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

(72) Inventor; and

(75) Inventor/Applicant (for US only): **DIJKHUIZEN, Frans** [NL/SE]; Bankvägen 20, S-730 50 Skultuna (SE).(74) Agent: **AHRENGART, Kenneth**; Ingenjör Bååths Gata 11, S-721 83 Västerås (SE).

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(54) Title: AN APPARATUS FOR ASSISTING OR CONTROLLING THE ELECTRIC POWER TRANSMISSION IN A DC POWER TRANSMISSION SYSTEM

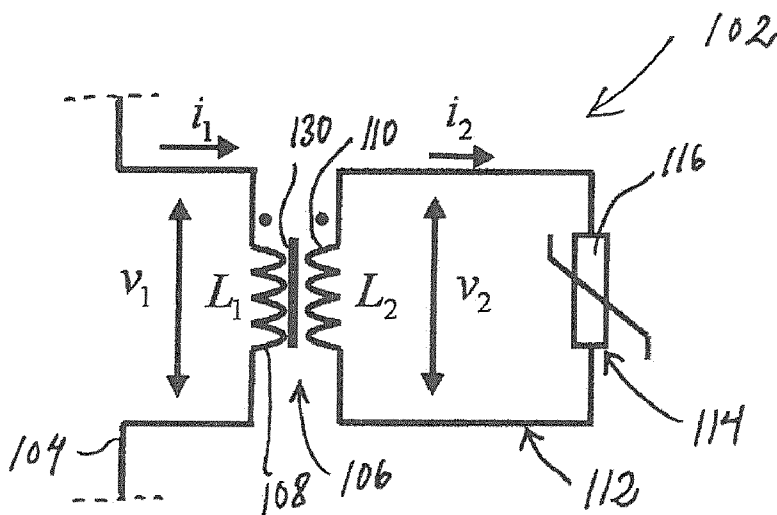


Fig. 1

(57) Abstract: An apparatus (102; 202; 302; 502; 602; 702) for assisting or controlling the electric power transmission in a direct current power transmission system (802; 810; 830; 900) comprising at least one direct current transmission or distribution line (104; 804; 812, 814, 816, 818, 820; 832; 914) for carrying direct current, DC, the apparatus comprising a transformer (106) having a primary winding (108) and at least one secondary winding (110), the primary winding being connectable in series with the DC transmission or distribution line to carry the current (i_1) of the DC transmission or distribution line, and the secondary winding is connected to an electrical load (112), wherein the transformer is arranged to supply a secondary current (i_2) to the electrical load, the secondary current being at least partially based on a surge current of the DC transmission or distribution line, and wherein the apparatus is arranged to limit the surge current by introducing at least one opposing voltage (v_1) in series with the DC transmission or distribution line, the at least one opposing voltage being at least partially based on the

current (i_2) of the electrical load. A direct current power transmission system comprising at least one apparatus (102; 202; 302; 502; 602; 702) mentioned above.

AN APPARATUS FOR ASSISTING OR CONTROLLING THE ELECTRIC POWER TRANSMISSION IN A DC POWER TRANSMISSION SYSTEM

Technical Field

The present invention relates to an apparatus for assisting or controlling
5 the electric power transmission in a direct current power transmission system comprising at least one direct current transmission or distribution line for carrying direct current, DC, the apparatus comprising a transformer having a primary winding and at least one secondary winding, the primary winding being connect-
10 able in series with the DC transmission or distribution line to carry the current of the transmission or distribution line, and the secondary winding is connected to an electrical load. Further, the present invention relates to a direct current power transmission system comprising at least one DC transmission or distribution line for carrying direct current and at least one apparatus of the above-mentioned sort.

Background of the Invention

15 A HVDC (high voltage direct current) power distribution network or a HVDC power transmission system uses direct current for the transmission of electrical power, in contrast to the more common AC systems. For long-distance distribution, HVDC systems may be less expensive and may suffer lower electrical losses. In general, a HVDC power transmission system comprises at least one
20 long-distance HVDC link or cable for carrying direct current a long distance, e.g. under sea, and converter stations for converting alternating current to direct current for input to the HVDC power transmission system and converter stations for converting direct current back to alternating current.

However, in HVDC power transmission systems, it may be necessary to
25 rapidly limit the current in the DC power transmission system and also quickly interrupt the current, since the alternating voltage network is through a converter directly connected to the DC power transmission system, which may mean suddenly very high currents, transient currents, directly into the DC power transmission system, when for example a ground fault occurs there. Mechanical breakers
30 in the DC power transmission system may often not be enough, since the time available for breaking the current may be too short for such a mechanical breaker.

US 7,408,755 B1 discloses a circuit for inrush/transient current limitation and overload/short circuit protection for a DC voltage power supply.

US 7,974,059 B2 describes a power supply apparatus comprising a DC power source that outputs DC voltage, a power supply circuit to which the DC voltage output from the DC power source is applied, and a current limiting unit connected in series between the DC power source and the power supply circuit.

5 US 6,624,993 B1 discloses a fault current limiting system for DC and pulsed circuit systems.

EP 1 526 624 A2 describes an assembly which rapidly identifies a short circuit in an alternating current or direct current power supply system and shuts down the system at once. The short circuit current flows through a high temperature super-conductor current limiter (HTS) in series with a switchgear station.

US 5,596,472 discloses an apparatus for controlling an over-current tripping device of a high-speed DC circuit breaker, at least partially based on an output signal generated by a current transformer.

JP 54137646 describes a protective circuit for DC current transformer.

15 WO 2011/057675 A1 discloses a breaking device for breaking a direct current flowing through a HVDC power transmission or distribution line. The breaking device comprises a parallel connection of a main breaker and a non-linear resistor, the main breaker comprising at least one power semiconductor switch of a first current direction, and a series connection of a high speed switch and an auxiliary
20 breaker, the high speed switch comprising at least one mechanical switch, and the auxiliary breaker has a smaller on-resistance than the main breaker and comprises at least one power semiconductor switch of the first current direction, where the series connection is connected in parallel to the parallel connection.

The Object of the Invention

25 The object of the present invention is to improve the electric power transmission in a DC power transmission system, especially in a HVDC power transmission system. It is also an object of the present invention to provide an improved control of the electric power transmission in a DC power transmission system. Another object of the present invention is to provide an improved DC power
30 transmission system, especially a HVDC power transmission system.

Summary of the Invention

The above-mentioned object of the present invention is attained by providing an apparatus for assisting or controlling the electric power transmission in a

direct current power transmission system comprising at least one direct current transmission or distribution line for carrying direct current, DC, the apparatus comprising a transformer having a primary winding and at least one secondary winding, the primary winding being connectable in series with the DC transmission or
5 distribution line to carry the current of the DC transmission or distribution line, and the secondary winding is connected to an electrical load, wherein the transformer is arranged to supply a secondary current to the electrical load, the secondary current being at least partially based on a surge current of the DC transmission or distribution line, and wherein the apparatus is arranged to limit the surge current
10 by introducing at least one opposing voltage in series with the DC transmission or distribution line, the at least one opposing voltage being at least partially based on the current of the electrical load.

By means of the apparatus according to the present invention, transient surge currents occurring in the system are efficiently limited and the system is efficiently protected against surge currents, also called fault currents or over-currents.
15 By means of the apparatus according to the present invention, an improved control of the electric power transmission in a DC power transmission system is provided, and the electric power transmission in a DC power transmission system, especially in a HVDC power transmission system, is improved. By the surge current limitation provided by the inventive apparatus, the stress on the at least one DC line and any converter stations is reduced. By means of the apparatus according to the present invention, an improved DC power transmission system is provided. Further, the
20 inventive apparatus provides a "passive" surge current limitation and electric power transmission control, i.e. no active measures performed by an operator are necessary to provide the surge current limitation and the control, as the surge current limitation automatically reacts. The performance of the apparatus is energized by the surge current per se, and no additional power source is required for the apparatus.

The control of the electric power transmission or the surge current limitation is attained by the apparatus' introduction, or injection, of an opposing voltage
30 in series with the DC transmission or distribution line. The injected opposing voltage produces a fictive resistance. The fictive resistance provides an active power extraction or output from the DC transmission or distribution line (since a resistance consumes power/energy). The apparatus' active power extraction or output

from the DC transmission or distribution line results in a decrease or limitation of a surge current arising in the DC line. The active power extracted from the DC transmission or distribution line may be absorbed by the electrical load. Thus, the opposing voltage opposes the transient current increase of a surge current. For
5 example, the opposing voltage may be introduced as a positive voltage in series with the DC transmission or distribution line for reducing or limiting a surge current arising in the line.

A surge current may be defined as a short-duration, high-amperage electric current wave that may sweep through an electrical network, as a power transmission network, when some portion of it is influenced by a fault or failure.
10

When a correct direct current is carried by the DC transmission or distribution line and by the primary winding of the transformer, i.e. a direct current essentially without any variations in current and without any surge current, no varying magnetic field is created through the secondary winding, and, consequently, no
15 voltage is induced across the secondary winding and no current is supplied to the electrical load. Thus, the electrical load has no influence on the current of the DC transmission or distribution line during steady state or normal operating conditions. When, a surge current is generated in the DC transmission or distribution line and in the primary winding of the transformer, the current derivate of the surge current
20 creates a varying magnetic field through the secondary winding, and, consequently, a secondary voltage is induced across the secondary winding, and a secondary current is then supplied to the electrical load.

The electrical load may comprise an electric circuit, at least one electrical device or an electric circuit comprising at least one electrical device.
25

The DC transmission or distribution line may be any electrical conductor or electrically conductive element or means arranged between a first position and a second position for carrying direct current.

According to an advantageous embodiment of the apparatus according to the present invention, the apparatus comprises a plurality of transformers, the primary winding of each transformer is connectable in series with the DC transmission or distribution line to carry the current of the DC transmission or distribution line, and the secondary winding of each transformer is connected to an electrical load. By means of this embodiment, the surge current limitation and the electric power transmission control are further improved. The flexibility of the surge current
30

limitation and of the electric power transmission control is improved as the number of transformers may easily be increased or reduced for specific applications.

According to a further advantageous embodiment of the apparatus according to the present invention, the primary windings of the plurality of transformers
5 are connected in series with one another. By means of this embodiment, the surge current limitation and the electric power transmission control are further improved.

According to another advantageous embodiment of the apparatus according to the present invention, the transformer is arranged to DC isolate the electric load from the DC transmission or distribution line. The electric load is DC isolated
10 in that no DC path exists or is provided between the DC transmission or distribution line and the electric load. Thus, the electric load does not influence the electric power transmission of the DC transmission or distribution line when the line carries a correct direct current. By means of this embodiment, the surge current limitation and the electric power transmission control are further improved.

15 According to still another advantageous embodiment of the apparatus according to the present invention, the electrical load comprises an electrical device of a group of electrical devices comprising a nonlinear resistor, an inductor and a linear resistor. By means of this embodiment, the surge current limitation and the electric power transmission control are further improved. The electrical load may
20 comprise more than one electrical device, i.e. a plurality of electrical devices. When the apparatus comprises a plurality of transformers, the transformers may be connected to different types of electrical devices in relation to one another, or they may be connected to the same type of electrical device.

According to an advantageous embodiment of the apparatus according to
25 the present invention, the electrical load comprises an electrical device of a group of electrical devices comprising a nonlinear resistor and an inductor.

According to a further advantageous embodiment of the apparatus according to the present invention, the electrical load comprises an electrical device comprising a nonlinear resistor.

30 According to another advantageous embodiment of the apparatus according to the present invention, the nonlinear resistor comprises a voltage-dependent nonlinear resistor. A voltage-dependent nonlinear resistor is a device which has a voltage-dependent nonlinear resistance. In general, a voltage-dependent nonlinear resistor conducts a very low current, but when the voltage across the voltage-de-

pendent nonlinear resistor exceeds a certain level it will conduct a substantially increased current. The threshold or clamping voltage, of each voltage-dependent nonlinear resistor may be adapted to specific applications. By means of this embodiment, the surge current limitation and the electric power transmission control
5 are further improved.

According to yet another advantageous embodiment of the apparatus according to the present invention, the voltage-dependent nonlinear resistor comprises a surge arrester. The surge arrester, or lightning arrester, per se can be structured in various suitable ways known to the skilled person, and may e.g. be in
10 the form of a zinc oxide surge arrester, which is also denominated MOV (Metal Oxide Varistor). However, other types of surge arresters are possible. The surge arrester normally conducts a very low current, but when the voltage across the surge arrester exceeds a certain level it will conduct a substantially increased current. By means of this embodiment, the surge current limitation and the electric
15 power transmission control are further improved.

According to still another advantageous embodiment of the apparatus according to the present invention, the apparatus is arranged to limit surge current of the DC transmission or distribution line by introducing, in series with the DC transmission or distribution line, at least one opposing voltage that is at least partially based on the electrical device current. By means of this embodiment, the
20 surge current limitation and the electric power transmission control are further improved.

According to a further advantageous embodiment of the apparatus according to the present invention, each transformer comprises an air core or a metal
25 core. The metal core may be a solid metal core or a laminated metal core. The metal core may be an iron core. Other cores may also be possible.

According to another advantageous embodiment of the apparatus according to the present invention, the primary winding and the secondary winding of the transformer are coaxial. By means of this embodiment, the surge current limitation
30 and the electric power transmission control are further improved.

According to yet another advantageous embodiment of the apparatus according to the present invention, the apparatus is arranged to assist or control the electric power transmission in a high voltage direct current, HVDC, power transmission system comprising at least one HVDC transmission or distribution line for

carrying high voltage direct current. The apparatus may also be arranged to assist or control the electric power transmission in an ultra-high voltage direct current, UHVDC, power transmission system, or an extra high voltage direct current power transmission system, each system comprising at least one HVDC transmission or distribution line. However, the apparatus may also be arranged to assist or control the electric power transmission in other DC power transmission systems, e.g. a medium voltage DC power transmission system. The inventors have found that the innovative apparatus is especially advantageous for HVDC and UHVDC power transmission system, respectively, and the surge current limitation and the electric power transmission control in these systems are further improved.

The various components of the apparatus of the present invention, which are connected or connectable to one another or to other units, may be electrically connected, or connectable, to one another or to other units, e.g. via electrical conductors, e.g. busbars or DC lines, and/or may be indirectly connected, or connectable, to one another or to other units, e.g. electrically or inductively, e.g. via additional intermediate electric equipment or units located and connected/connectable between the components.

In general, High Voltage may be about 1-1.5 kV and above. However, for HVDC applications and systems, High Voltage may be about 150 kV and above, e.g. 320 kV, 640 kV, 800 kV or 1000 kV, and above. The apparatus and/or the system according to the present invention are advantageously adapted for the above-mentioned HVDC voltage levels and above. For UHVDC applications and systems, Ultra High Voltage may be about 1100 kV and above.

The above-mentioned object of the present invention is also attained by a direct current power transmission system comprising at least one direct current transmission or distribution line for carrying direct current, DC, wherein the system comprises at least one apparatus as claimed in any of the claims 1-11 for assisting or controlling the electric power transmission in the system, and/or at least one apparatus according to any of the above-mentioned embodiments of the apparatus. Positive technical effects of the direct current power transmission system according to the present invention, and its embodiments, correspond to the above-mentioned technical effects mentioned in connection with the apparatus according to the present invention, and its embodiments. The at least one direct current transmission or distribution line may be one or a plurality of direct current trans-

mission or distribution lines. The at least one apparatus may be one or a plurality of apparatuses, e.g. two or more apparatuses. A plurality of apparatuses may be connected to the same DC transmission or distribution line, or to different DC transmission or distribution lines.

5 According to an advantageous embodiment of the direct current power transmission system according to the present invention, the system comprises a breaking device for breaking the current of the at least one direct current transmission or distribution line, the breaking device being connected in series with the at least one apparatus. The inventors of the present invention have found that the
10 combination of the inventive apparatus and a breaking device is advantageous for the electric power transmission control, and by means of this embodiment, the electric power transmission control is further improved. The breaking device may comprise a mechanical switch and/or at least one power semiconductor switch. As disclosed in the detailed description of preferred embodiments, the breaking de-
15 vice may comprise a parallel connection of a main breaker and a non-linear resistor, the main breaker comprising at least one power semiconductor switch of a first current direction, and a series connection of a high speed switch and an auxiliary breaker, the high speed switch comprising at least one mechanical switch, and the auxiliary breaker has a smaller on-resistance than the main breaker and com-
20 prises at least one power semiconductor switch of the first current direction, where the series connection is connected in parallel to the parallel connection.

 According to a further advantageous embodiment of the direct current power transmission system according to the present invention, the system comprises a plurality of converters connected to the at least one DC transmission or
25 distribution line, each of the converters being arranged to convert alternating current to direct current for input to the at least one DC transmission or distribution line, and/or direct current to alternating current. A plurality of converters may be two or more converters. Each converter may be in the form of a converter station, e.g. a VSC (Voltage Sourced Converter), structured in ways known to the person
30 skilled in the art.

 According to another advantageous embodiment of the direct current power transmission system according to the present invention, the system comprises a plurality of DC transmission or distribution lines. A plurality of DC trans-

mission or distribution lines may be two or more DC transmission or distribution lines.

According to yet another advantageous embodiment of the direct current power transmission system according to the present invention, the system comprises at least three converters, each of the converters being arranged to convert alternating current to direct current for input to the at least one DC transmission or distribution line, and/or direct current to alternating current. Advantageously, the system comprises at least four converters, or at least five converters.

According to still another advantageous embodiment of the direct current power transmission system according to the present invention, the at least one DC transmission or distribution line comprises at least one long-distance HVDC link. Advantageously, the HVDC transmission lines may comprise at least two long-distance HVDC links or cables.

The above-mentioned embodiments and features of the apparatus and the direct current power transmission system, respectively, according to the present invention may be combined in various possible ways providing further advantageous embodiments.

Further advantageous embodiments of the apparatus and the direct current power transmission system, respectively, according to the present invention and further advantages with the present invention emerge from the detailed description of embodiments.

Brief Description of the Drawings

The present invention will now be described, for exemplary purposes, in more detail by way of embodiments and with reference to the enclosed drawings, in which:

- Fig. 1 is a schematic block diagram illustrating a first embodiment of the apparatus according to the present invention;
- Fig. 2 is a schematic diagram illustrating the characteristics of an electrical device of the first embodiment of Fig. 1;
- Fig. 3 is a schematic block diagram illustrating a second embodiment of the apparatus according to the present invention;
- Fig. 4 is a schematic block diagram illustrating a third embodiment of the apparatus according to the present invention;

- Fig. 5 is a schematic block diagram illustrating a fourth embodiment of the apparatus according to the present invention;
- Fig. 6 is a schematic block diagram illustrating a fifth embodiment of the apparatus according to the present invention;
- 5 Fig. 7 is a schematic block diagram illustrating aspects of a sixth embodiment of the apparatus according to the present invention;
- Fig. 8 is a schematic block diagram illustrating a first embodiment of the direct current power transmission system according to the present invention, comprising an apparatus according to the present invention;
- 10 Fig. 9 is a schematic block diagram illustrating a second embodiment of the direct current power transmission system according to the present invention, comprising a plurality of apparatuses according to the present invention;
- 15 Fig. 10 is a schematic block diagram illustrating a third embodiment of the direct current power transmission system according to the present invention, comprising an apparatus according to the present invention; and
- 20 Fig. 11 is a schematic block diagram illustrating a fourth embodiment of the direct current power transmission system according to the present invention, comprising an apparatus according to the present invention.

Detailed Description of Preferred Embodiments

Each of the Figs. 1 and 3-4 schematically illustrates embodiments of the apparatus 102, 202, 302 according to the present invention, each apparatus 102, 202, 302 being arranged to assist or control the electric power transmission in a direct current power transmission system comprising at least one direct current transmission or distribution line 104 for carrying direct current, DC, i_l . The DC transmission or distribution line 104 may e.g. comprise a DC cable, busbar, or any other electrical conductor or electrically conductive element or means for carrying direct current. Each apparatus 102, 202, 302 comprises a transformer 106, 206, 306 having a primary winding 108, 208, 308 and a secondary winding 110, 210, 310, the primary winding 108, 208, 308 being connectable in series with the DC transmission or distribution line 104 to carry the current i_l of the DC transmission

or distribution line 104, and the secondary winding 110, 210, 310 is connected to an electrical load 112, 212, 312. Alternatively, the transformer may comprise a plurality of secondary windings each having an electrical load.

The electrical load 112 of the first embodiment of the apparatus 102,
5 shown in Fig. 1, comprises an electrical device 114 comprising a nonlinear resistor 216. The nonlinear resistor 116 may comprise a voltage-dependent nonlinear resistor, e.g. a surge arrester. However, other sorts of voltage-dependent nonlinear resistors are possible.

The electrical load 212 of the second embodiment of the apparatus 202,
10 shown in Fig. 3, comprises an electrical device 214 comprising a linear resistor 216.

The electrical load 312 of the third embodiment of the apparatus 302, shown in Fig. 4, comprises an electrical device 314 comprising an inductor 316, e.g. a coil.

15 During normal operating conditions, steady state, a correct direct current, i.e. a direct current essentially without any variations in current, is carried by the DC transmission or distribution line 104 and by the primary winding 108, 208, 308 of the transformer 106, 206, 306. Each transformer 106, 206, 306 is arranged to DC isolate the electric load 112, 212, 312, from the DC transmission or distribution
20 line 104. The electric load 112, 212, 312 is DC isolated in that no DC path exists or is provided between the DC transmission or distribution line 104 and the electric load 112, 212, 312. When a correct direct current, i.e. a non-varying current, is carried by the DC transmission or distribution line 104 and by the primary winding 108, 208, 308, no varying magnetic field is created through the secondary winding
25 110, 210, 310, and, consequently, no voltage is induced across the secondary winding 110, 210, 310 and no current is supplied to the electrical load 112, 212, 312. Thus, the electrical load 112, 212, 312 has no influence on the current i_l of the DC transmission or distribution line during steady state, i.e. each transformer 106, 206, 306 DC isolates the electric load 112, 212, 312.

30 When a fault occurs in the DC transmission or distribution line 104, a transient surge current is generated in the DC line 104 and in the primary winding 108, 208, 308 of the transformer 106, 206, 306, e.g. as a result of a transient voltage drop,. A surge current may be defined as a short-duration, high-amperage electric current wave that sweeps through the transmission system. Each transformer 106,

206, 306 is arranged to supply a secondary current i_2 to the electrical load 112, 212, 312, the secondary current i_2 being at least partially based on a surge current of the DC line 104. The apparatus 102, 202, 302 is arranged to limit the surge current by introducing at least one opposing voltage v_1 in series with the DC line 104, the at least one opposing voltage v_1 being at least partially based on the current i_2 of the electrical load 112, 212, 312. More specifically, the apparatus 102, 202, 302 may be arranged to limit surge current of the DC line 104 by introducing, in series with the DC line 104, at least one opposing voltage v_1 that is at least partially based and dependent on the electrical device current i_2 . When, a surge current is generated in the DC line 104 and in the primary winding 108, 208, 308, the current derivative of the surge current creates a varying magnetic field through the secondary winding 110, 210, 310, for reasons well known to the person skilled in the art. As a consequence, a secondary voltage v_2 is induced across the secondary winding 110, 210, 310 and a secondary current i_2 is supplied to the electrical load 112, 212, 312.

The control of the electric power transmission or the surge current limitation is attained by the apparatus' 102, 202, 302 introduction, or injection, of an opposing voltage in series with the DC line 104. The injected opposing voltage produces a fictive resistance. The fictive resistance provides an active power extraction or output from the DC line 104 (since a resistance consumes power/energy). The apparatus' 102, 202, 302 active power extraction or output from the DC line 104 results in a decrease, or limitation, of the surge current, which arises in the DC line 104. The active power extracted from the DC line 104 may be absorbed by the electrical load 112, 212, 312. Thus, the opposing voltage v_1 opposes the transient current increase of a surge current. For example, the opposing voltage v_1 may be introduced as a positive voltage in series with the DC line 104 for reducing or limiting a surge current. The apparatus 102, 202, 302 provides a "passive" surge current limitation and electric power transmission control, i.e. no active measures performed by an operator are necessary to provide the surge current limitation and the control.

With reference to Figs. 1 and 2, the surge current limitation of the innovative apparatus is hereinafter explained in more detail with reference to the first embodiment of the apparatus 102 which has a nonlinear resistor 116. Fig. 2 is a schematic diagram illustrating the non-linear characteristics of a nonlinear resistor

116 of the first embodiment of Fig. 1, which are well known to the person skilled in the art. The transformer relations of the transformer 106 may be given by the following expressions:

$$v_1 = i_1 R_1 + L_1 \frac{di_1}{dt} - M_{12} \frac{di_2}{dt} \quad [1]$$

$$v_2 = -i_2 R_2 - L_2 \frac{di_2}{dt} + M_{21} \frac{di_1}{dt} \quad [2]$$

10 where v_1 is the voltage across the primary winding 108, v_2 is voltage across the secondary winding 110, i_1 is the primary current through the primary winding 102, i_2 is the secondary current through the secondary winding 110 and the electrical load 112, R_1 is the resistance of the primary winding 108, R_2 is the resistance of the secondary winding 110, L_1 is the inductance of the primary winding 108, L_2 is
15 the inductance of the secondary winding 110, and M_{12} and M_{21} are the mutual inductances. The mutual inductances M_{12} , M_{21} may be given by the following expression:

$$M_{12} = M_{21} = M = k \sqrt{L_1 L_2} \quad [3],$$

20 where k is the coupling factor. The secondary voltage v_2 may be equal to the voltage across the nonlinear resistor 116 according to the expression:

$$v_2 = K(i_2)^\alpha \quad [4],$$

25

where α depends on the operating region of the nonlinear resistor 116 and K is a constant. If the resistance of the primary and secondary windings 108, 110, respectively, is neglected for illustrative purposes, i.e. $R_1 = R_2 = 0$, and expression [4] is incorporated in expression [2], the following expression is obtained:

$$L_2 \frac{di_2}{dt} = M \frac{di_1}{dt} - K(i_2)^\alpha \quad [5].$$

If expression [5] is incorporated in expression [1], the following expression is obtained:

$$v_1 = L_1 \frac{di_1}{dt} - \frac{M^2}{L_2} \frac{di_1}{dt} + \frac{MK}{L_2} (i_2)^\alpha \quad [6].$$

With there is a 1:1 turn ratio for the primary and secondary windings 108, 110,
 5 where

$$i_2 = \frac{n_1}{n_2} i_1 = i_1 \quad [7],$$

expression [6] turns into the following expression:
 10

$$v_1 = L_1 \frac{di_1}{dt} - \frac{M^2}{L_2} \frac{di_1}{dt} + \frac{MK}{L_2} (i_1)^\alpha \quad [8].$$

Expression [8] clearly illustrates the influence of the nonlinear resistor 116 on the
 15 voltage v_1 across the primary winding 108 and thus on the current i_1 of the DC line
 104 when a varying surge current is generated in the DC line 104.

With reference to Fig. 5, a fourth embodiment of the apparatus 502
 according to the present invention is illustrated. The apparatus 502 comprises a
 plurality of transformers 506, 507, where the primary winding 508, 509 of each
 20 transformer 506, 507 is connectable to and connectable in series with the DC line
 104 to carry the current of the DC line 104. The primary windings 508, 509 of the
 plurality of transformers 506, 507 may be connected in series with one another.
 The secondary winding 510, 511 of each transformer 506, 507 is connected to an
 electrical load 512, 513. More specifically, the fourth embodiment of the apparatus
 25 502 comprises two transformers 506, 507. In the fourth embodiment, each electri-
 cal load 512, 513 comprises an electrical device 514, 515 comprising a nonlinear
 resistor 516, 517. Otherwise, the fourth embodiment of the apparatus 502 essen-
 tially corresponds to the embodiments of Figs. 1 and 3-4. In Fig. 6, a fifth embodi-
 ment of the apparatus 602 is illustrated, which essentially corresponds to the em-
 30 bodiment of Fig. 5, but where one of the electrical devices has been replaces and
 instead comprises an inductor 616.

With reference to Fig. 7, a sixth embodiment of the apparatus 702 accord-
 ing to the present invention is illustrated. The apparatus 702 comprises a plurality
 of transformers 706, 707, 718, where the primary winding 708, 709, 720 of each

transformer 706, 707, 718 is connectable to and connectable in series with the DC line 104 to carry the current of the line 104. The primary windings 708, 709, 720 of the plurality of transformers 706, 707, 718 may be connected in series with one another. The secondary winding 710, 711, 722 of each transformer 706, 707, 718 is connected to an electrical load 712, 713, 724. More specifically, the sixth embodiment of the apparatus 702 comprises three transformers 706, 707, 718. However, it is also possible to provide the apparatus with more transformers, or fewer transformers. In the sixth embodiment, two electrical loads 712, 724 comprise an electrical device 714, 726 comprising an inductor 716, 728, and one electrical load 713 comprises an electrical device 715 comprising a linear resistor 717. Otherwise, the sixth embodiment of the apparatus 702 essentially corresponds to the embodiments of Figs. 1 and 3-4. The electrical devices of the embodiments of Figs. 5-7, may be replaced by any of the other electrical devices shown in the embodiments of Figs 1 and 3-4.

Each transformer 106, 206, 306, 506, 507, 606, 607, 706, 707, 718 may comprise a core 130, 230, 330, 530, 630, 730, which may be an air core or a metal core, e.g. an iron core. The metal core may be a solid metal core or a laminated metal core. The primary winding 108, 208, 308, 508, 509, 608, 609, 708, 709, 720 and the secondary winding 110, 210, 310, 510, 511, 610, 611, 710, 711, 722 of the transformer may be coaxial. Each of the primary and secondary windings may comprise a coil, and the primary and secondary windings may surround the same core. When the apparatus 502, 602, 702 comprises a plurality of transformers 506, 507, 606, 607, 706, 707, 718, the transformers 506, 507, 606, 607, 706, 707, 718 may be structures in the same manner or they may differ from one another, e.g. with regard to the coupling coefficient, the ratio of the number of turns of the primary and secondary windings, respectively etc.

The DC line 104 may be a HVDC transmission or distribution line of HVDC power transmission system, and each apparatus 102, 202, 302, 502, 602, 702 may be arranged to assist or control the electric power transmission in the HVDC power transmission system. Figs. 1-7 also illustrates embodiments of the direct current power transmission system according to the present invention, comprising the DC line 104 for carrying direct current, DC, and respective apparatus 102, 202, 302, 502, 602, 702 for assisting or controlling the electric power transmission in the system.

With reference to Fig. 8, a further embodiment of the DC power transmission system 802 according to the present invention is schematically illustrated. The system 802 comprises at least one DC transmission or distribution line 804 and may comprise a plurality of apparatuses 102 according to the first embodiment as disclosed above (see Fig. 1). In Fig. 8, only three apparatuses 102 are shown, but it should be understood that the system 802 may comprise more apparatuses 102 than the three shown. The DC power transmission system 802 may comprise at least one converter 806, e.g. a converter station, such as a VSC, electrically connected to the DC line 804. The converter 806 may be arranged to convert alternating current to direct current for input to the DC transmission line 804 and convert direct current to alternating current for input to at least one neighbouring AC system. The system may also comprise a second converter (not shown), e.g. a converter station, such as a VSC, electrically connected to the DC line 804 and arranged to convert alternating current to direct current for input to the DC transmission line 804 and convert direct current to alternating current for input to at least one neighbouring AC system. The DC power transmission system 802 may be a HVDC power transmission system, and the at least one DC transmission or distribution line 804 may be a HVDC transmission line.

With reference to Fig. 8, there is an impedance Z of the DC line 804 between the converter 806 and the plurality of apparatuses 102, and the converter 806 supplies a voltage V_{dc} . In the event of a fault in the system 802, herein as a fault to the right of the plurality of apparatuses 102 and illustrated by a lightning symbol, the DC voltage may be rapidly reduced, e.g. to about zero, resulting in that the current delivered by the converter 806 may be increased, e.g. as illustrated by the following expression:

$$I_{fault} = I_{dc,nom} + \frac{V_{dc}}{Z} l(t - t_{fault}) \quad [9],$$

where $l = 1$ for $t > t_{fault}$. Otherwise l is zero. In order to limit the undesired fault current I_{fault} , or surge current, the apparatuses 102 are arranged to introduce an opposing voltage v_1 , so that expression [9] instead is expressed as:

$$I_{fault} = I_{dc,nom} + \frac{V_{dc} - v_1}{Z} l(t - t_{fault}) \quad [10],$$

whereby the opposing voltage v_1 reduces or limits the fault current I_{fault} .

With reference to Fig. 9 another embodiment of the of the DC power transmission system 810 according to the present invention is schematically illustrated.

- 5 The system 810 may be a HVDC power transmission system and may comprise a plurality of HVDC transmission lines 812, 814, 816, 818, 820 for carrying direct current. The HVDC transmission lines 812, 814, 816, 818, 820 may e.g. comprise HVDC cables, busbars, or other DC conductors. The HVDC transmission lines 812, 814, 816, 818, 820 may comprise at least one long-distance HVDC link 812, 10 818. In Fig. 9, a first and a second HVDC transmission line 812, 818 of said plurality of HVDC transmission lines 812, 814, 816, 818, 820 are in the form of long-distance HVDC links. HVDC transmission lines and links are well known to the skilled person and thus not discussed in further detail. The HVDC power transmission system 810 comprises a plurality of converters 822, 824, 826, 828, e.g. con- 15 verter stations, electrically connected to the HVDC transmission lines 812, 814, 816, 818, 820. In Fig. 9, four converters 822, 824, 826, 828 are provided, but there may be more or fewer converters. Each of the converters 822, 824, 826, 828 may be arranged to convert alternating current to direct current for input to the HVDC transmission lines 812, 814, 816, 818, 820 and convert direct current to alternating 20 current for input to neighbouring AC systems. One of the long-distance HVDC links 818 is provided with the first embodiment of the apparatus 102, disclosed above, and the other long-distance HVDC link 812 is provided with the fourth embodiment of the apparatus 502 disclosed above. However, the apparatuses 102, 502 may be connected to the system 810 at other locations or connection points.
- 25 The HVDC power transmission system 810 may be adapted for single phase power or multi-phase power, e.g. three-phase power, and the components of the system and the apparatus may be configured accordingly in ways known to the skilled person. It is to be understood that the system 810 may instead be provided with one or a plurality of the other embodiments of the apparatus according to the 30 present invention disclosed above, or combinations thereof.

With reference to Fig. 10 yet another embodiment of the DC power transmission system 830 according to present invention is schematically illustrated. In addition to the first embodiment of the apparatus 102 disclosed above, the system may comprise a breaking device 834 for breaking the current of a DC

transmission or distribution line 832. The breaking device 834 is connected in series with the apparatus 102. The breaking device 834 may comprise a mechanical switch and/or at least one power semiconductor switch. It is to be understood that the system 830 may be provided with more than one apparatus according to the present invention. Alternatively, the first embodiment of the apparatus 102 of the system of Fig. 10 may be replaced by any of the embodiments of the apparatus disclosed above.

With reference to Fig. 11 still another embodiment of the DC power transmission system 900 according to present invention is schematically illustrated, comprising a DC transmission or distribution line 914 to which an apparatus 102 according to the first embodiment of the apparatus 102 disclosed above is connected. In addition to the first embodiment of the apparatus 102, the system 900 may comprise a breaking device 913 connected in series with the apparatus 102 and in series with the DC line 914. In this embodiment of system 900, the breaking device 913 comprises a parallel connection of a main breaker 908 and a non-linear resistor 911, the main breaker 908 comprising at least one power semiconductor switch 901 of a first current direction 904, and a series connection of a high speed switch 910 and an auxiliary breaker 909. The high speed switch 910 comprises at least one mechanical switch. The auxiliary breaker 909 has a smaller on-resistance than the main breaker 908 and comprises at least one power semiconductor switch 901 of the first current direction 904. Said series connection is connected in parallel to said parallel connection. The main breaker 908 may comprise a plurality of power semiconductor switches 901 of the first current direction 904. In Fig. 11, each power semiconductor switch 901 is included in a base element 906. Further, the apparatus 102 is also connected in series with a reactor 912, e.g. a coil. However, the reactor 912 may be excluded from the system 900. The inventors have found that the combination of the apparatus of the present invention and the breaking device 913 of Fig. 11 improves the surge current limitation and the electric power transmission control. By means of the apparatus 102, the semiconductor chip area may be reduced, and the breaking speed of the high speed switch 910 is less crucial, i.e. the high speed switch 910 does not need to be that fast, whereby productions costs are reduced. A more detailed disclosure of the breaking device 913 of Fig. 11 is found in WO-A1-2011/057675 which is hereby incorporated by reference. Alternatively, the first embodiment of the appa-

ratus 102 of the system 900 of Fig. 11 may be replaced by any of the embodiments of the apparatus as disclosed above.

The various components of the apparatus and the system of the present invention, which are connected or connectable to one another or to other units, 5 may be electrically connected, or connectable, to one another or to other units, e.g. via electrical conductors, e.g. busbars or DC lines, and/or may be indirectly connected, or connectable, e.g. electrically, to one another or to other units, e.g. via additional intermediate electric equipment or units located and connected/connectable between the components.

10 The invention shall not be considered limited to the embodiments illustrated, but can be modified and altered in many ways by one skilled in the art, without departing from the scope of the appended claims.

CLAIMS

1. An apparatus (102; 202; 302; 502; 602; 702) for assisting or controlling the electric power transmission in a direct current power transmission system (802; 810; 830; 900) comprising at least one direct current transmission or distribution line (104; 804; 812, 814, 816, 818, 820; 832; 914) for carrying direct current, DC, the apparatus comprising a transformer (106) having a primary winding (108) and at least one secondary winding (110), the primary winding being connectable in series with the DC transmission or distribution line to carry the current (i_1) of the DC transmission or distribution line, and the secondary winding is connected to an electrical load (112), **characterized** in that the transformer is arranged to supply a secondary current (i_2) to the electrical load, the secondary current being at least partially based on a surge current of the DC transmission or distribution line, and in that the apparatus is arranged to limit the surge current by introducing at least one opposing voltage (v_1) in series with the DC transmission or distribution line, the at least one opposing voltage being at least partially based on the current (i_2) of the electrical load.
2. An apparatus according to claim 1, **characterized** in that the apparatus (502; 602; 702) comprises a plurality of transformers (506, 507; 606, 607; 706, 707, 718), in that the primary winding (508, 509) of each transformer (506, 507) is connectable in series with the DC transmission or distribution line (104) to carry the current (i_1) of the DC transmission or distribution line, and in that the secondary winding (510, 511) of each transformer is connected to an electrical load (512, 513).
3. An apparatus according to claim 2, **characterized** in that the primary windings (508, 509) of the plurality of transformers (506, 507) are connected in series with one another.
4. An apparatus according to any of the claims 1 to 3, **characterized** in that the transformer (106) is arranged to DC isolate the electric load (112) from the DC transmission or distribution line (104).

5. An apparatus according to any of the claims 1 to 4, **characterized** in that the electrical load (112; 212; 312) comprises an electrical device (114; 214; 314) of a group of electrical devices comprising a nonlinear resistor (116), an inductor (316) and a linear resistor (216).

5

6. An apparatus according to any of the claims 1 to 4, **characterized** in that the electrical load (112; 312) comprises an electrical device (114; 314) of a group of electrical devices comprising a nonlinear resistor (116) and an inductor (316).

10

7. An apparatus according to any of the claims 1 to 4, **characterized** in that the electrical load (112) comprises an electrical device (114) comprising a nonlinear resistor (116).

15 8. An apparatus according to any of the claims 5 to 7, **characterized** in that the nonlinear resistor (116) comprises a voltage-dependent nonlinear resistor.

9. An apparatus according to claim 8, **characterized** in that the voltage-dependent nonlinear resistor comprises a surge arrester.

20

10. An apparatus according to any of the claims 5 to 9, **characterized** in that the apparatus (102; 202; 302; 502; 602; 702) is arranged to limit surge current of the DC transmission or distribution line (104) by introducing, in series with the DC transmission or distribution line, at least one opposing voltage (v_1) that is at
25 least partially based on the electrical device current (i_2).

11. An apparatus according to any of the claims 1 to 10, **characterized** in that the apparatus (102; 202; 302; 502; 602; 702) is arranged to control the electric power transmission in a high voltage direct current, HVDC, power transmission
30 system (802; 810; 830; 900) comprising at least one HVDC transmission or distribution line (104; 804; 812, 814, 816, 818, 820; 832; 914) for carrying high voltage direct current.

12. A direct current power transmission system (802; 810; 830; 900) comprising at least one direct current transmission or distribution line (104; 804; 812, 814, 816, 818, 820; 832; 914) for carrying direct current, DC, wherein the system comprises at least one apparatus (102; 202; 302; 502; 602; 702) as claimed in any of
5 the claims 1-11 for assisting or controlling the electric power transmission in the system.

13. A direct current power transmission system according to claim 12,
characterized in that the system (802; 810; 830; 900) comprises a breaking
10 device (834; 913) for breaking the current of the at least one direct current transmission or distribution line (823; 914), and in that the breaking device is connected in series with the at least one apparatus (102; 202; 302; 502; 602; 702).

14. A direct current power transmission system according to claim 12 or
15 13, **characterized** in that the system (810) comprises a plurality of converters (822, 824, 826, 828) connected to the at least one DC transmission or distribution line (812, 814, 816, 818, 820), each of the converters being arranged to convert alternating current to direct current for input to the at least one DC transmission or distribution line, and/or direct current to alternating current.

20

15. A direct current power transmission system according to any of the claims 12 to 14, **characterized** in that the system (810) comprises a plurality of DC transmission or distribution lines (812, 814, 816, 818, 820).

25 16. A direct current power transmission system according to any of the claims 12 to 15, **characterized** in that the system (810) comprises at least three converters (822, 824, 826, 828), each of the converters being arranged to convert alternating current to direct current for input to the at least one DC transmission or distribution line (812, 814, 816, 818, 820), and/or direct current to alternating current.
30

17. A direct current power transmission system according to any of the claims 12 to 16, **characterized** in that the at least one DC transmission or distribution

line (812, 814, 816, 818, 820) comprises at least one long-distance HVDC link (812, 818).

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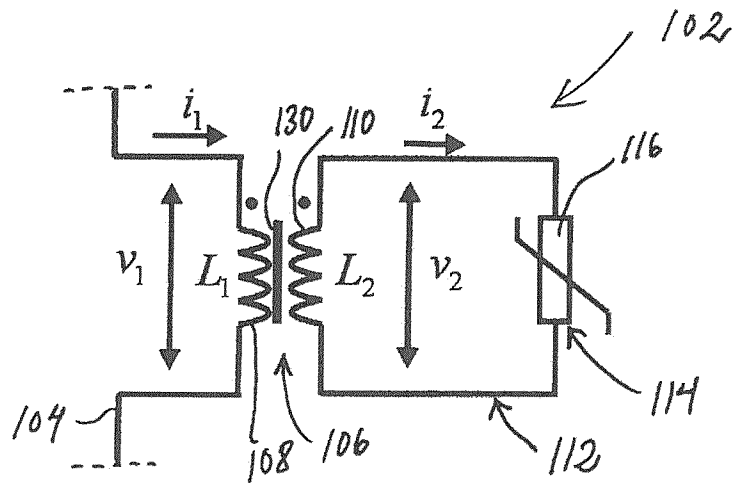


Fig. 1

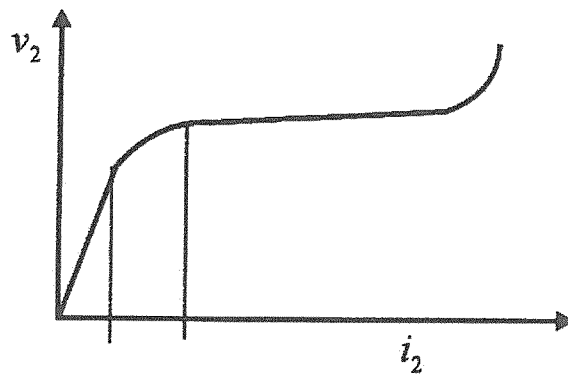


Fig. 2

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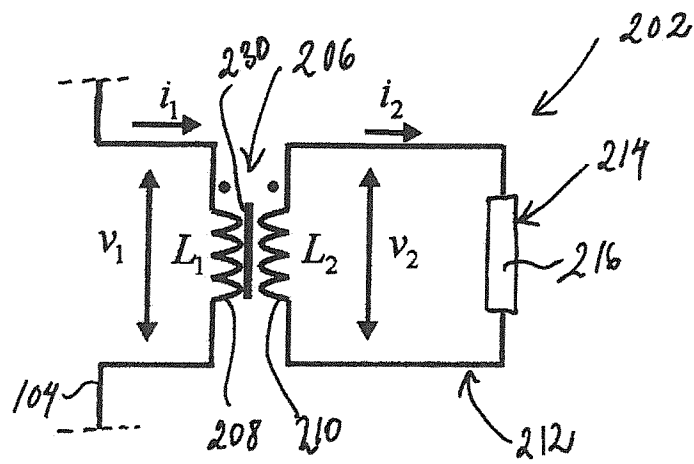


Fig. 3

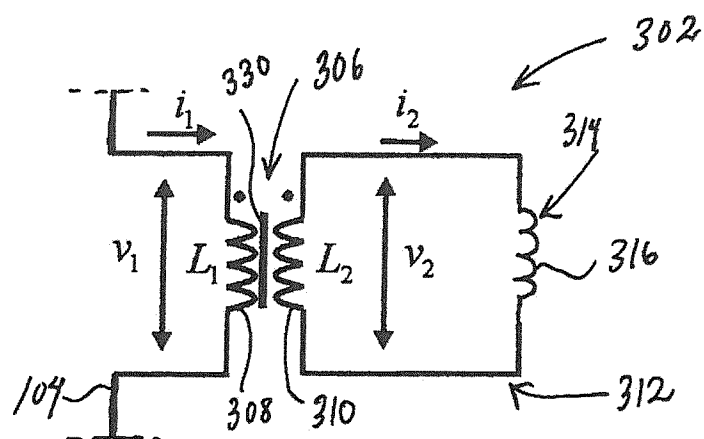
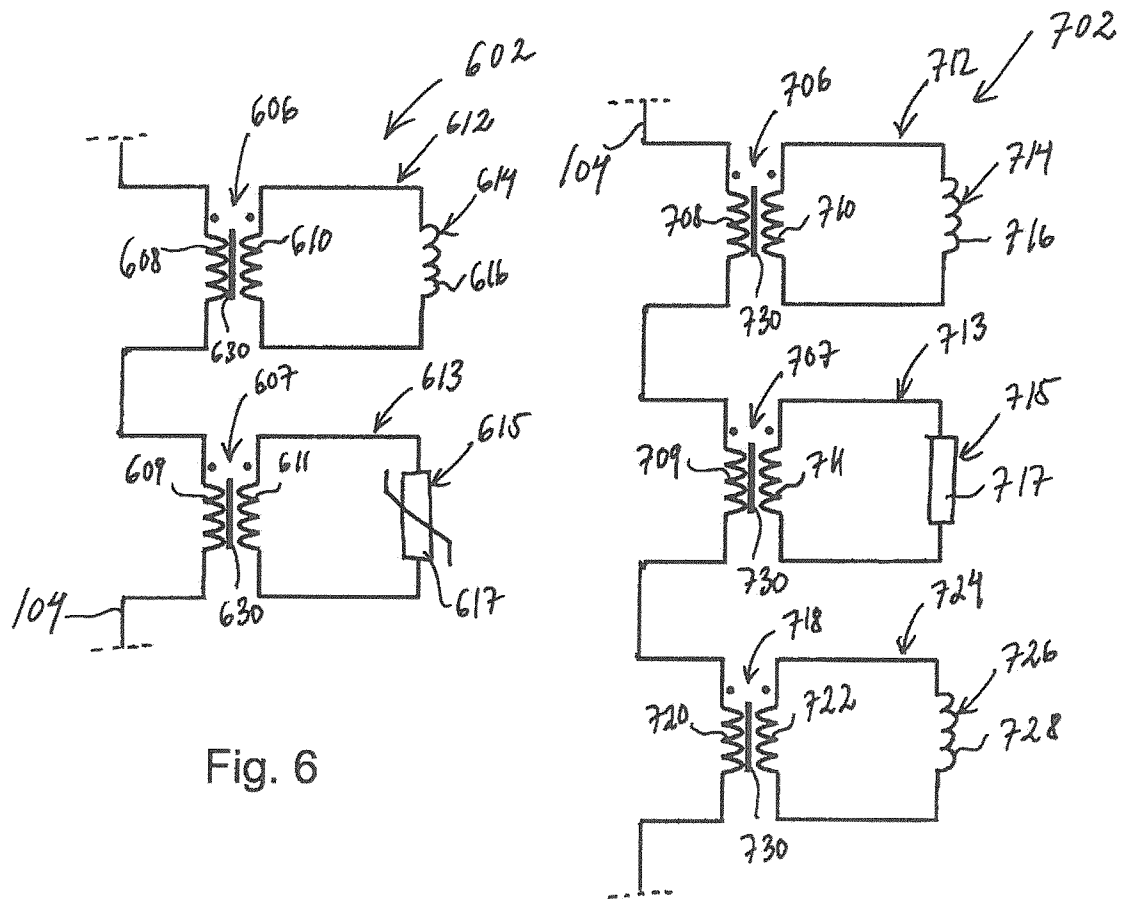
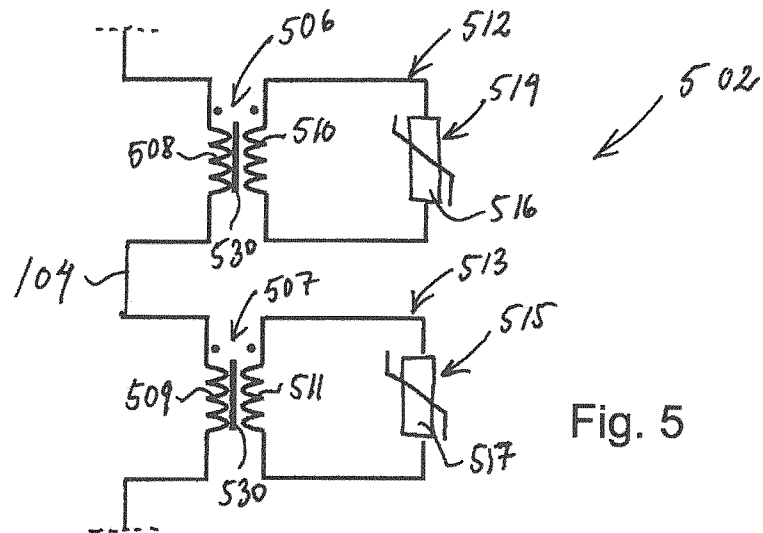


Fig. 4

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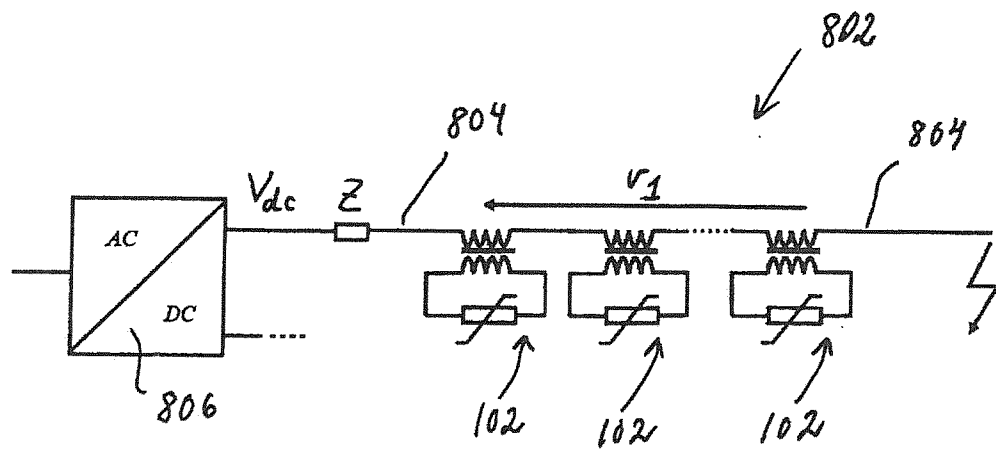


Fig. 8

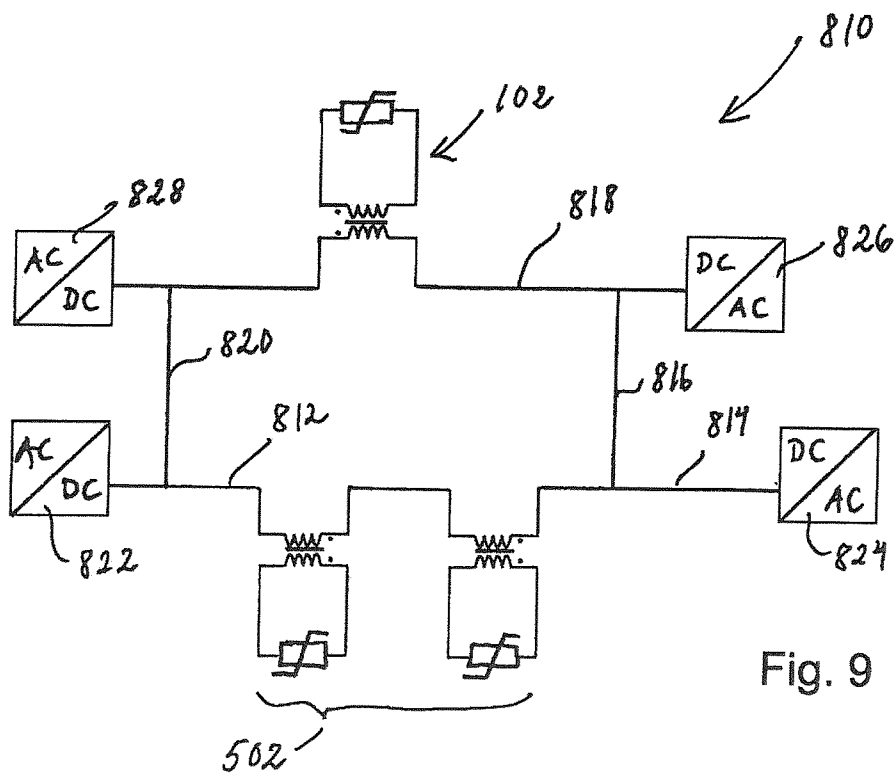


Fig. 9

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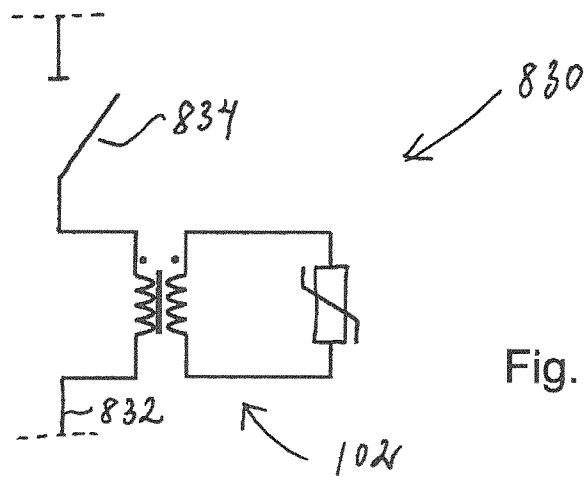


Fig. 10

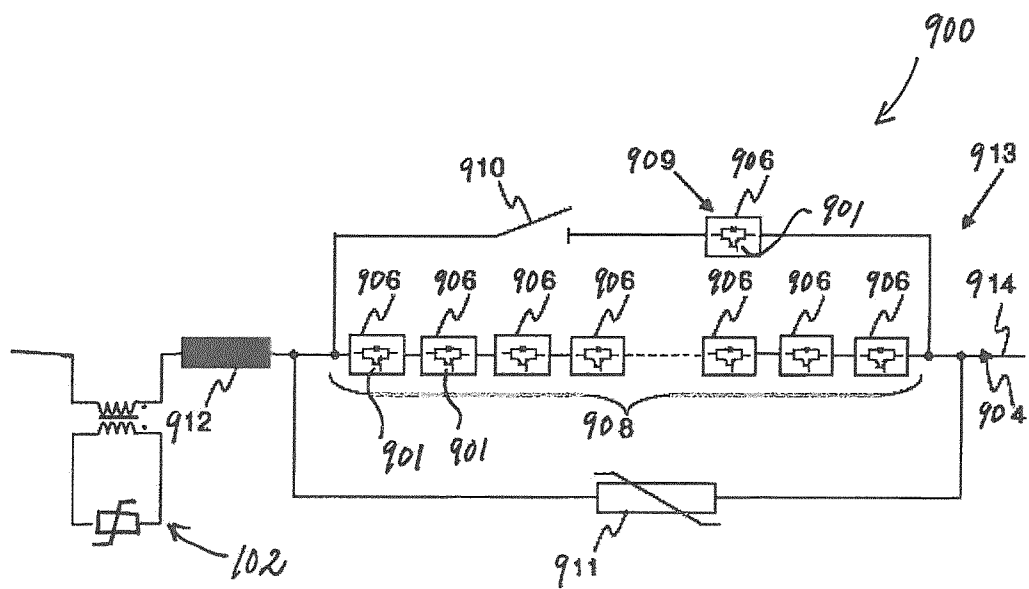


Fig. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2012/059629

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02H9/02
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02H

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 610 432 A2 (ABB RESEARCH LTD [CH]) 28 December 2005 (2005-12-28) paragraphs [0018] - [0028]; figure 5 -----	1-17
X	US 5 161 082 A (ALFONSO MANUEL M [NL]) 3 November 1992 (1992-11-03) column 4, line 35 - column 7, line 15; figures 3,4 -----	1
X	US 5 443 664 A (NAKAJIMA SHIN [JP] ET AL) 22 August 1995 (1995-08-22) column 1, lines 24-43; figures 1,3,5,6 column 7, lines 53-64 -----	1



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"&" document member of the same patent family

Date of the actual completion of the international search

29 January 2013

Date of mailing of the international search report

08/02/2013

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Bergler, Christian

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2012/059629

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