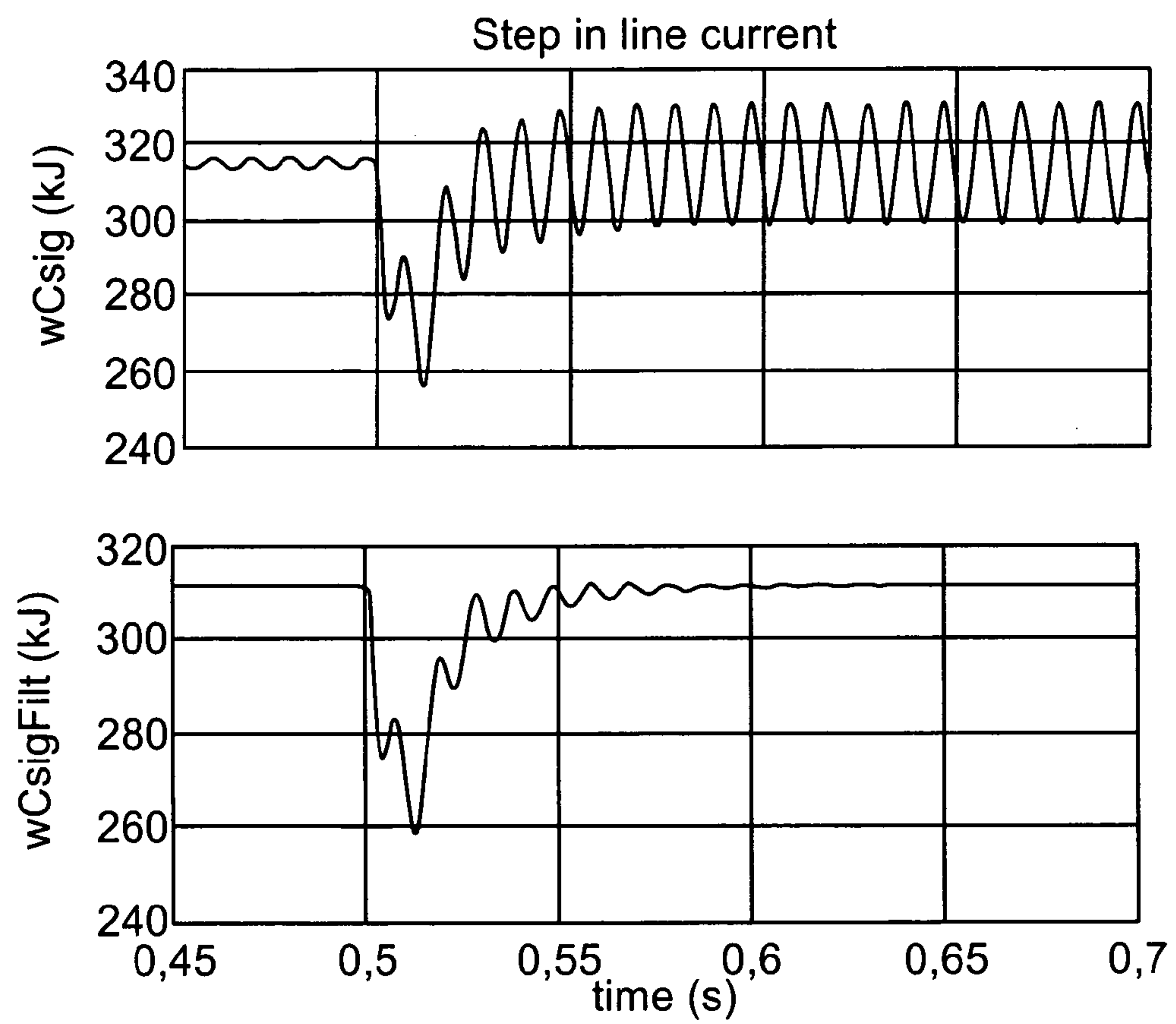


Fig. 7

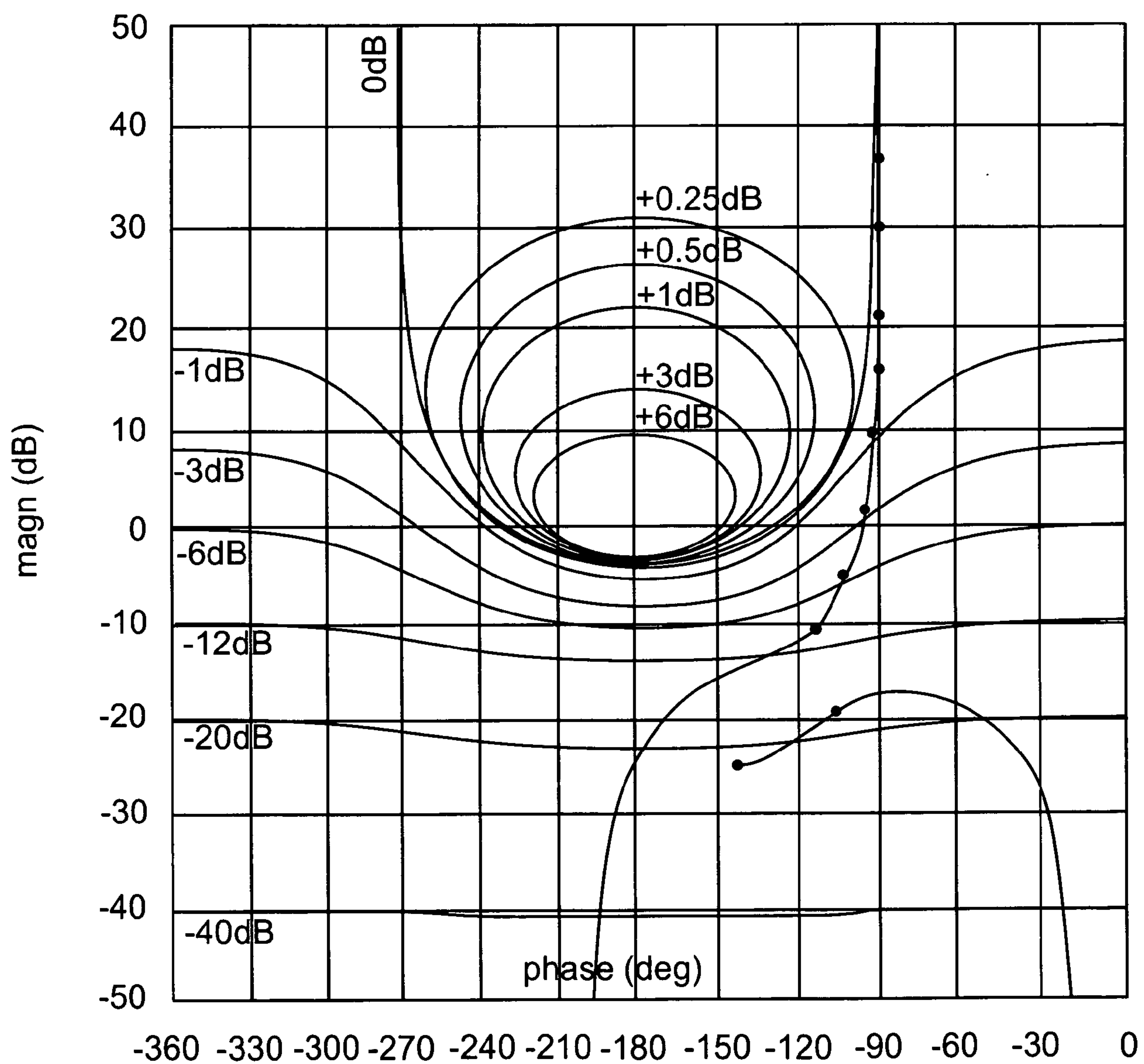


Fig. 8

