



(51) International Patent Classification:

H02M 1/12 (2006.01) *H02J 3/01* (2006.01)
H02M 1/14 (2006.01) *H03H 11/00* (2006.01)

(21) International Application Number:

PCT/AU2012/000141

(22) International Filing Date:

14 February 2012 (14.02.2012)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

2011900474 14 February 2011 (14.02.2011) AU

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM,

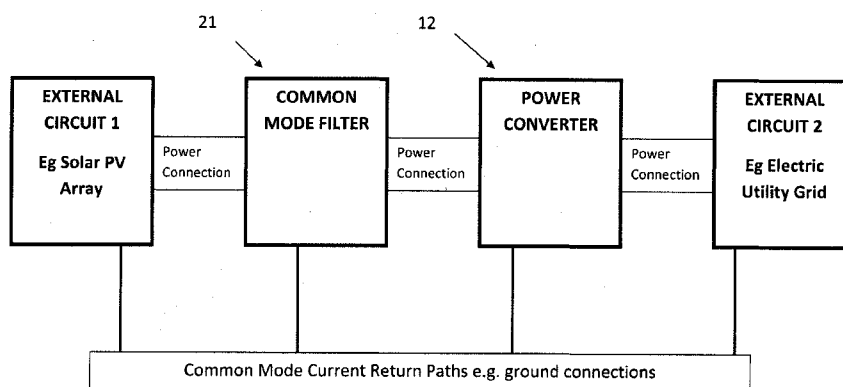
AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

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

Published:

- with international search report (Art. 21(3))
- with amended claims (Art. 19(1))

(54) Title: COMMON-MODE FILTER DEVICE AND SYSTEM



Common Mode Filter in relation to Associated Systems

Figure 4

(57) Abstract: A common-mode filter device and system for regulating aspects of power conversion by a power converter from external source such as solar panels to another external circuit wherein the common-mode filter device substantially attenuates common-mode voltage at the switching frequency plus harmonics of the power converter. The power converter can be single phase, but is preferably a multiple phase.



Common-mode Filter Device and System

Field of the Invention

The present invention relates to a device and system for power converters and inverter systems using an active common-mode filter. In particular it relates to a common-mode filter device and system for regulating aspects of power conversion from external source such as solar panels to an electricity utility grid but is not limited to such.

Background to the Invention

Power converters are used to transfer electric power between electric circuits. Each electric circuit is connected to a different power port of the power converter. Each power port has at least two power conductors. The power port voltages are characterized by the Differential-Mode (DM) voltages and the Common-Mode (CM) voltage. The DM voltages are the potential differences between pairs of power conductors. The CM voltage is the average potential difference between all of the power conductors and a reference potential, such as ground (earth). Similarly, the power port currents are characterized by the DM currents and the CM current. The DM currents are the differences between the currents in pairs of power conductors. The CM current is the sum of the currents on all power conductors.

Throughout this document the following acronyms are used:

CM	Common-Mode
DM	Differential-Mode
EMI	ElectroMagnetic Interference
PWM	Pulse Width Modulation
UPS	Uninterruptible Power Supply
VSI	Voltage Source Inverter

In a well-designed power converter, the power flow is primarily via the designated power conductors. Therefore, the CM current is small and the power flow at power port is primarily determined by the DM voltage and DM currents. When selecting a power converter topology, the DM voltage and DM current characteristics are the main consideration. The CM voltage and CM current characteristics are typically of secondary importance. For a power converter, key performance measures include the operating DM voltage range, the power conversion efficiency, installed cost, size and mass.

Many of the best performing power converters have a systematic CM voltage between the power ports. For example, the three-phase Voltage Source Inverter (VSI) is a DC to AC switched-mode type power converter with a significant CM voltage difference between the DC and AC power ports. See Figure 1 for an example VSI circuit. The CM voltage includes components at DC, harmonics of the AC port frequency and harmonics of the VSI switching frequency. See Figure 2 for an example VSI CM voltage waveform. See Figure 3 for a typical plot of the low frequency (switching averaged) component of the VSI CM voltage waveform.

High efficiency inverters are desirable but the cost must be justified. Presently the VSI has high efficiency and low cost but the associated CM voltage creates unacceptably high ground current when used with photovoltaic power sources. It is therefore beneficial to provide high efficiency power converters that are low cost and which operate with low ground current when used with photovoltaic power sources.

In many applications using a VSI, the external circuit impedance between the power ports is high, so the CM voltage difference creates only a small CM current. For example, the majority of variable speed motor drives use a three-phase VSI. The CM voltage difference is applied across the motor winding insulation, which is typically of special type. The insulation is characterized by a small capacitance to ground (earth). The AC component of the CM voltage, creates a small CM current in the insulation capacitance, which is usually tolerable.

In some applications the capacitance to ground is significant, for example, solar photovoltaic power generation systems connected to the AC utility grid. Power converters with CM voltage difference at the switching frequency and harmonics typically create unacceptable levels of CM current. For large photovoltaic systems, power converters with CM voltage difference at the utility grid frequency and harmonics may also create unacceptable levels of CM current. For other applications, such as double conversion Uninterruptible Power Supply (UPS) systems, there is a low impedance external circuit for CM current between the input and output power ports. In this case, any significant CM voltage will result in unacceptable levels of CM current.

Prior art solutions for applications with high ground capacitance or low impedance external CM circuits include:

- Power converter topologies with low or zero CM voltage. This is usually at the expense of performance in other key areas such as: DM voltage range, power conversion efficiency, installed cost, size and mass.
- 5 • Power converter topologies with significant CM voltage, used in conjunction with an isolation transformer. The transformer reduces the power conversion efficiency and increases installation cost, size and mass.

10 It is therefore an object of the invention to provide an improved common-mode filter device and system that overcomes or at least substantially ameliorates one or more of the problems of the prior art.

Summary of the Invention

15 The invention therefore provides in one form a common-mode filter device and system for regulating aspects of power conversion by a power converter from external source such as solar panels to another external circuit wherein the common-mode filter device substantially attenuates common-mode voltage at the switching frequency plus harmonics of the power converter. The power converter can be single phase.

20 Preferably the power converter is multiple phase. Therefore in accordance with the invention there is provided a common-mode filter device and system for regulating aspects of power conversion from external source such as solar panels to an AC system such as an electricity utility grid wherein the CM filter device substantially
25 attenuates CM voltage at the AC system fundamental frequency plus harmonics and at the switching frequency plus harmonics of the associated power converter.

The CM filter device can include an active filter configuration.

30 The CM filter device can include a passive filter configuration.

The active or passive filter of the common-mode filter device and system can have a CM transformer with multiple primary windings. The primary windings all have an equal number of turns. A primary winding is connected in series with each power
35 terminal of the power port.

An active CM filter can further include secondary windings.

In one form the active CM filter can include control power sources which can be connected to a controlled voltage source via an inductive impedance.

- 5 The CM filter device can include the inductive impedance in the range 25% to 200% of the CM transformer magnetizing inductance measured at the secondary winding and at the switching frequency of the associated power converter.

10 In accordance with one form of the invention there is provided an active filter to be used in series with a power converter to support the CM voltage difference between the power converter ports and to control the CM current to acceptable levels.

15 The active filter can make use of real time measured CM current and provide real time control of CM current with CM current return paths and impedances.

20 The active filter can be an active power source which is a controllable voltage source with a series impedance coupled to the secondary winding of the CM transformer.

25 The series impedance can be primarily an inductive impedance.

30 The inductive impedance is in the range 25% to 200% of the CM transformer magnetizing inductance measured at the secondary winding and at the switching frequency of the associated power converter.

- 35 In one preferred form the controllable voltage source is a full-bridge with pulse width modulation PWM. However the controllable voltage source can be a half-bridge with PWM.

40 The controllable voltage source PWM period can be synchronized to the switching transitions of the associated power converter.

45 Preferably the CM transformer has a magnetizing inductance in the range 0.1H to 10H measured at a primary winding and at the utility grid frequency. This can be achieved with the CM transformer having a core made of amorphous metal (metglas).

In one form of the invention the common-mode filter device and system is for a power converter used to transfer electric power between electric circuits with each electric circuit connected to a different power port of the power converter and each power port having at least two power conductors with the power port voltages being characterized by the Differential-Mode (DM) voltages and the Common-Mode (CM) voltage wherein the DM voltages are the potential differences between pairs of power conductors and the CM voltage is the average potential difference between all of the power conductors and a reference potential, such as ground (earth) and the power port currents being characterized by the DM currents and the CM current with the DM currents being the differences between the currents in pairs of power conductors and the CM current being the sum of the currents on all power conductors which flows back into one or more other power ports of the power converter via an external circuit, typically involving the ground (earth) conductor;

wherein the common-mode filter device and system includes an active filter used in series with a power port of the power converter to limit and control the AC component of common-mode current at the power port;

and wherein the common-mode current at the power port is measured and the AC component of common-mode current is limited and controlled using a feedback controller to adjust the controlled voltage source.

One method to resolve the problem of CM inductor saturation is to apply a CM filter that attenuates both switching frequency and low frequency CM voltage. This also has the benefit of limiting the low frequency CM current. The drawback is that a passive CM filter to attenuate the low frequency CM voltage adds significant cost, size and mass to the power converter. It is also difficult to provide effective damping to prevent resonance and CM voltage overshoots. These limitations may be overcome using an active CM filter.

Most prior art applications for active CM filters have been limited to increased performance in EMI filters. In EMI filter applications the CM voltage is small compared to the DM voltages and is only attenuated significantly at high frequency (typically > 100kHz). Design limitations of these systems, such as capacitive coupling and/or voltage based control, prevent them being extended to low frequency CM voltages or CM voltages at levels significant compared with the DM voltages.

Other prior art applications for active CM filters in variable speed motor drives have provided attenuation of switching frequency CM voltages at levels significant

compared to the DM voltage. Due to design limitations, such as voltage based control, these systems cannot be extended to low frequency CM voltages.

5 The active filter of the common-mode filter device and system can have a transformer with multiple primary windings and a secondary winding. The primary windings all have an equal number of turns. A primary winding is connected in series with each power terminal of the power port. The secondary winding is connected to a controlled voltage source via an impedance.

10 The invention enables the best performing power converters, such as a standard VSI, to be used without isolation transformers in applications with high ground capacitance or low impedance external CM circuits. For example, solar photovoltaic applications and double conversion Uninterruptible Power Supplies.

15 This invention implements an active filter that attenuates both switching frequency and low frequency CM voltages, even when these are significant compared to the DM voltages.

20 The active CM filter can have a transformer with multiple primary windings and a single secondary winding. The primary windings all have an equal number of turns. A primary winding is connected in series with each power terminal of the power converter port to which the CM filter is attached. The secondary winding is connected to an active control power source.

25 In one embodiment, the active control power source is a controlled voltage source with series inductive impedance.

30 In one form the CM current at the power port can be measured. The AC component of CM current is limited and controlled using a feedback controller to adjust the active control power source.

35 In other embodiments, estimates or measurements of the CM voltage at the power converter power port are also used to provide feedforward control of the active control power source. This can reduce the AC component of CM current at frequencies above the bandwidth of the closed-loop CM current controller. For example, at the power converter switching frequency and harmonics.

In further embodiments, active damping of the CM filter response is obtained by appropriate closed-loop dynamics in the CM current feedback controller.

5 In some embodiments, a circuit is provided to return the CM current from the output of the CM transformer to one or more other power ports of the power converter.

In a typical case, this circuit will include at least one series capacitive impedance.

10 In other embodiments, the CM current from the output of the CM transformer returns to other power ports of the power converter via external circuits, such as insulation capacitance.

The operation of the disclosed active filter is similar in concept to a passive CM filter, except that the active control forces the majority of the CM transformer magnetizing current to flow in the secondary control winding, rather than in the primary windings. The method makes the effective impedance of the CM transformer much higher than a passive CM transformer, choke or inductor of equivalent size. This reduces the cost, size and mass of the disclosed active CM filter compared to a passive CM filter.

15 20 In concept it is also possible to add a CM filter in series with a power converter to support the CM voltage difference between the power converter ports and to control the CM current to acceptable levels. With this method, a high performance power converter, such as a VSI, may be used in applications with high ground capacitance or with low impedance external CM circuits. The CM filter may be of passive or active type.

25 In prior art, it is common to use passive CM filters in series with one or more power ports of a power converter to reduce conducted Electro-Magnetic Interference (EMI). In this application, the CM voltage is small compared to the DM voltages and is only attenuated significantly at high frequency (typically > 100kHz).

30 There have also been some passive CM filters designed to attenuate the switching frequency component of CM voltage, even when this is significant compared to the DM voltages. The main application for these filters has been in variable speed motor drives, but they are not in widespread use. It is difficult to extend the use of switching frequency CM filters to applications with high ground capacitance or low impedance external CM circuits. A particular problem is saturation in the CM filter inductors

caused by low frequency CM currents. One method to resolve the problem of CM inductor saturation is to apply a CM filter that attenuates both switching frequency and low frequency CM voltage.

- 5 The invention also provides a means for regulating aspects of power conversion from external source, such as solar panels, to an electricity utility grid in applications with high ground capacitance or low impedance external CM circuits including the steps of:

10 connecting an active CM filter device in series between an external source power circuit and a power converter

measuring CM current at CM filter input or output

provide active CM current return based on measured CM current

whereby the power converter regulates the CM voltage difference between the power converter ports and controls the CM current to acceptable levels.

15

The active filter can make use of real time measured CM current and provide real time control of CM current with CM current return paths and impedances. The function of the active filter is to limit and control the AC component of CM current at the power port

20

The active filter can include a transformer with multiple primary windings and a secondary winding. Each primary winding has an equal number of turns. A primary winding is connected in series with each power terminal of the power port. The secondary winding is connected to an active power source.

25

The active filter includes a measurement related to the CM current at the power port. The active filter includes a control mechanism using feedback of said measurement to control the active power source such that the CM current at the port is controlled or limited.

30

The active filter can include an additional measurement or estimation of the CM voltage supported by the primary windings of the CM transformer.

35

The control mechanism can use feedforward of the CM voltage measurement or estimation to control the active power source such that the CM current at the port is reduced.

In another form the control mechanism uses the CM voltage measurement or estimation to control the active power source to provide active damping of the CM filter.

- 5 In a still further form of the invention the active filter in series with a power converter can include DC blocking capacitors in series with an AC power port, such that the flow of DC CM current is limited and controlled by the series capacitors and the flow of AC CM current is limited and controlled by the active CM filter.

10 **Brief Description of the Drawings**

Preferred embodiments of the invention will now be described, by way of illustration only, with reference to the accompanying drawings, in which:

Figure 1 is a circuit diagram of a typical Voltage Source Inverter (VSI) circuit;

- 15 Figure 2 is a common mode voltage graph of a typical Voltage Source Inverter (VSI) circuit at the DC power port;

Figure 3 is a common mode voltage graph of a typical Voltage Source Inverter (VSI) circuit at the DC power port with values averaged over each switching period T_s ;

- 20 Figure 4 is a diagrammatic operative block diagram of a common-mode filter device and system in accordance with a first embodiment of the invention;

Figure 5 is a circuit diagram of a typical Voltage Source Inverter (VSI) circuit of a common-mode filter device and system in accordance with a second embodiment of the invention using a common mode active filter;

- 25 Figure 6 is a diagrammatic circuit diagram of a controller for common-mode filter device and system in accordance with a third embodiment of the invention with active common mode filter;

Figure 7 is a diagrammatic circuit diagram of a controller for common-mode filter device and system in accordance with a fourth embodiment of the invention with common mode voltage feedforward;

- 30 Figure 8 is a diagrammatic circuit diagram of a controller for common-mode filter device and system in accordance with a fifth embodiment of the invention with active damping and common mode voltage feedforward;

- 35 Figure 9 is a circuit diagram of a controller for common-mode filter device and system in accordance with a sixth embodiment of the invention with active control power source;

Figure 10 is a diagrammatic circuit diagram of a controller for common-mode filter device and system in accordance with a seventh embodiment of the invention

with combined active common mode filter for control of AC component of common mode current and series capacitors for blocking DC components of common mode current;

5 Figure 11 is a diagrammatic circuit diagram of a controller for common-mode filter device and system in accordance with an eighth embodiment of the invention with Controller for Output Common-Mode Current and Voltage with Common-Mode Voltage Feedforward and Inner Loop for Common-Mode Control Current

10 Figure 12 is a diagrammatic circuit diagram of a controller for common-mode filter device and system in accordance with an ninth embodiment of the invention with Controller using Measured Functions of CM Current;

Figure 13 is a diagrammatic circuit diagram of a controller for common-mode filter device and system in accordance with an tenth embodiment of the invention with passive low pass filter for grid frequency harmonic and switching frequency harmonic common mode voltage;

15 Figure 14 is a diagrammatic circuit diagram of a voltage source inverter with reduced ground voltage with a common-mode filter device and system in accordance with an eleventh embodiment of the invention which attenuates high frequency and low frequency ground voltage;

20 Figure 15 is a diagrammatic circuit diagram of a voltage source inverter with reduced ground voltage with an active common-mode filter device and system in accordance with a twelfth embodiment of the invention which active circuit carries magnetising current with increased effective filter inductance;

Figure 16 is a graphical display of the resultant low common mode voltage inverter CM voltage waveform;

25 Figure 17 is a graphical display of the magnetic material characteristics of the CM inductor used in embodiments of CM filter of the common-mode filter device and system in accordance with the invention;

30 Figure 18 is a diagrammatic view of an active common-mode filter device in accordance with an embodiment of the invention showing the CM transformer and relative size of the CM filter with the power converter; and

35 Figure 19 is diagrammatic view of a toroidal type transformer showing the core, coil former and support structure of the CM transformer with the actual windings not shown but are located in the grooves of the coil former of the CM inductor used in embodiments of CM filter of the common-mode filter device and system in accordance with the invention.

Figures 20A to 20D are various constructional views of the toroidal type transformer showing the core, coil former and support structure of the CM transformer of Figure 19.

Figures 21A to 21D are various constructional views of the toroidal type transformer showing the actual windings are located in the grooves of the coil former of the CM inductor of the CM transformer of Figure 19.

Figure 22 is a schematic circuit diagram of a VSI with series active CM filter. The active CM filter is composed of the CM Transformer (LCM) and CM current return path (Cdn, Rdn, Cdna). Figure 22 also shows the CM current measurement IDC_CM and the, CM transformer secondary control current input, IDC_CTRL_IN and IDC_CTRL_OUT for connection to the active CM control bridge power circuit.

Figure 23 is a schematic circuit diagram of the CM control bridge power circuit.

15 **Description of a Preferred Embodiment of the Invention**

Referring to Figure 4 there is shown a block diagram and partial circuit diagram showing the common-mode filter device and system in an example circuit. The device can use either an active common-mode filter or a passive common-mode filter. A power converter is shown with an AC power port that is connected to the AC utility grid and a DC power port that is connected to the input port of the active CM filter. The output port of the active CM filter is connected to an external circuit, such as a power source or load.

The common-mode filter device and system in this form has the common-mode filter used in series with a power converter to support the common-mode voltage difference between the power converter ports and to control the common-mode current to acceptable levels. The power converter can be a VSI. The common-mode filter makes use of real time measured common-mode current and provides real time control of common-mode current with common-mode current return paths and impedances.

In accordance with the invention and with reference to Figures 5 to 10 there is shown a common-mode filter device and system 21 including an active filter used in series between an external circuit 11 such as a solar photovoltaic array and a power converter 12 feeding power to an electricity utility grid 13. The CM filter device connecting two power conductors 35, 36 having primary windings 33, 34 respectively to power port 25, of the power converter and limiting and controlling the AC

component of common-mode current at the power port 25 by having the common-mode current at the power port measured by a CM current measurement device 41A or 41B at the CM filter input port 35 on the power convertor end of the power conductors or at the CM filter output port 37 at the external circuit end of the power conductors 31, 32 and the AC component of common-mode current is limited and controlled using a feedback controller 51 to adjust the controlled voltage source.

The CM filter 21 consists of a CM transformer and one or more CM current return circuits 53, 54 and 55 connected between the power converter and the external circuit 11, first power conductor 31 at the CM filter output port 37 or second power conductor 32 at the CM filter output port 37 respectively. CM current from the DC power port 25 flows through the primary windings 33, 34 of the CM transformer and returns to the power converter via the CM current return circuits 53, 54 and 55. The CM current return circuits can include filter components with defined impedances. These are shown in Figure 4 as Z_{cm_p} and Z_{cm_n} . Alternatively, the CM current return circuits 53, 54 and 55 can be parasitic components such as insulation capacitance in the external circuits. This is shown in Figure 4 as Z_{cm_ext} .

The CM transformer has multiple primary windings 33, 34 and a secondary winding 58. The primary windings all have an equal number of turns. A primary winding is connected in series with each power terminal of the power converter port to which the CM filter is attached. The secondary winding is connected to an active control power source 52 directly controlled by the CM current controller 51. Figure 4 shows a typical implementation of the active control power source as a controlled voltage source 56 with series inductive impedance 57.

The CM current is measured by a current sensor 41A or 41B at either the input port 35 or output port 37 of the CM filter 21. A sensor at the input port of the CM filter measures the total CM current from the DC port of the power converter. A sensor at the output port of the CM filter measures the total CM current delivered to the external circuit, this excludes any CM current that returns via CM current return paths within the filter. The CM filter device also contains the CM Current Controller 51 which applies feedback of the CM current measurement to adjust the active control power source 56, such that the CM current is controlled and limited.

It can be seen that the common-mode filter device and system 21 provides a means for regulating aspects of power conversion from external source, such as solar

panels, to an electricity utility grid in applications with high ground capacitance or low impedance external CM circuits including the steps of: connecting an active CM filter device in series between an external source power circuit and a power converter, measuring CM current at CM filter input or output, providing active CM current return
5 based on measured CM current, whereby the power converter regulates the CM voltage difference between the power converter ports and controls the CM current to acceptable levels.

A wide range of CM Current Control structures can be used. It is recognized that the
10 CM Current Controller can be implemented entirely in hardware, or in a combination of hardware and firmware associated with a programmable hardware device.

To prevent saturation of the CM transformer, the active CM filter can only attenuate the AC component of CM voltage. Therefore, the CM current measurement is
15 typically processed by a high pass filter to extract the AC component. In a typical application the cut-off frequency of the high pass filter is between 50% and 300% of the AC utility grid frequency. In practice there is also a bandwidth limit on the CM current sensor. Therefore, the CM current signal is typically band-passed filtered to produce the measurement I_{dc_cm} . This filtering may be done by the CM current
20 sensor characteristics possibly in conjunction with external circuits.

The action of the CM Current Controller is to control and limit the CM Current towards a zero value or small value reference. It is therefore recognized that the invention will give satisfactory operation in the presence of significant accuracy and
25 linearity errors in the CM Current measurement.

Figure 6 is a block diagram of an example CM Current Controller. The measured CM current is processed by a high pass filter and compared to a zero value CM current reference in a summing block to produce the CM Current Error Signal. The I_{dc_cm}
30 Controller acts on the CM Current Error Signal to produce a Secondary Control Current reference, $I_{cm_s_ctrl}^*$, which is compared to the measured Secondary Control Current, $I_{cm_s_ctrl}$, in a summing block to produce the Secondary Control Current Error Signal. The $I_{cm_s_ctrl}$ Controller acts on the Secondary Control Current Error Signal to produce a control voltage for the active control power source,
35 $V_{cm_s_ctrl}$.

- In the Figure 6 example, the controller has a nested loop structure, with an inner controller for $I_{cm_s_ctrl}$. This is useful to limit the level of $I_{cm_s_ctrl}$ according to the specifications of the active control power source. However it is recognized that the I_{dc_cm} Controller could be used to control the active control power source directly.
- 5 Both the I_{dc_cm} Controller and the $I_{cm_s_ctrl}$ Controller are shown as linear PI controllers without limiting. It is recognized that many different linear or non-linear control structures are suitable for this application and that many intermediate variables could be subject to limits such as $I_{cm_s_ctrl}^*$ and $V_{cm_s_ctrl}$.
- 10 Figure 7 is a block diagram of an alternative example CM Current Controller, with feedforward of the measured or estimated CM voltage to the active control power source voltage. This example does not show an inner loop controller for $I_{cm_s_ctrl}$, but this could be included in the dynamics of the I_{dc_cm} Controller. The CM voltage at the power converter power port, V_{dc_cm} , is measured or estimated from
- 15 knowledge of the power converter operating state. This is multiplied by the Feedforward Controller Gain to produce a feedforward voltage which is combined in a summation block with the output of the I_{dc_cm} Controller to produce the active control power source voltage, $V_{cm_s_ctrl}$.
- 20 Figure 8 is a block diagram of an alternative example CM Current Controller, with active damping of the CM filter and feedforward of the CM voltage. This example does not show an inner loop controller for $I_{cm_s_ctrl}$, but this could be included in the dynamics of the I_{dc_cm} Controller. The CM voltage at the power converter power port, V_{dc_cm} , is measured or estimated from knowledge of the power converter
- 25 operating state. This is multiplied by the Feedforward Controller Gain to produce a feedforward voltage which is combined in a summation block with the output of the I_{dc_cm} Controller to produce the active control power source voltage, $V_{cm_s_ctrl}$. In this example, the Active Damping Controller acts on V_{dc_cm} to produce a non-zero CM Current reference for the I_{dc_cm} Controller. Typically, the Active Damping
- 30 Controller has a resistive characteristic in the region of the CM filter resonance, with significantly reduced gain at frequencies above and below this region.
- Figure 9 is a block diagram and partial circuit diagram showing an example active control power source. A source of DC power supplies a DC voltage, V_{psu_ctrl} , to a
- 35 Full Bridge circuit. The Active Control Power Source Controller provides PWM control signals to the Full Bridge, to control the output voltage, $V_{cm_s_ctrl}$, or output current, $I_{cm_s_ctrl}$, towards reference values from the DC CM Current Controller.

Figure 10 shows a configuration with a combined active CM filter for control of the AC component of CM Current and series capacitors for blocking the DC component of CM Current. The series capacitors, C_{ac_series} , are applied in series with the AC power port of the power converter. The active CM filter is shown in series with the DC power port of the power converter. The series capacitors support the DC component of CM voltage from the power converter. The active CM filter supports the AC component of CM voltage from the power converter. The example configuration is suitable in applications where a low impedance external CM circuit exists. For example, solar photovoltaic power generation systems connected to the AC utility grid, where the positive or negative solar array conductor is connected to ground (earth).

Referring to Figures 11 and 12 there is shown that the common-mode filter device and system can operate with the active filter making use of function of real time measured common-mode current in various ways and providing real time control of common-mode current across common-mode current return paths and impedances.

This includes the concept where the common-mode current is measured and apply feedback to reduce the common-mode current at either input or output port of the filter. This will cover any scheme where a function of the common-mode current is used as the feedback variable. In one form 2 variables can be measured, one is the voltage across the common-mode return path (the common-mode output voltage of the filter), the other is the common-mode current delivered to the external circuit. Feedback is applied to both of these variables to control the voltage source of the controlled power source and reduce the common-mode current. Proportional feedback on the voltage is used because this is in effect the integrated value of the common-mode current. Integral feedback on the current can be used. Clearly there are many ways that different related variables could be used to achieve the same effect but all use the concept of measured function of the common-mode current or measured function of the common-mode current or voltage at the filter input or output port.

Figure 11 shows the active filter making use of functions of real time measured common-mode current. It should be noted that $I_{DC_CM_OUT}$ and $V_{DC_CM_OUT}$ are functions of I_{DC_CM} .

In particular

$$I_{DC_CM_OUT} = (Z_{CM_TOTAL} / Z_{CM_EXT}) \cdot I_{DC_CM}$$

$$V_{DC_CM_OUT} = Z_{CM_TOTAL} \cdot I_{DC_CM}$$

$$Z_{CM_TOTAL} = (1 / (1/Z_{CM_P} + 1/Z_{CM_N} + 1/Z_{CM_EXT}))$$

5

Figure 12 shows wherein the function of real time measured common-mode current includes measurement and feedback control of the voltage across the common-mode current return path. The common-mode filter device and system makes use of measured functions of the common-mode current and provides feedback applied on the Common-Mode output circuit and Common-Mode output Voltage.

10

Referring to Figure 13 there is shown a block diagram and partial circuit diagram showing the common-mode filter device and system in an example circuit. The device a passive common-mode filter. A power converter is shown with an AC power port that is connected to the AC utility grid and a DC power port that is connected to the output port of the passive CM filter.

15

The common-mode filter device and system in this form has the common-mode filter used in series with a power converter to support the common-mode voltage difference between the power converter ports and to control the common-mode current to acceptable levels. The power converter is a VSI. The passive common-mode filter includes a common mode transformer and a common-mode current return path consisting of a capacitance with parallel branch of series capacitor and resistor so as to create a damped low pass filter that substantially attenuates CM voltage at the AC system fundamental frequency plus harmonics and at the switching frequency plus harmonics of the associated power converter.

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Figure 14 shows a passive embodiment, this is equivalent to Figure 13, but the CM filter representation is a bit simplified and the Power Converter is shown in more detail. Figure 15 is an active embodiment, although the drawing is simplified and does not show the CM current measurement and control blocks. This is equivalent to Figure 5, but the CM filter representation is simplified and the Power Converter is shown in more detail. Figure 16 is an actual measured waveform that shows the improvement in CM voltage provided by the active CM filter (compared to CM voltage of the VSI without filter shown in Figures 2 and 3 – which are theoretical waveforms). Figure 17 is the magnetizing curve for the inductor core. It shows very high permeability, as required to keep the magnetizing current low.

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With reference to Figures 18 and 19 there is shown a toroidal type transformer of Figure 18 forming the common-mode filter 21 embedded in a typical power converter 12. The main visible component of the CM filter is the CM transformer, which is
5 shown in constructional form in Figures 20A to 20D.

Figure 18 in particular shows the relative size of the CM Filter compared with the power converter which is one substantial advantage of this system. Figure 19 and Figures 20A to 20D show the core, coil former and support structure of the CM
10 transformer. The actual windings are shown Figures 19A to 19D in the grooves of the coil former.) This is a toroidal type transformer construction, but other types could also be used to form a common mode inductor.

A common-mode inductor being an inductive component with multiple windings
15 arranged so that a flux change in the core induces voltages of the same polarity in each winding. A typical common-mode inductor has strong coupling between the windings and is similar to a voltage transformer in that the magnetizing current is small compared to the current ratings of the windings. Use of a common-mode transformer indicates that the device is operating primarily as a voltage transformer.
20 The CM transformer must be designed to support both the switching frequency and low frequency CM voltage without saturation or overheating of the core. Also, the magnetizing inductance of the CM transformer must be large enough so that the peak magnetizing current is within the capability of the active control power source.

25 **Example CM Transformer Specification**

The DC-side common-mode main inductor of the 50kVA solar Grid Connect Inverter.

The DC-side Common-Mode main inductor is located between the GCI booster and inverter stage. It supports the AC component of common-mode voltage produced by the inverter stage. The common-mode voltage includes significant components at
30 triplen harmonics of the line frequency. There are also significant components at the inverter switching frequency and harmonics.

The key function of the DC-side CM main inductor is to prevent AC components of ground circulating current, when the DC side load is ground referenced, or has
35 significant ground capacitance, as is the case for a large solar array. (The DC

component of ground circulating current is prevented by control of the inverter switching patterns.) The design enables the inverter to be ground referenced on both the AC-side and DC-side. (The DC-side ground reference must be close to the DC bus voltage mid-point, unless DC blocking capacitors are also fitted to the AC-side of the inverter.)

The DC-side CM main inductor includes 3 windings. There are two main windings for DC positive and DC negative. There is also a control winding, which is driven by an external control circuit, such that the majority of the inductor magnetizing current flows in the control winding. This method allows the DC-side CM filter to use smaller values of inductance and capacitance than would otherwise be necessary. In this design, the control winding is driven by a low voltage circuit, so there is a significant turns ratio, n_{dc_cm} , between the main windings and the control winding.

The inductor magnetic field is dominated by the line frequency third harmonic, but there are also significant components at other line frequency triplen harmonics and at the fundamental and harmonic switching frequencies. The inductor core design needs to address the significant switching frequency component. It is also important to limit the power loss of the inductor to achieve a high power conversion efficiency.

20

The Electrical Specifications include:

Configuration: 1 coupled inductor, with 2 main windings of equal turns in a common-mode configuration and a control winding a common-mode configuration. The turns ratio between the main windings and the control winding is $n_{dc_cm} : n_{dc_cm} : 1$

25

Main winding to control winding turns ratio, $n_{dc_cm} :$ $\geq \text{ceil}((3.V_{dc_max})/(4.V_{ctrl_min})) = 28$

Main winding self inductance, $L_{dc_cm} :$ $\geq \Delta\psi_{max}/(2.\sqrt{2}.I_{ctrl_max}/n_{dc_cm}) = 0.00826. n_{dc_cm}$

In this case, inductance is defined as $\psi_{max_peak}/I_{cm_max}$, to give an "integrated value" of inductance, rather than an incremental value of inductance. The key is that the lower bound on the inductance is defined by the maximum available control current and the maximum applied volt seconds. It is assumed that the peak flux linkage corresponds to a balanced AC flux density variation.

The inductor must meet this specification over all manufacturing tolerance.

35

Main winding leakage inductance, $L_{dc_cm_lk} \leq 0.02 * L_{dc_cm}$

The inductor must meet this specification over all manufacturing tolerance.

Control winding leakage inductance, $L_{dc_cm_ctrl_lk} \leq 0.02 * L_{dc_cm} / n_{dc_cm}^2$

5

Main winding current rating: 80ADC

(with No significant line frequency or switching frequency harmonic current.)

Control winding current rating: 8Arms (line frequency third harmonic)

- 10 This includes a smaller amount of other line frequency triplen harmonic current and switching frequency current. The exact control winding current can be derived from the specified inductor voltage, self inductance and turns ratio.

Nominal switching frequency: 15 kHz

- 15 The design should tolerate switching frequency in the range 10 kHz to 30 kHz
(Operation above 20kHz will be restricted to fundamental current levels of < 25% of rated current)

Inductor voltage: $\leq 300V_{rms}$ (Total)

20

The inductor voltage has significant components at triplen harmonics of the line frequency and at the switching frequency and associated harmonics. The exact values depend on the several factors including AC and DC side voltage. In general, the total line frequency voltage increases with the AC-side voltage. The total rms
25 switching frequency voltage increases with both the DC-side voltage and reduces with the AC-side voltage. A selection of results is given in Table 1 and Table 2. These are at the worst case DC-side voltage of 800V. The results show the rms value for the total line frequency voltage and the rms value at each line frequency harmonic number, N_{FL} . There is also the rms value for the total switching frequency
30 voltage and the rms value at each switching frequency harmonic number, N_{FS} .

V_{AC_PN}	Total	$N_{FL} = 3$	$N_{FL} = 9$	$N_{FL} = 15$
200 (50Hz)	43	42	4.7	2.0
231 (50Hz)	49	48	5.2	2.1
305 (60Hz)	64	63	6.2	2.7

Table 1: Line frequency voltages at several AC-side operating voltages

V_{AC_PN}	Total	$N_{Fs} = 1$	$N_{Fs} = 2$	$N_{Fs} = 3$	$N_{Fs} = 4$	$N_{Fs} = 5$	$N_{Fs} = 6$	$N_{Fs} = 7$	$N_{Fs} = 8$
200	278	250	44	68	21	27	15	33	13
231	252	217	46	81	20	31	15	23	15
305	177	129	47	60	22	40	14	30	18

Table 2: Switching frequency voltages at several AC-side operating voltages

The maximum flux linkage change that occurs is $\Delta\psi_{max} = 0.187Vs$.

- 5 This is a superposition of both line frequency and switching frequency values. The common-mode inductor voltage is established at a controlled rate, such that the core flux swing corresponding to $\Delta\psi_{max}$ can be assumed to be balanced around zero. The common-mode inductor should be designed to support a flux linkage change of up to 0.1Vs starting with a core at zero flux density, without entering the saturation region.
- 10 As an example, a flux linkage swing of 0.1Vs, should not cause an initially unfluxed core of longitudinal annealed metglas 2605SA1 to exceed a flux density of 1.4T.

Maximum power loss: 125W @ 75ADC, 25C cooling air

- 15 Stray field Issues: The stray flux from the inductor should be minimized to prevent stray field losses and interference. The inductor base plate will be mounted directly to a steel plate. The inductor should be designed to minimize stray field losses in this plate. (Note: Except for this steel plate, no ferrous material will be used within 20mm of the inductor core.)

20

Insulation to winding to winding: 1000VDC continuous, 2500V (DC, 50Hz or 60Hz) for 1 minute

Insulation to ground: 1000VDC continuous, 2500V (DC, 50 Hz or 60 Hz) for 1 minute

- 25 The control winding insulation to ground should be rated for 600V continuous.

Cooling air temperature: -20C to 50C

Cooling air flow rate: $> 0.005m^3s^{-1}$

Cooling air speed: $> 0.3ms^{-1}$

30

An example design is provided for reference purposes. This is a high level design and does not include full details of mounting and termination. The example design should not be used by potential suppliers without further work using magnetic

analysis software and/or experimentation to verify key parameters such as inductance, leakage inductance and losses. Without this additional work, the example design may fail to meet the specification.

5 Example CM Transformer Implementation

Referring to Figures 17, 18A to 18D and 19A to 19D, one form of such a common mode inductor has the characteristics of:

Inductance: $L_{cm} = 0.61H \pm 25\%$ at peak flux density 1.2T, 150Hz defined as $L_{cm}(B)$
 $= N.B.A./l_{cm}(B)$

Inductance: $L_{cm} = 0.034H \pm 25\%$ at peak flux density 50mT, 10kHz defined as $L_{cm}(B) = N.B.A./l_{cm}(B)$

Core: Custom Metglas part

Shape: Toroid core in plastic case

Core inner Diameter: 90.0mm

Core outer Diameter: 185mm

Core depth: 60.0mm

Case inner Diameter: 85.5mm inside, 81.5mm outside

Case outer Diameter: 192.0mm inside, 197.0mm outside

Case depth: 62mm inside, 72.0mm outside (5.5mm radius on OD and

ID edges)

Core material: Metglass 2605SA1 *longitudinal field annealed*

Case material: Plastic with working temperature $\geq 180C$

Air gap: None.

Winding 1: 30-turns on one side of the core covering the angle approximately $+10^\circ$ to $+170^\circ$

The coil has 4 layers connected in parallel. Each layer has 30 turns of 10AWG heavy enamelled round copper magnet wire (UL180C rated, e.g. MW30). (Typical conductor diameter = 2.59mm. Typical total diameter $\leq$ 2.69mm.)

The wires are evenly spaced on each layer. To maintain wire spacing, the first and second layers are aligned by grooves in the end faces of the plastic case of the core.

- 5 The winding is secured by ties to points on the plastic case of the core.
The 4 10AWG wires are then formed into flying leads.

Winding 2: As winding 1, except on the other side of the core covering the angle -10° to -170°.

- 10 The winding orientation is set to create a common-mode inductor.

Winding 3: 1-turn 16-AWG insulated copper wire. With 500mm flying leads.

Insulation rating = 600V at 180C. For example, PTFE insulated UL1213 wire.

15

Insulation: UL Class 180C

Winding: The wire coating is sufficient for turn-to-turn and layer-to-layer insulation.

- 20 Outside (wrapper): Winding 1 and Winding 2 are finished with at least 2 layers of glass-fibre tape.

Leads to terminations: Glass-fibre tube.

- 25 Winding to Winding. Two inter-winding spacers are integrated into the plastic core case. These are raised sections in the end-faces of 9mm height that extend from an inner radius of 25mm to an outer radius of 106mm. Each spacer covers an arc of 10°.

- 30 Mounting: The core is mounted in vertical configuration in a U shaped bracket that connects via M6 tapped holes in the inter-winding spacers.

30

Finish: Varnish finish to UL Class 180C. Mask or avoid terminations.

- 35 With reference to Figures 22 and 23 it can be seen that the diagrams each show part of the overall system. Figure 22 is a functional circuit schematic of the power converter and series active CM filter and Figure 23 is a detailed circuit schematic of the active power source. The interfaces on each do not align completely and are

described with different names to each other however it can be understood that the two are linked by this interface to supply the secondary CM control current, ICM_S_CTRL, from the active power source to the series active filter CM transformer secondary winding and such interface would be understood by person skilled in the art in order to understand the invention disclosed and claimed herein.

Figures 22 and 23 show a partial schematic circuit diagram of a VSI with series active CM filter. Referring to Figure 22, the active CM filter is composed of the CM Transformer part name LCM and CM current return path formed of part names Cdn, Rdn and Cdna. The CM Transformer primary windings are connected in series with the DC power port of a VSI. Figure 22 shows the CM current measurement IDC_CM at the output of the CM active filter.

Figure 22 also shows the CM transformer secondary control current input, IDC_CTRL_IN and output IDC_CTRL_OUT for connection to the active CM control bridge power circuit, which shown in Figure 23 as connector DC CM CTRL. This interface supplies the secondary CM control current, ICM_S_CTRL, from the active power source to the series active filter CM transformer secondary winding. The full-bridge controlled voltage source is realized using power integrated circuit U11 and associated components. The series inductive element is realized with parts L5, L6 and L7. The ICM_S_CTRL current measurement is provided by part CS1. The ICM_S_CTRL measurement, full-bridge controlled voltage source PWM control and status signals are connected to a digital control system (not shown) at the connector CONTROL BRD. The digital control system also receives the IDC_CM measurement signal and other related measurements. The digital control system implements the feedback and feedforward control schemes to limit and control IDC_CM.

While we have described herein particular embodiments of a common-mode filter device and system, it is further envisaged that other embodiments of the invention could exhibit any number and combination of any one of the features previously described. Those of skill in the art will appreciate that such modifications or changes to the particular embodiments exemplified can be made without departed from the scope of the invention. All such modifications and changes are intended to be included within the scope of this invention.

In particular the above applications are where the power converter and series active CM filter are connected to the utility grid. However other applications include where

- the power converter and series active CM filter are connected to an array of solar photovoltaic cells. Further it includes applications where the CM filter is connected between the two power converters of a double conversion Uninterruptible Power Supply UPS. Still further applications include where the active CM filter supports CM
- 5 voltage AC components at harmonics of the utility grid frequency at a level significant compared to the utility grid DM voltages. Clearly persons skilled in the art would see the analogous and obvious variations to the above and these are included within the scope of the invention.
- 10 Further there can be specific variations in structure. For example an active filter of the invention can include components to provide a CM return circuit with defined impedance for the CM current at the power port to return to the power converter after passing through the CM transformer. These CM return circuit components can have predominantly capacitive impedance.
- 15 However, it is to be understood that any variations and modifications which can be made without departing from the spirit and scope thereof are included in the scope of the invention as defined in the following claims.

CLAIMS

1. A common-mode filter device and system for regulating aspects of power conversion by a power converter from external source such as solar panels to another external circuit wherein the common-mode filter device substantially attenuates common-mode voltage at the switching frequency plus harmonics of the power converter.
2. A common-mode filter device and system according to claim 1 wherein the power converter is single phase.
3. A common-mode filter device and system according to claim 1 wherein the power converter is multiple phase.
4. A common-mode filter device and system according to claim 1 for regulating aspects of power conversion from external source such as solar panels to an AC system such as an electricity utility grid wherein the common-mode filter device substantially attenuates common-mode voltage at the AC system fundamental frequency plus harmonics and at the switching frequency plus harmonics of the associated power converter.
5. A common-mode filter device and system according to any one of claims 1 to 4 wherein the common-mode filter device include an active filter configuration.
6. A common-mode filter device and system according to any one of claims 1 to 4 wherein the common-mode filter device include a passive filter configuration.
7. A common-mode filter device and system according to any one of claims 1 to 5 wherein the common-mode filter device and system has active common-mode filter provided by a common-mode transformer (common-mode inductor) with multiple primary windings.
8. A common-mode filter device and system according to claim 7 wherein the primary windings all have an equal number of turns and each primary winding is connected in series with each power terminal of the power port.
9. A common-mode filter device and system according to claim 7 or 8 wherein an active common-mode filter further includes secondary windings.

10. A common-mode filter device and system according to claim 9 wherein in one form the active common-mode filter includes control power sources which are coupled to the secondary windings.
- 5 11. A common-mode filter device and system according to claim 10 wherein control power source is composed of a controlled voltage source in series with an inductive impedance.
- 10 12. A common-mode filter device and system according to claim 11 wherein the control power source device includes the series inductive impedance in the range 25% to 200% of the common-mode transformer magnetizing inductance measured at the secondary winding and at the switching
- 15 frequency of the associated power converter.
13. A common-mode filter device and system according to any one of the preceding claims having a common-mode filter and a power converter connected in series to support the common-mode voltage difference between
- 20 the power converter ports and to control the common-mode current to acceptable levels.
14. A common-mode filter device and system according to claim 13 wherein the common-mode filter is an active filter.
- 25 15. A common-mode filter device and system according to claim 13 wherein the common-mode filter is a passive filter.
16. A common-mode filter device and system according to claim 13 wherein the
- 30 power converter is a Voltage Source Inverter.
17. A common-mode filter device and system according to claim 13 wherein the active filter makes use of function of real time measured common-mode current and provides real time control of common-mode current across
- 35 common-mode current return paths and impedances.
18. A common-mode filter device and system according to claim 17 wherein the function of real time measured common-mode current includes measurement

and feedback control of the voltage across the common-mode current return path.

- 5 19. A common-mode filter device and system according to claim 13 wherein the active filter makes use of real time measured common-mode current and provides real time control of common-mode current with common-mode current return paths and impedances.
- 10 20. A common-mode filter device and system according to claim 13 wherein the common-mode filter consists of a common-mode transformer and one or more common-mode current return circuits connected between the power converter and the external circuit, first power conductor at the CM filter output port or second power conductor at the common-mode filter output port respectively.
- 15 21. A common-mode filter device and system according to claim 20 wherein the active filter includes an active power source coupled to a secondary winding of the common-mode transformer.
- 20 22. A common-mode filter device and system according to claim 20 or 21 wherein the active filter includes an active power source composed of a controlled voltage source in series with an inductive impedance.
- 25 23. A common-mode filter device and system according to claim 22 wherein the series impedance is primarily an inductive impedance.
- 30 24. A common-mode filter device and system according to claim 23 wherein the series inductive impedance of the active power source is in the range 25% to 200% of the common-mode transformer magnetizing inductance measured at the secondary winding and at the switching frequency of the associated power converter.
- 35 25. A common-mode filter device and system according to claim any one of claims 20 to 24 having a controllable voltage source which is a full-bridge with pulse width modulation (PWM).

26. A common-mode filter device and system according to claim any one of claims 20 to 24 having a controllable voltage source which is a half-bridge with pulse width modulation (PWM).
- 5 27. A common-mode filter device and system according to claim 25 or 26 wherein the controllable voltage source PWM period is synchronized to the switching transitions of the associated power converter.
- 10 28. A common-mode filter device and system according to claim any one of claims 20 to 24 wherein the common-mode transformer has a magnetizing inductance in the range 0.1H to 10H measured at a primary winding and at the utility grid frequency.
- 15 29. A common-mode filter device and system according to claim any one of claims 20 to 24 wherein the common-mode transformer has a core made of amorphous metal (metglas) or nanocrystalline metal.
- 20 30. A common-mode filter device and system according to claim 13 wherein the common-mode filter device and system is for a power converter used to transfer electric power between electric circuits with each electric circuit connected to a different power port of the power converter and each power port having at least two power conductors with the power port voltages being characterized by the Differential-Mode (DM) voltages and the Common-Mode (CM) voltage wherein the DM voltages are the potential differences between
- 25 pairs of power conductors and the common-mode voltage is the average potential difference between all of the power conductors and a reference potential, such as ground (earth) and the power port currents being characterized by the DM currents and the common-mode current with the DM currents being the differences between the currents in pairs of power
- 30 conductors and the common-mode current being the sum of the currents on all power conductors which flows back into one or more other power ports of the power converter via an external circuit, typically involving the ground (earth) conductor;
- 35 a. wherein the common-mode filter device and system includes an active filter used in series with a power port of the power converter to limit and control the AC component of common-mode current at the power port;

- b. and wherein the a function of the common-mode current at the power port is measured and the AC component of common-mode current is limited and controlled using a feedback controller to adjust the active filter control.

5

31. A common-mode filter device and system according to claim any one of claims 20 to 24 wherein common-mode transformer saturation is controlled by a common-mode filter that attenuates both switching frequency and low frequency common-mode voltage.

10

32. A common-mode filter device and system wherein the active filter of the common-mode filter device and system has a transformer with multiple primary windings and a secondary winding; the primary windings having an equal number of turns and each primary winding connected in series with each power terminal of the power port; and the secondary winding is connected to a controlled voltage source via an impedance wherein this invention implements an active filter that attenuates both switching frequency and low frequency common-mode voltages, even when these are significant compared to the DM voltages.

15

20

33. A common-mode filter device and system according to claim 32 wherein common-mode transformer saturation is controlled by a common-mode filter that attenuates both switching frequency and low frequency common-mode voltage.

25

34. A common-mode filter device and system according to claim 32 wherein in one form the common-mode current at the power port is measured, the AC component of common-mode current is limited and controlled using a feedback controller to adjust the active control power source.

30

35. A common-mode filter device and system according to claim 32 wherein the active filter makes use of function of real time measured common-mode current and provides real time control of common-mode current across common-mode current return paths and impedances.

35

36. A common-mode filter device and system according to claim 32 wherein the function of real time measured common-mode current includes measurement and feedback control of the voltage across the common-mode current return path.

37. A common-mode filter device and system according to claim 32 wherein estimates or measurements of the common-mode voltage at the power converter power port are used to provide feedforward control of the active control power source to reduce the AC component of common-mode current at frequencies above the bandwidth of the closed-loop common-mode current controller including at the power converter switching frequency and harmonics.
38. A common-mode filter device and system according to claim 32 wherein active damping of the common-mode filter response is obtained by appropriate closed-loop dynamics in the common-mode current feedback controller.
39. A common-mode filter device and system according to claim 32 wherein a circuit is provided to return the common-mode current from the output of the common-mode transformer to one or more other power ports of the power converter.
40. A common-mode filter device and system according to claim 39 wherein this circuit includes at least one series capacitive impedance.
41. A common-mode filter device and system according to claim 32 wherein the common-mode current from the output of the common-mode transformer returns to other power ports of the power converter via external circuits, such as insulation capacitance.
42. A common-mode filter device and system according to claim 32 wherein the operation of the disclosed active filter is similar in concept to a passive common-mode filter, except that the active control forces the majority of the common-mode transformer magnetizing current to flow in the secondary control winding, rather than in the primary windings wherein the effective impedance of the common-mode transformer is much higher than a passive common-mode transformer, choke or inductor of equivalent size.
43. A common-mode filter device and system according to claim 32 wherein a common-mode filter is in series with a power converter to support the

common-mode voltage difference between the power converter ports and to control the common-mode current to acceptable levels.

- 5 44. A means using a common-mode filter device and system for regulating aspects of power conversion from external source, such as solar panels, to an electricity utility grid in applications with high ground capacitance or low impedance external common-mode circuits including the steps of:
- a. connecting an active common-mode filter device in series between an external source power circuit and a power converter
 - 10 b. measuring a function of the common-mode current at common-mode filter input or output
 - c. provide active common-mode current return based on measured common-mode current
- 15 wherein the power converter regulates the common-mode voltage difference between the power converter ports and controls the common-mode current to acceptable levels.
- 20 45. A means using a common-mode filter device and system according to claim 44 wherein the active filter uses function of real time measured common-mode current and provides real time control of common-mode current across common-mode current return paths and impedances.
- 25 46. A common-mode filter device and system according to claim 44 wherein the function of real time measured common-mode current includes measurement and feedback control of the voltage across the common-mode current return path.
- 30 47. A means using a common-mode filter device and system according to claim 44 wherein the active filter uses real time measured common-mode current and provides real time control of common-mode current with common-mode current return paths and impedances wherein the active filter limits and controls the AC component of common-mode current at the power port.
- 35 48. A means using a common-mode filter device and system according to any one of claims 44 to 47 wherein the active filter include a common-mode transformer with multiple primary windings and a secondary winding with each primary winding having an equal number of turns and each primary

winding connected in series with each power terminal of the power port and the secondary winding being connected to an active power source.

- 5 49. A means using a common-mode filter device and system according to claim 48 wherein the active filter includes a measurement related to the common-mode current at the power port wherein the active filter includes a control mechanism using feedback of said measurement to control the active power source such that the common-mode current at the port is controlled or limited.
- 10 50. A means using a common-mode filter device and system according to claim 48 wherein the active filter includes an additional measurement or estimation of the common-mode voltage supported by the primary windings of the common-mode transformer.
- 15 51. A means using a common-mode filter device and system and system according to claim 48 wherein the control mechanism uses feedforward of the common-mode voltage measurement or estimation to control the active power source such that the common-mode current at the port is reduced.
- 20 52. A means using a common-mode filter device and system according to claim 48 wherein the control mechanism uses the common-mode voltage measurement or estimation to control the active power source to provide active damping of the common-mode filter.
- 25 53. A means using a common-mode filter device and system according to claim 44 wherein the active filter is in series with a power converter and includes DC blocking capacitors in series with an AC power port, such that the flow of DC common-mode current is limited and controlled by the series capacitors and the flow of AC common-mode current is limited and controlled by the
- 30 active common-mode filter.
54. A common-mode filter device and system substantially as hereinbefore described with reference to the examples and the drawings.
- 35 55. A means using a common-mode filter device and system substantially as hereinbefore described with reference to the examples and the drawings.

CLAIMS

1. A common-mode filter device and system for regulating aspects of power conversion by a power converter from external source such as solar panels to another external circuit wherein the common-mode filter device substantially attenuates common-mode voltage at the switching frequency plus harmonics of the power converter.
2. A common-mode filter device and system according to claim 1 wherein the power converter is single phase.
3. A common-mode filter device and system according to claim 1 wherein the power converter is multiple phase.
4. A common-mode filter device and system according to claim 1 for regulating aspects of power conversion from external source such as solar panels to an AC system such as an electricity utility grid wherein the common-mode filter device substantially attenuates common-mode voltage at the AC system fundamental frequency plus harmonics and at the switching frequency plus harmonics of the associated power converter.
5. A common-mode filter device and system according to any one of claims 1 to 4 wherein the common-mode filter device include an active filter configuration.
6. A common-mode filter device and system according to any one of claims 1 to 4 wherein the common-mode filter device include a passive filter configuration.
7. A common-mode filter device and system according to any one of claims 1 to 5 wherein the common-mode filter device and system has active common-mode filter provided by a common-mode transformer (common-mode inductor) with multiple primary windings.
8. A common-mode filter device and system according to claim 7 wherein the primary windings all have an equal number of turns and each primary winding is connected in series with each power terminal of the power port.
9. A common-mode filter device and system according to claim 7 or 8 wherein an active common-mode filter further includes secondary windings.

10. A common-mode filter device and system according to claim 9 wherein in one form the active common-mode filter includes control power sources which are coupled to the secondary windings.
- 5 11. A common-mode filter device and system according to claim 10 wherein control power source is composed of a controlled voltage source in series with an inductive impedance.
- 10 12. A common-mode filter device and system according to claim 7 wherein the common-mode filter device include the inductive impedance in the range 25% to 200% of the common-mode transformer magnetizing inductance measured at the secondary winding and at the switching frequency of the associated power converter.
- 15 13. A common-mode filter device and system according to any one of the preceding claims having a common-mode filter and a power converter connected in series to support the common-mode voltage difference between the power converter ports and to control the common-mode current to acceptable levels.
- 20 14. A common-mode filter device and system according to claim 13 wherein the common-mode filter is an active filter.
15. A common-mode filter device and system according to claim 13 wherein the common-mode filter is a passive filter.
- 25 16. A common-mode filter device and system according to claim 13 wherein the power converter is a Voltage Source Inverter.
- 30 17. A common-mode filter device and system according to claim 13 wherein the active filter makes use of function of real time measured common-mode current and provides real time control of common-mode current across common-mode current return paths and impedances.
- 35 18. A common-mode filter device and system according to claim 17 wherein the function of real time measured common-mode current includes measurement and feedback control of the voltage across the common-mode current return path.
19. A common-mode filter device and system according to claim 13 wherein the active filter makes use of real time measured common-mode current and provides real time

control of common-mode current with common-mode current return paths and impedances.

5 20. A common-mode filter device and system according to claim 13 wherein the common-mode filter consists of a common-mode transformer and one or more common-mode current return circuits connected between the power converter and the external circuit, first power conductor at the CM filter output port or second power conductor at the common-mode filter output port respectively.

10 21. A common-mode filter device and system according to claim 20 wherein the active filter includes an active power source coupled to a secondary winding of the common-mode.

15 22. A common-mode filter device and system according to claim 20 or 21 wherein the active filter includes an active power source composed of a controlled voltage source in series with an inductive impedance.

20 23. A common-mode filter device and system according to claim 22 wherein the series impedance is primarily an inductive impedance.

25 24. A common-mode filter device and system according to claim 23 wherein the inductive impedance is in the range 25% to 200% of the common-mode transformer magnetizing inductance measured at the secondary winding and at the switching frequency of the associated power converter.

30 25. A common-mode filter device and system according to claim any one of claims 20 to 24 having a controllable voltage source which is a full-bridge with pulse width modulation (PWM).

35 26. A common-mode filter device and system according to claim any one of claims 20 to 24 having a controllable voltage source which is a half-bridge with pulse width modulation (PWM).

27. A common-mode filter device and system according to claim 25 or 26 wherein the controllable voltage source PWM period is synchronized to the switching transitions of the associated power converter.

28. A common-mode filter device and system according to claim any one of claims 20 to 24 wherein the common-mode transformer has a magnetizing inductance in the range 0.1H to 10H measured at a primary winding and at the utility grid frequency.
- 5 29. A common-mode filter device and system according to claim any one of claims 20 to 24 wherein the common-mode transformer has a core made of amorphous metal (metglas).
- 10 30. A common-mode filter device and system according to claim 13 wherein the common-mode filter device and system is for a power converter used to transfer electric power between electric circuits with each electric circuit connected to a different power port of the power converter and each power port having at least two power conductors with the power port voltages being characterized by the Differential-Mode (DM) voltages and the Common-Mode (CM) voltage wherein the
- 15 DM voltages are the potential differences between pairs of power conductors and the common-mode voltage is the average potential difference between all of the power conductors and a reference potential, such as ground (earth) and the power port currents being characterized by the DM currents and the common-mode current with the DM currents being the differences between the currents in pairs of power
- 20 conductors and the common-mode current being the sum of the currents on all power conductors which flows back into one or more other power ports of the power converter via an external circuit, typically involving the ground (earth) conductor;
- a. wherein the common-mode filter device and system includes an active filter used in series with a power port of the power converter to limit and control the
- 25 AC component of common-mode current at the power port;
- b. and wherein the a function of the common-mode current at the power port is measured and the AC component of common-mode current is limited and controlled using a feedback controller to adjust the active filter control.
- 30 31. A common-mode filter device and system according to claim any one of claims 20 to 24 wherein common-mode transformer saturation is controlled by a common-mode filter that attenuates both switching frequency and low frequency common-mode voltage.
- 35 32. A common-mode filter device and system wherein the active filter of the common-mode filter device and system has a transformer with multiple primary windings and a secondary winding; the primary windings having an equal number of turns and each

primary winding connected in series with each power terminal of the power port; and the secondary winding is connected to a controlled voltage source via an impedance wherein this invention implements an active filter that attenuates both switching frequency and low frequency common-mode voltages, even when these are significant compared to the DM voltages.

33. A common-mode filter device and system according to claim 32 wherein common-mode transformer saturation is controlled by a common-mode filter that attenuates both switching frequency and low frequency common-mode voltage.

34. A common-mode filter device and system according to claim 32 wherein in one form the common-mode current at the power port is measured, the AC component of common-mode current is limited and controlled using a feedback controller to adjust the active control power source.

35. A common-mode filter device and system according to claim 33 wherein the active filter makes use of function of real time measured common-mode current and provides real time control of common-mode current across common-mode current return paths and impedances.

36. A common-mode filter device and system according to claim 33 wherein the function of real time measured common-mode current includes measurement and feedback control of the voltage across the common-mode current return path.

37. A common-mode filter device and system according to claim 32 wherein estimates or measurements of the common-mode voltage at the power converter power port are used to provide feedforward control of the active control power source to reduce the AC component of common-mode current at frequencies above the bandwidth of the closed-loop common-mode current controller including at the power converter switching frequency and harmonics.

38. A common-mode filter device and system according to claim 32 wherein active damping of the common-mode filter response is obtained by appropriate closed-loop dynamics in the common-mode current feedback controller.

39. A common-mode filter device and system according to claim 32 wherein a circuit is provided to return the common-mode current from the output of the common-mode transformer to one or more other power ports of the power converter.

40. A common-mode filter device and system according to claim 37 wherein this circuit includes at least one series capacitive impedance.

5 41. A common-mode filter device and system according to claim 32 wherein the common-mode current from the output of the common-mode transformer returns to other power ports of the power converter via external circuits, such as insulation capacitance.

10 42. A common-mode filter device and system according to claim 32 wherein the operation of the disclosed active filter is similar in concept to a passive common-mode filter, except that the active control forces the majority of the common-mode transformer magnetizing current to flow in the secondary control winding, rather than in the primary windings wherein the effective impedance of the common-mode transformer is much higher than a passive common-mode transformer, choke or
15 inductor of equivalent size.

43. A common-mode filter device and system according to claim 32 wherein a common-mode filter is in series with a power converter to support the common-mode voltage difference between the power converter ports and to control the common-mode
20 current to acceptable levels.

44. A means using a common-mode filter device and system for regulating aspects of power conversion from external source, such as solar panels, to an electricity utility grid in applications with high ground capacitance or low impedance external
25 common-mode circuits including the steps of:

- a. connecting an active common-mode filter device in series between an external source power circuit and a power converter
- b. measuring a function of the common-mode current at common-mode filter input or output
- 30 c. provide active common-mode current return based on measured common-mode current

wherein the power converter regulates the common-mode voltage difference between the power converter ports and controls the common-mode current to acceptable levels.

45. A means using a common-mode filter device and system according to claim 44 wherein the active filter uses function of real time measured common-mode current and provides real time control of common-mode current across common-mode current return paths and impedances.

5

46. A common-mode filter device and system according to claim 44 wherein the function of real time measured common-mode current includes measurement and feedback control of the voltage across the common-mode current return path.

10

47. A means using a common-mode filter device and system according to claim 44 wherein the active filter uses real time measured common-mode current and provides real time control of common-mode current with common-mode current return paths and impedances wherein the active filter limits and controls the AC component of common-mode current at the power port.

15

48. A means using a common-mode filter device and system according to any one of claims 44 to 47 wherein the active filter include a common-mode transformer with multiple primary windings and a secondary winding with each primary winding having an equal number of turns and each primary winding connected in series with each power terminal of the power port and the secondary winding being connected to an active power source.

20

49. A means using a common-mode filter device and system according to claim 48 wherein the active filter includes a measurement related to the common-mode current at the power port wherein the active filter includes a control mechanism using feedback of said measurement to control the active power source such that the common-mode current at the port is controlled or limited.

25

50. A means using a common-mode filter device and system according to claim 48 wherein the active filter includes an additional measurement or estimation of the common-mode voltage supported by the primary windings of the common-mode transformer.

30

51. A means using a common-mode filter device and system according to claim 48 wherein the control mechanism uses feedforward of the common-mode

35

voltage measurement or estimation to control the active power source such that the common-mode current at the port is reduced.

52. A means using a common-mode filter device and system according to claim 48 wherein the control mechanism uses the common-mode voltage measurement or estimation to control the active power source to provide active damping of the common-mode filter.

53. A means using a common-mode filter device and system according to claim 44 wherein the active filter is in series with a power converter and includes DC blocking capacitors in series with an AC power port, such that the flow of DC common-mode current is limited and controlled by the series capacitors and the flow of AC common-mode current is limited and controlled by the active common-mode filter.

54. A common-mode filter device and system substantially as hereinbefore described with reference to the examples and the drawings.

55. A means using a common-mode filter device and system substantially as hereinbefore described with reference to the examples and the drawings.

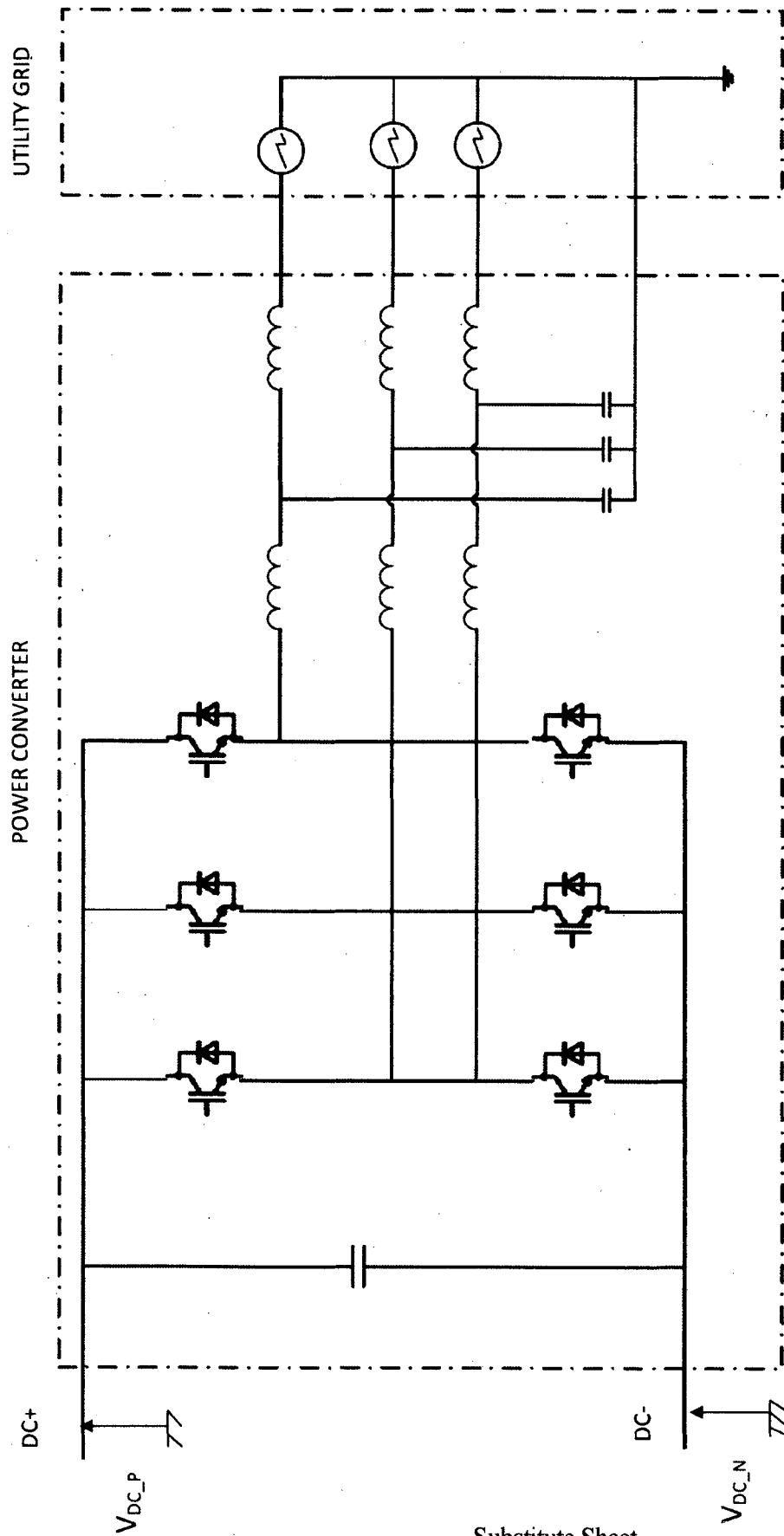
56. A common-mode (CM) filter device and system for regulating aspects of power conversion from external source, such as solar panels, to an electricity utility grid in applications with high ground capacitance or low impedance external common-mode circuits including:

a. the common-mode filter device connected in series between an external source power circuit and a power converter and including a common-mode blocking impedance, such as a common-mode transformer, connected between the common-filter input and output ports and a common-mode current return impedance from the filter output to the power converter forming a common-mode low-pass filter,

b. wherein above the filter cut-off frequency, the blocking impedance is greater than the return impedance and the common-mode filter provides significant voltage attenuation;

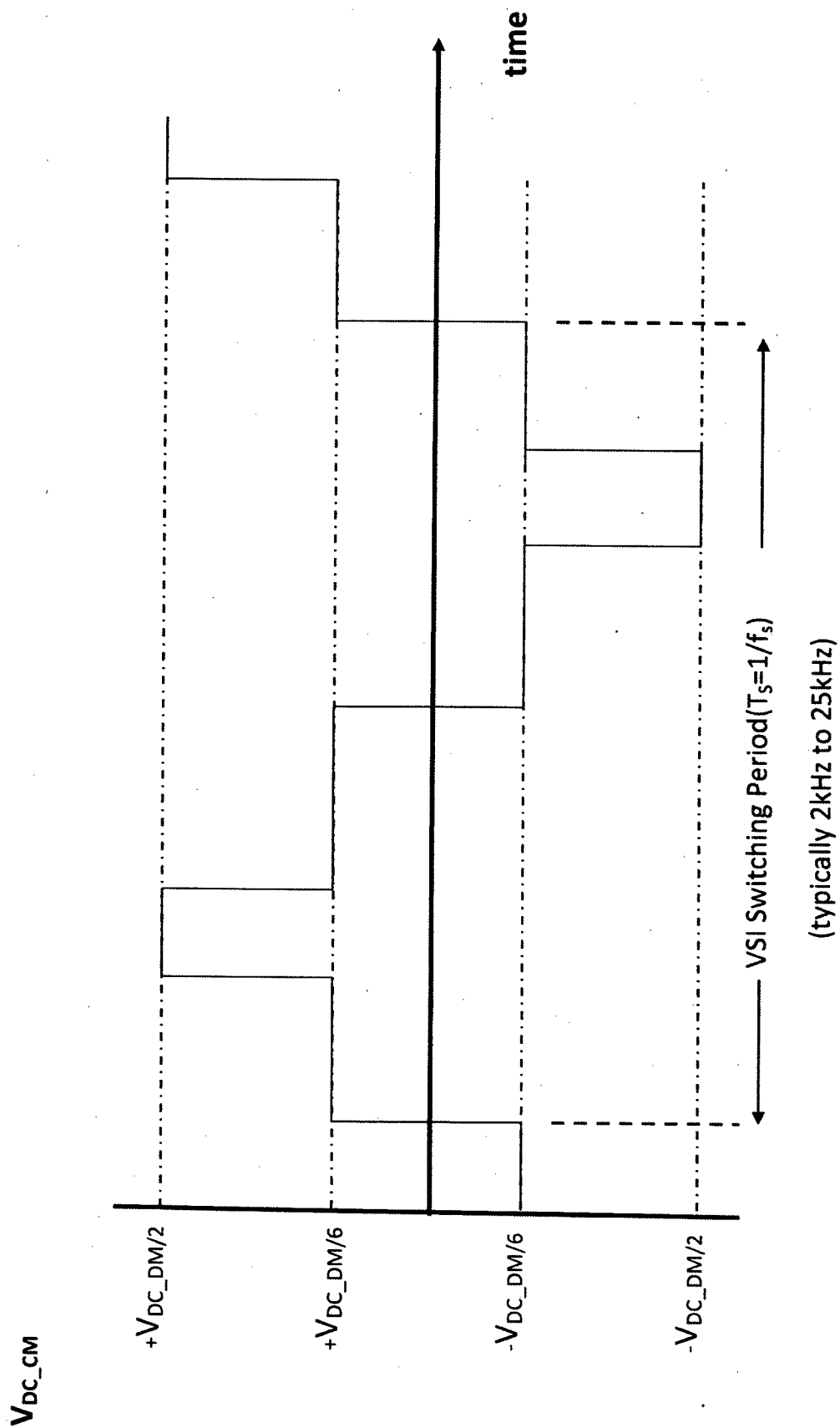
wherein the common-mode filter device substantially attenuates common-mode voltage at the Alternating Current (AC) system fundamental frequency plus harmonics and at the switching frequency plus harmonics of the associated power converter.

57. A controller for common-mode filter device and system in accordance with claim 56 wherein the common-mode filter device is a passive low-pass filter for filtering grid frequency harmonic and switching frequency harmonic common mode voltage.
58. A controller for common-mode filter device and system in accordance with claim 57 wherein the filter provides substantial attenuation of common-mode voltage and current above the cut-off frequency less than about 2 times the grid frequency.
59. A controller for common-mode filter device and system in accordance with claim 58 with passive low pass filter provides substantial attenuation of common-mode voltage and current substantially in the range of 1 Hz to 100Hz.
60. A controller for common-mode filter device and system in accordance with claim 59 wherein the power converter is a Voltage Source Inverter (VSI) and the passive common-mode filter includes a common mode transformer and a common-mode current return path consisting of a capacitance with parallel branch of series capacitor and resistor so as to create a damped low pass filter that substantially attenuates CM voltage at the AC system fundamental frequency plus harmonics and at the switching frequency plus harmonics of the associated power converter.
61. A controller for common-mode filter device and system in accordance with claim 56, wherein the CM current measurement is typically processed by a high pass filter to extract the AC component with the cut-off frequency of the high pass filter is between 50% and 300% of the AC utility grid frequency.



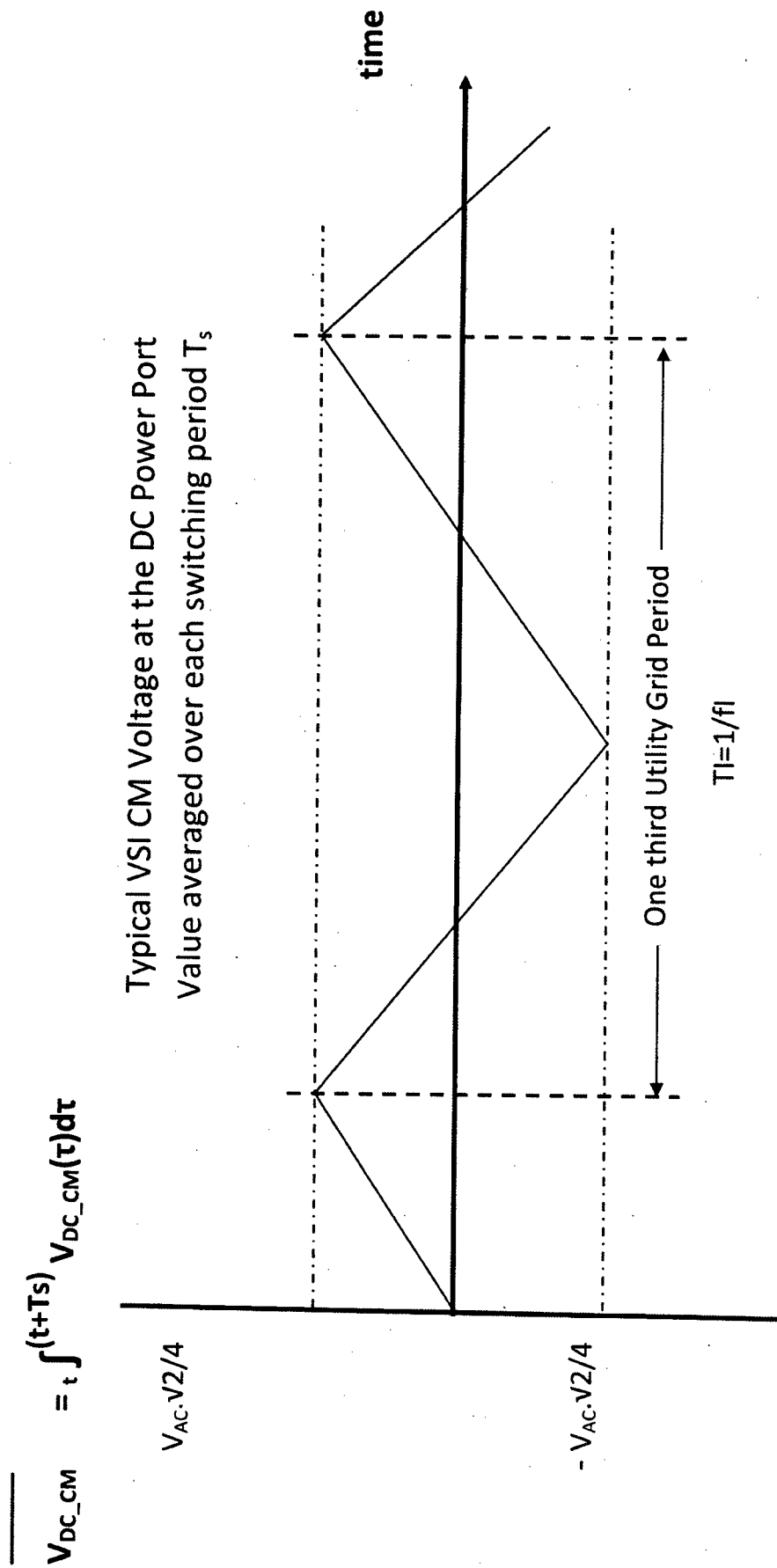
Typical VSI Circuit

Figure 1



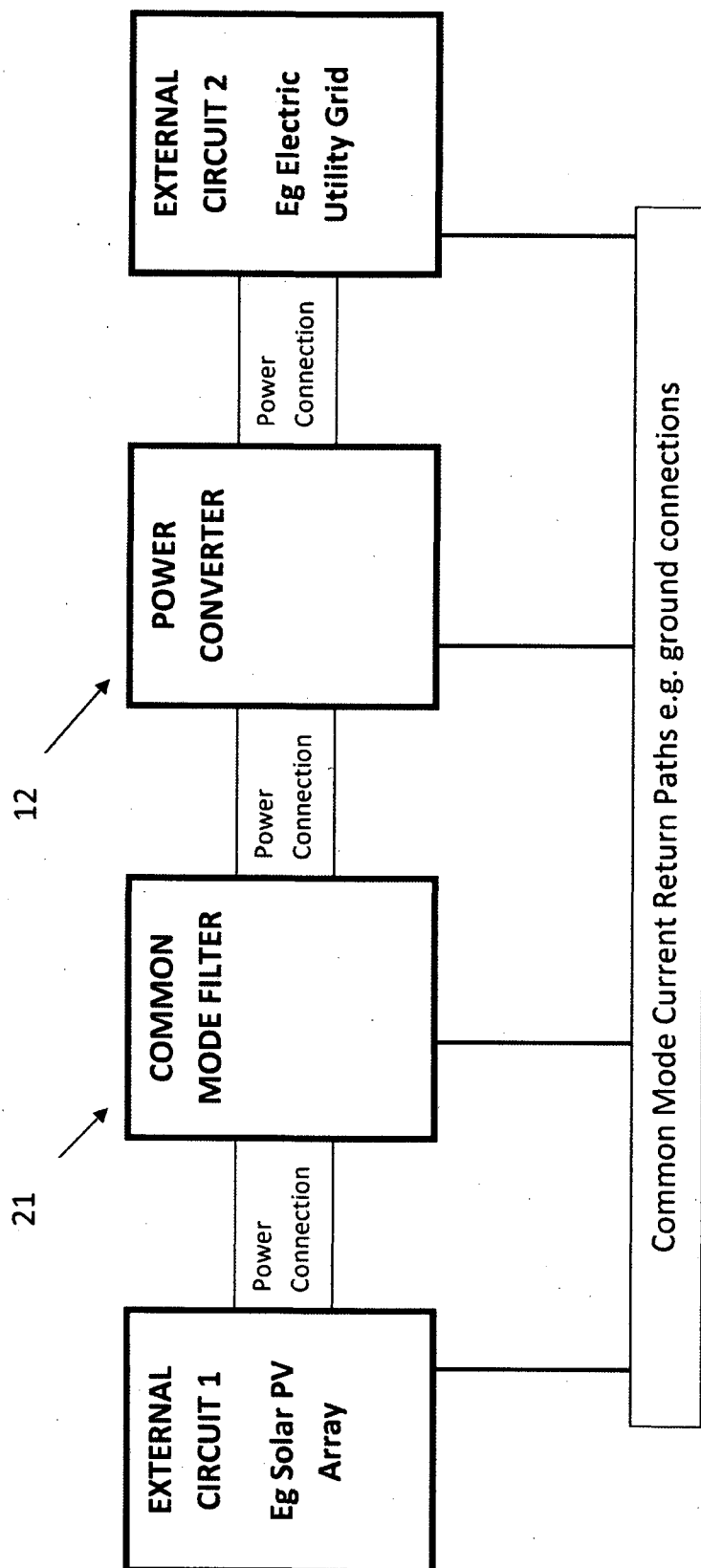
Typical VSI CM Voltage at the DC Power Port

Figure 2



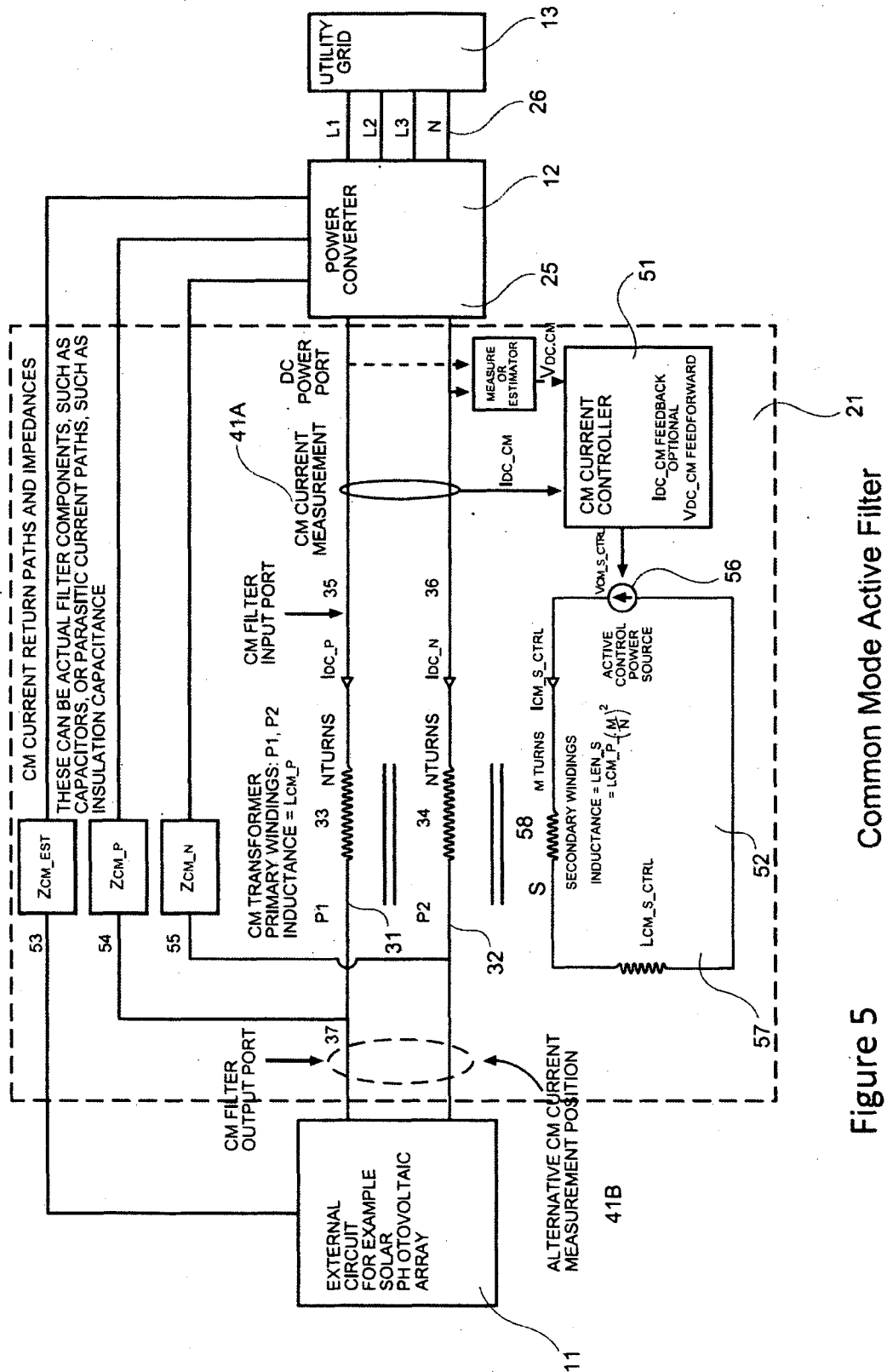
V_{AC} = Utility Grid Phase
To Neutral RMS Voltage

Figure 3

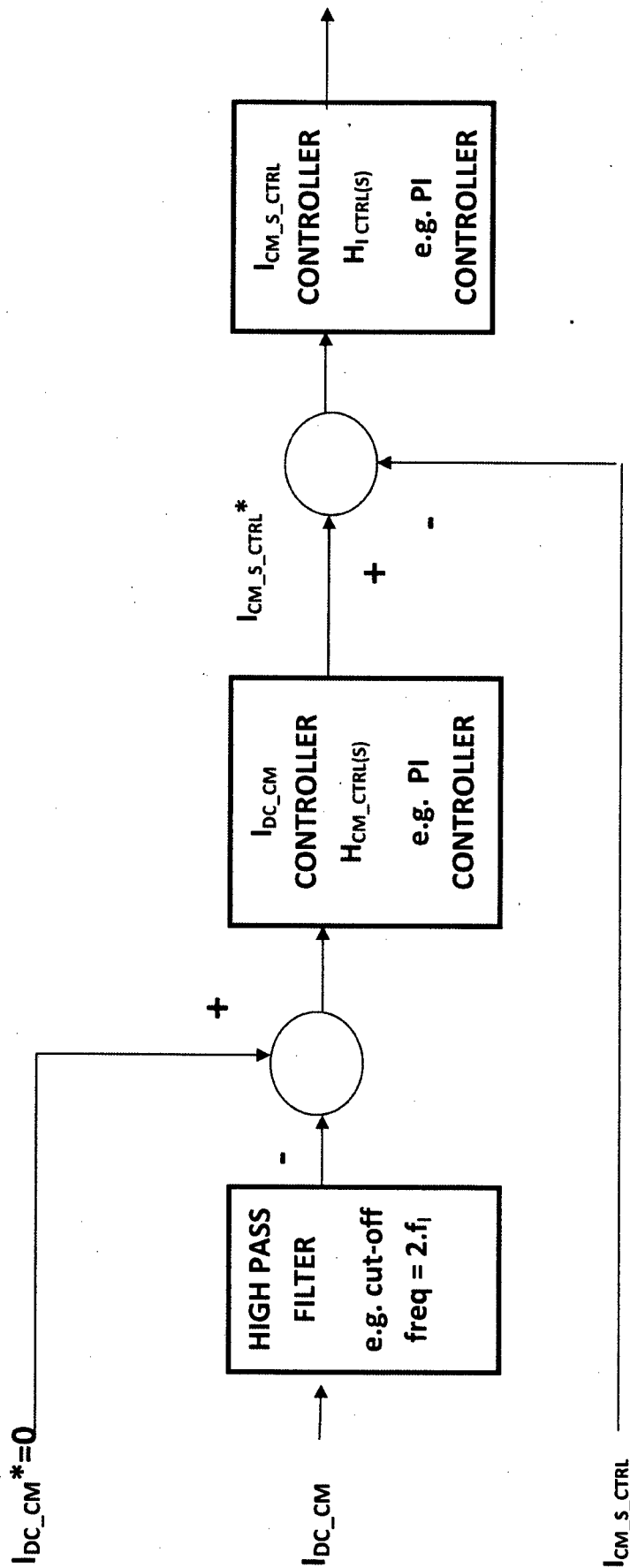


Common Mode Filter in relation to Associated Systems

Figure 4



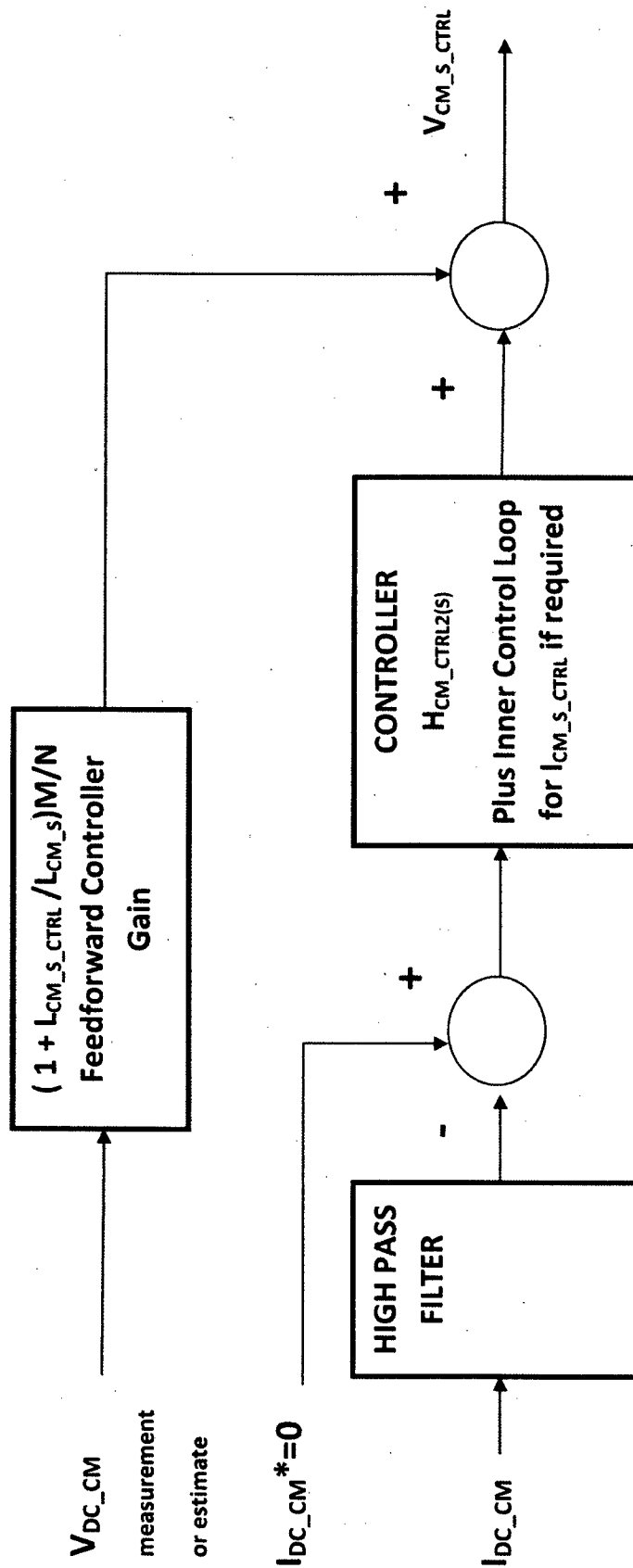
Common Mode Active Filter



*Denotes a Reference Quantity (Control Target)

Controller with Inner Loop Controller for $I_{CM_S_CTRL}$
 such as for limiting $I_{CM_S_CTRL}$
 or $H_{CM_S_CTRL}$ to control $V_{CM_S_CTRL}$ directly

Figure 6



* Denotes a Reference Quantity (Control Target)

Controller with CM Voltage Feedforward

Figure 7

Controller with Active Damping and CM Voltage Feedforward

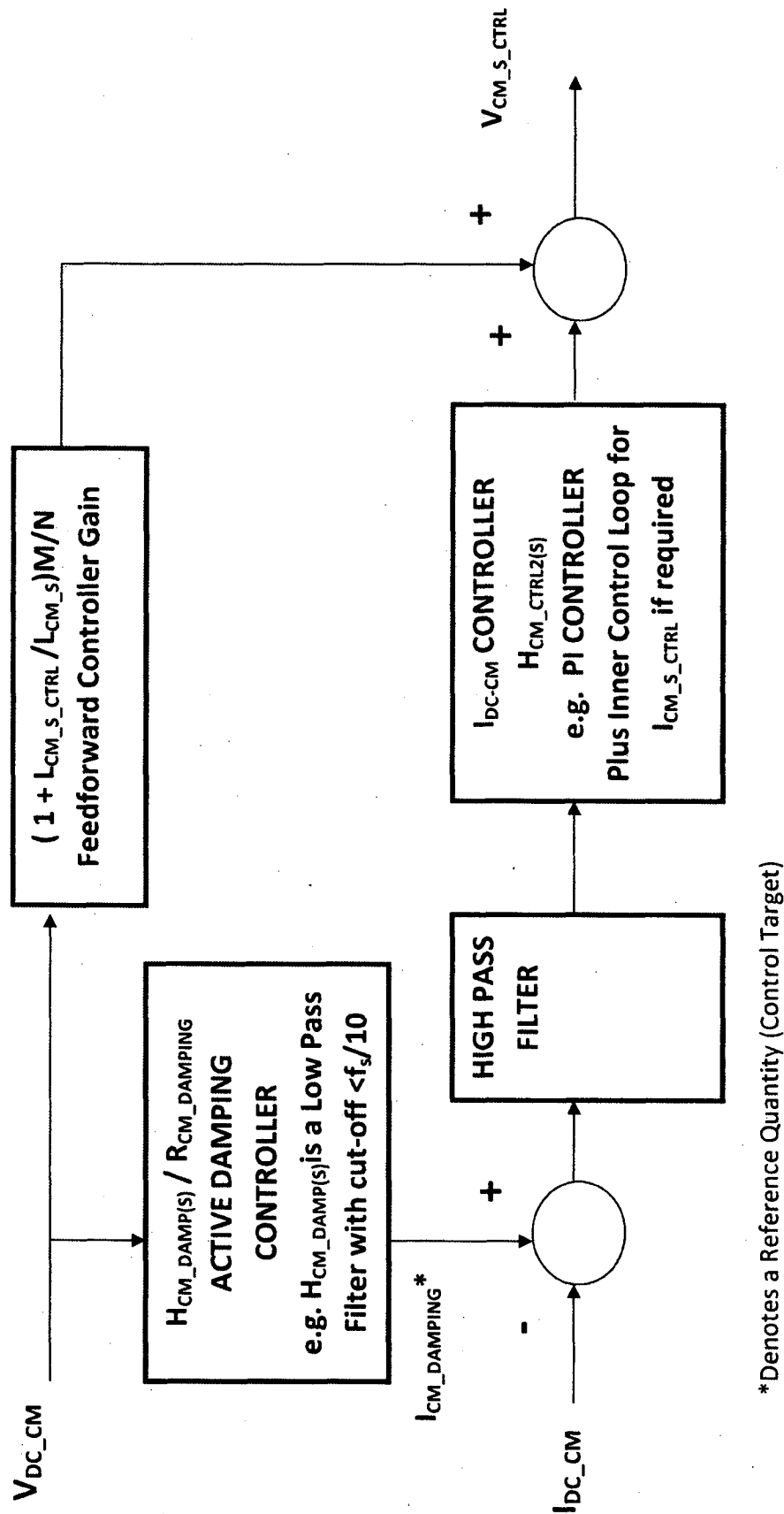


Figure 8

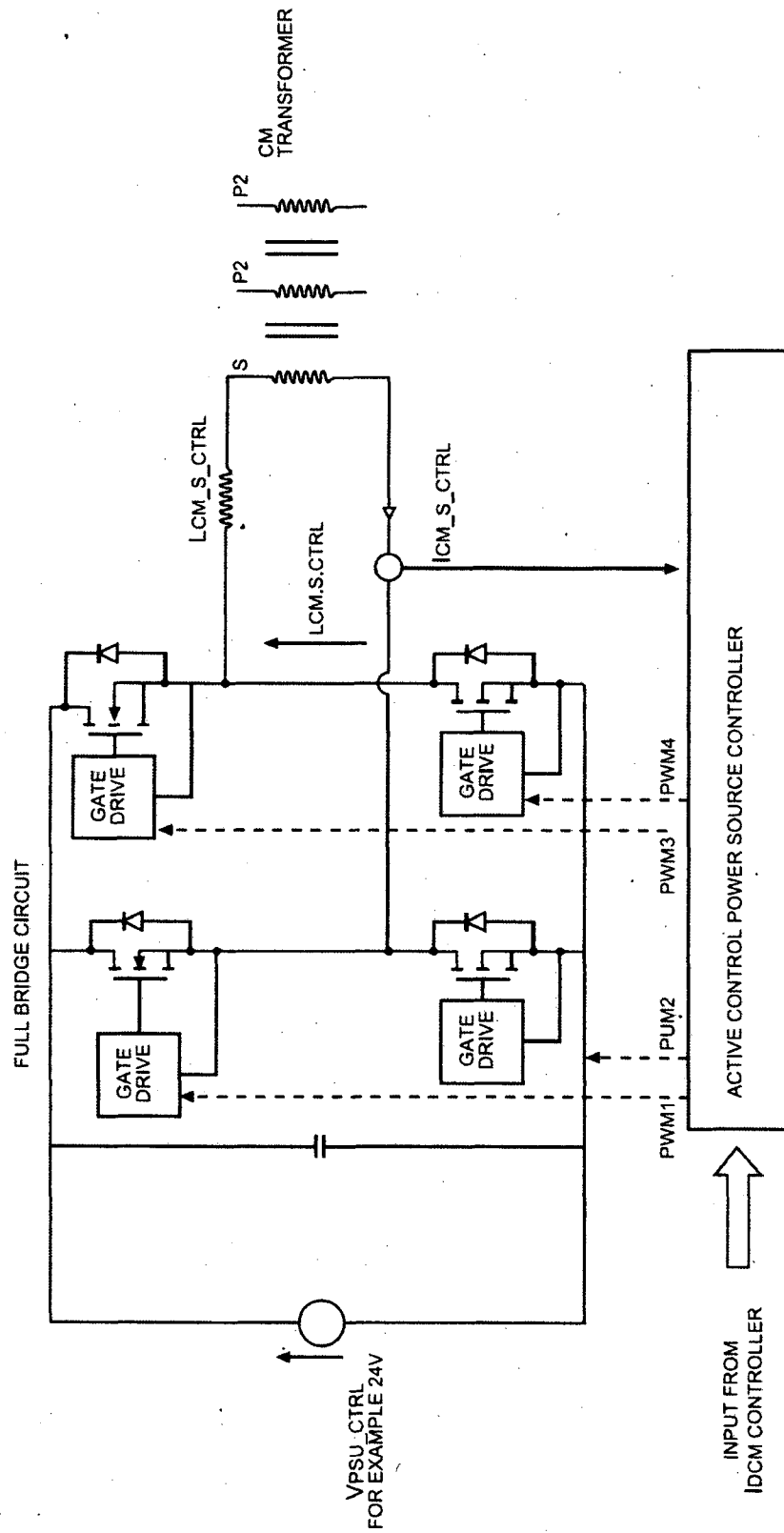
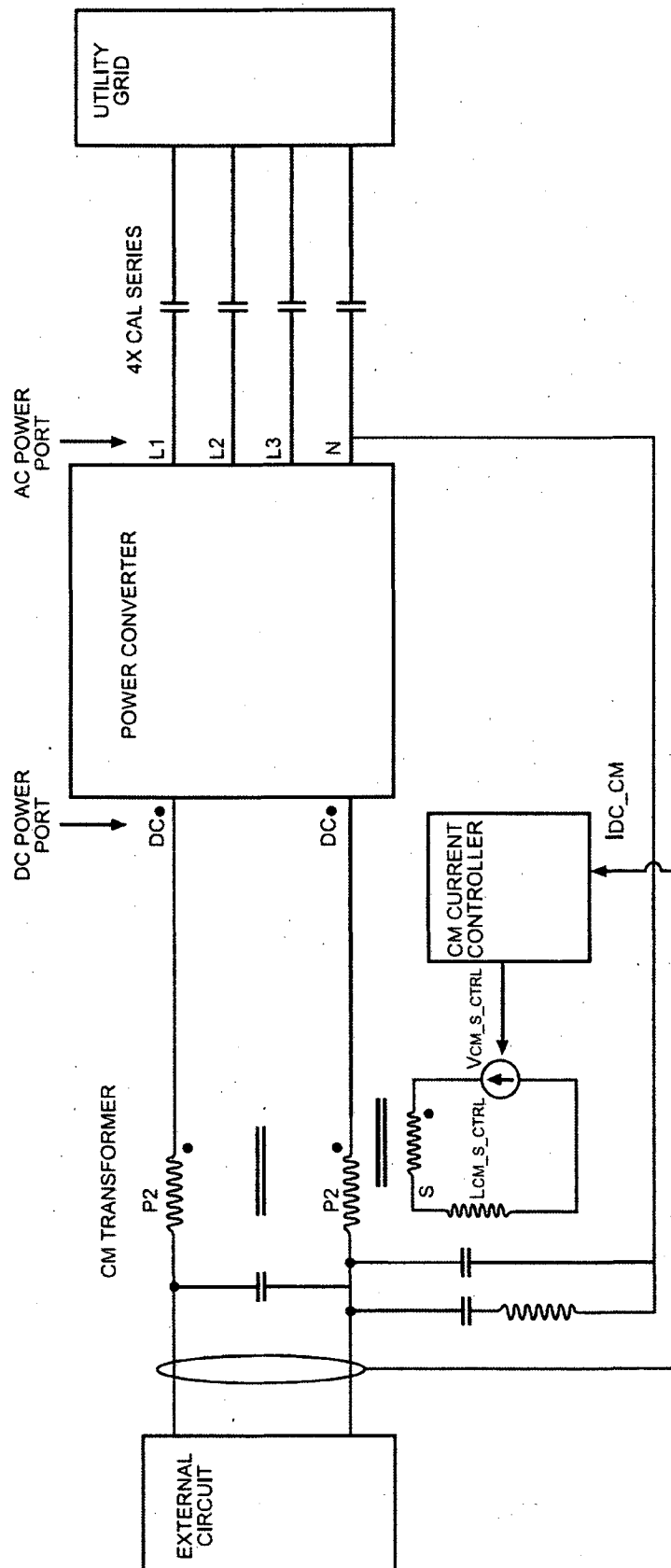
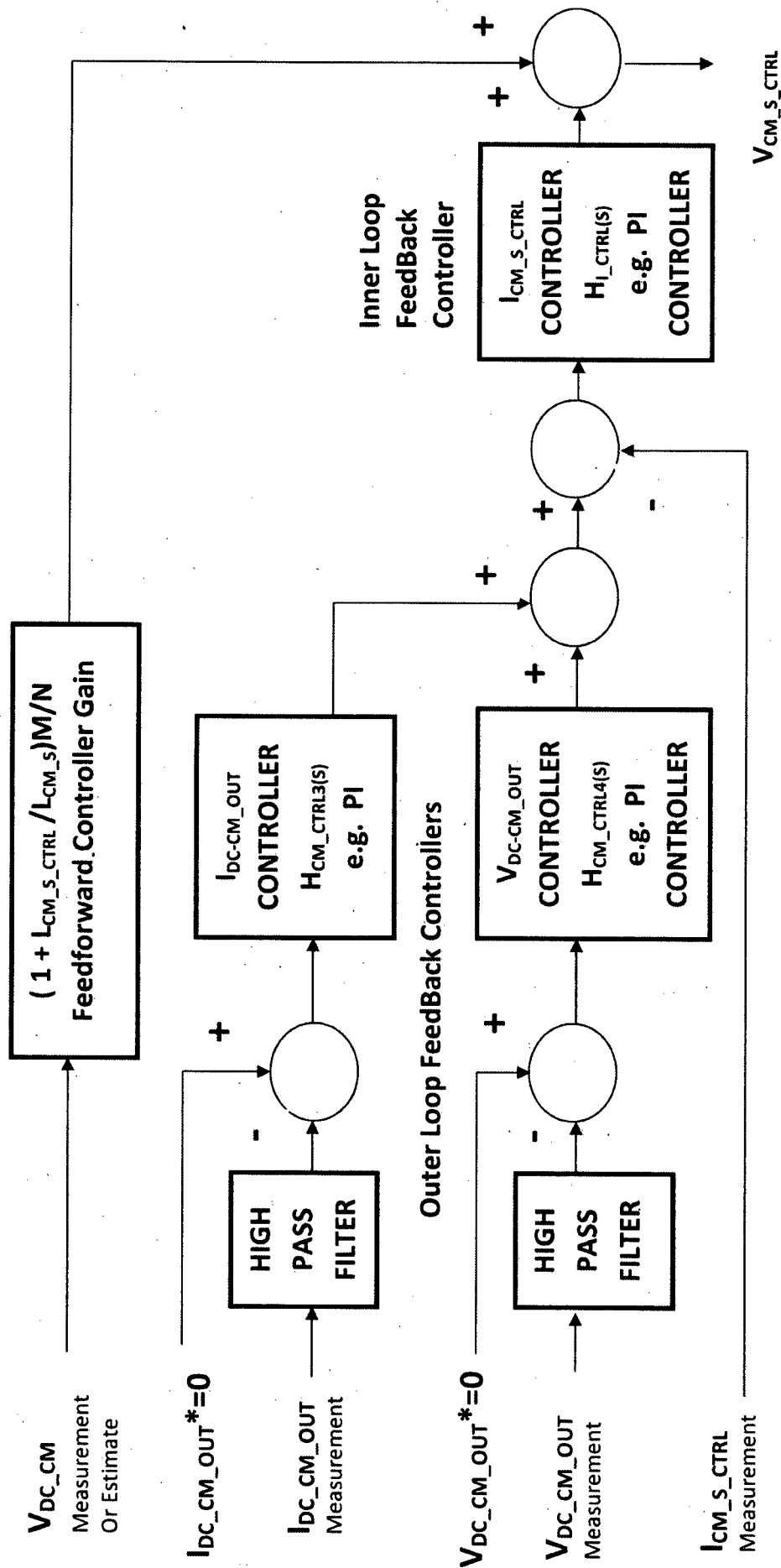


Figure 9 Active Control Power Source



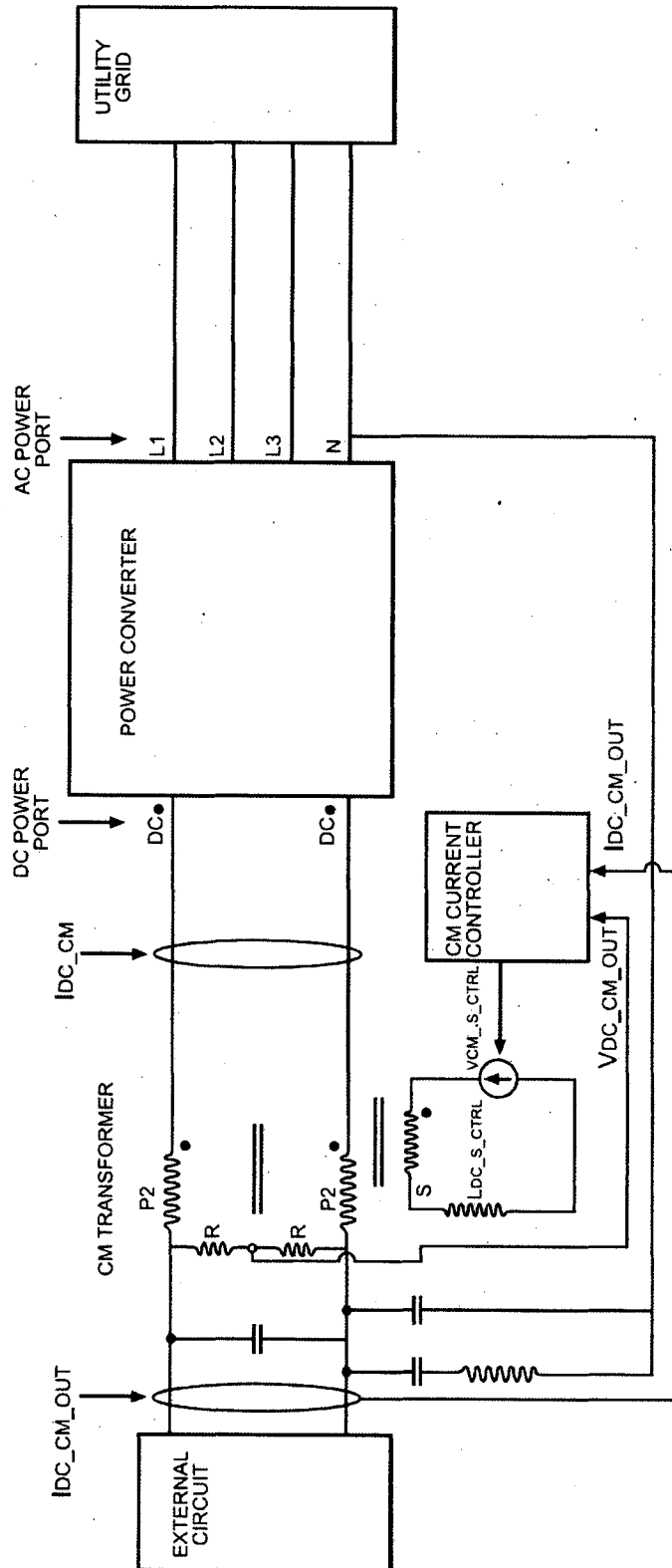
Combined Active CM Filter
for Control of AC component of CM Current and
series Capacitors for blocking DC component of CM Current

Figure 10



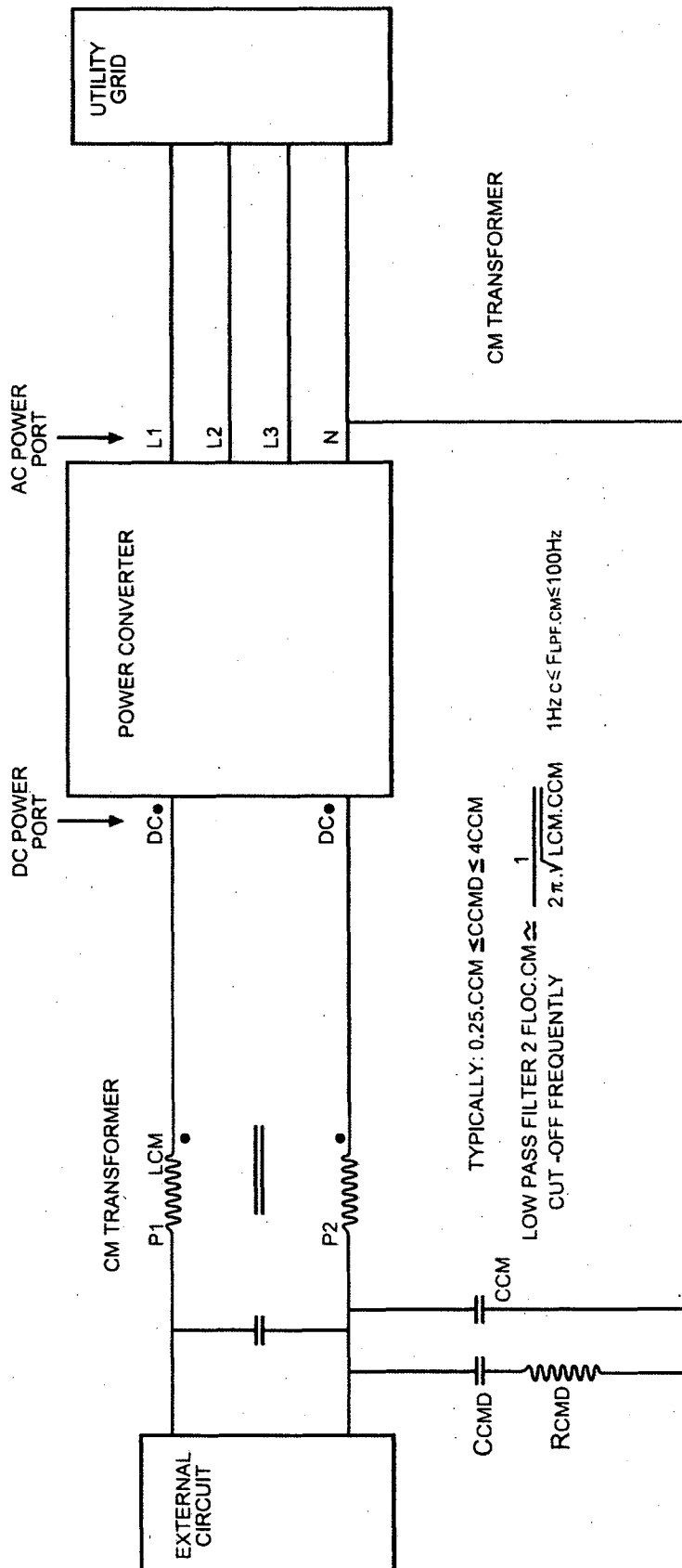
Controller for Output CM Current and Voltage with CM Voltage Feedforward
and Inner Loop for CM Control Current

Figure 11



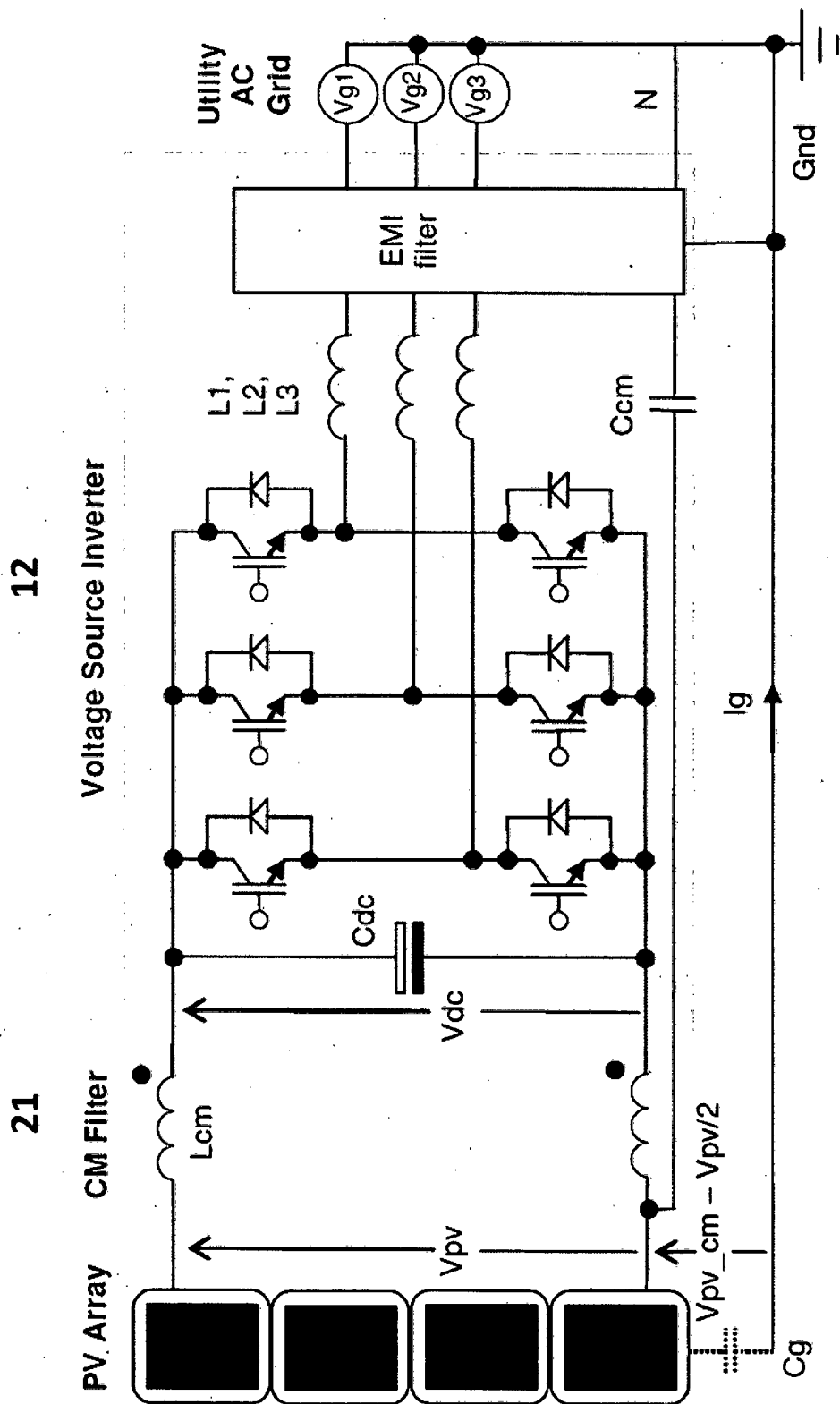
Controller using Measured Functions of CM Current

Figure 12



Example with Passive Low Pass Filter for Grid Frequency Harmonic and Switching Frequency Harmonic of CM Voltage

Figure 13

**FIGURE 14**

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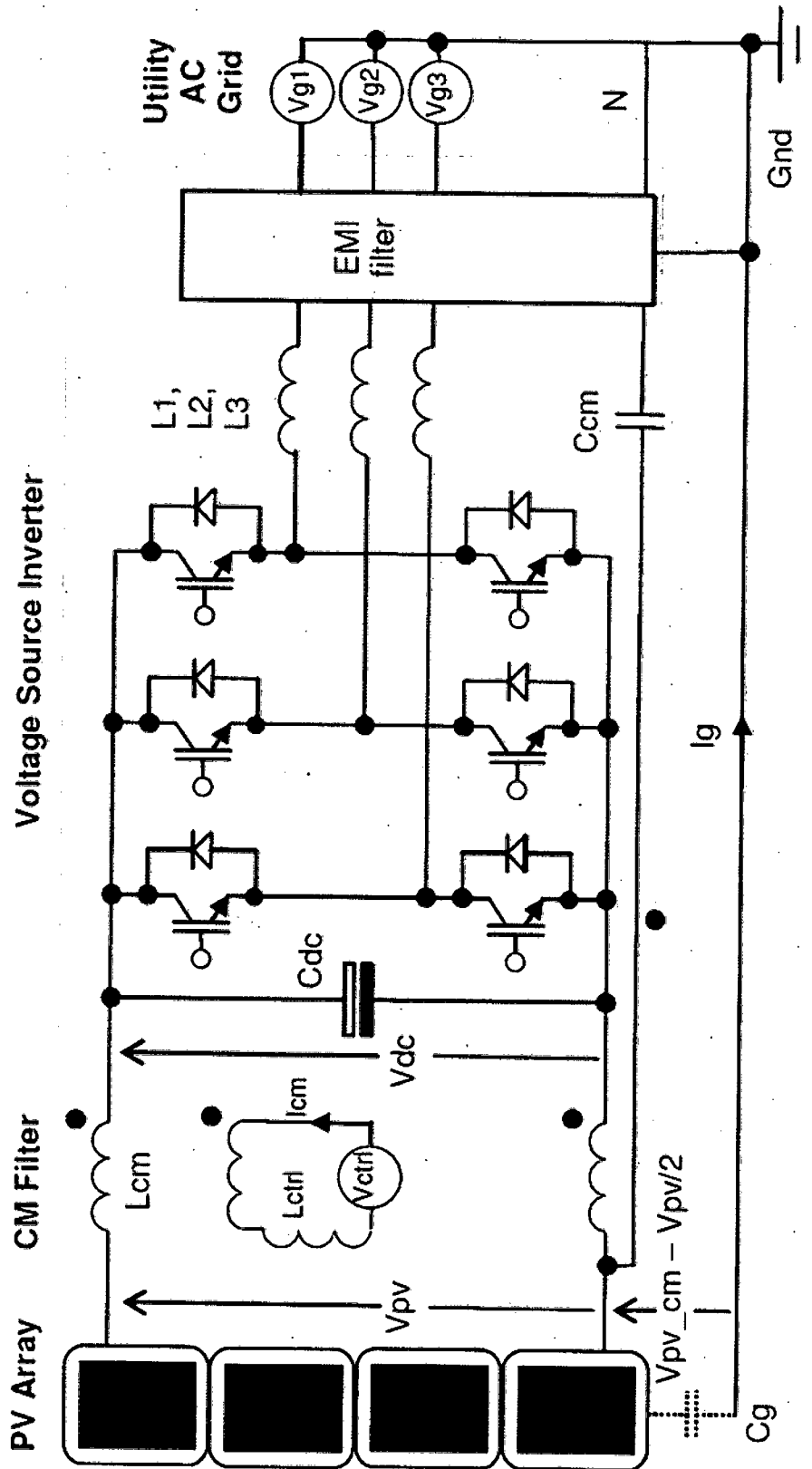


FIGURE 15

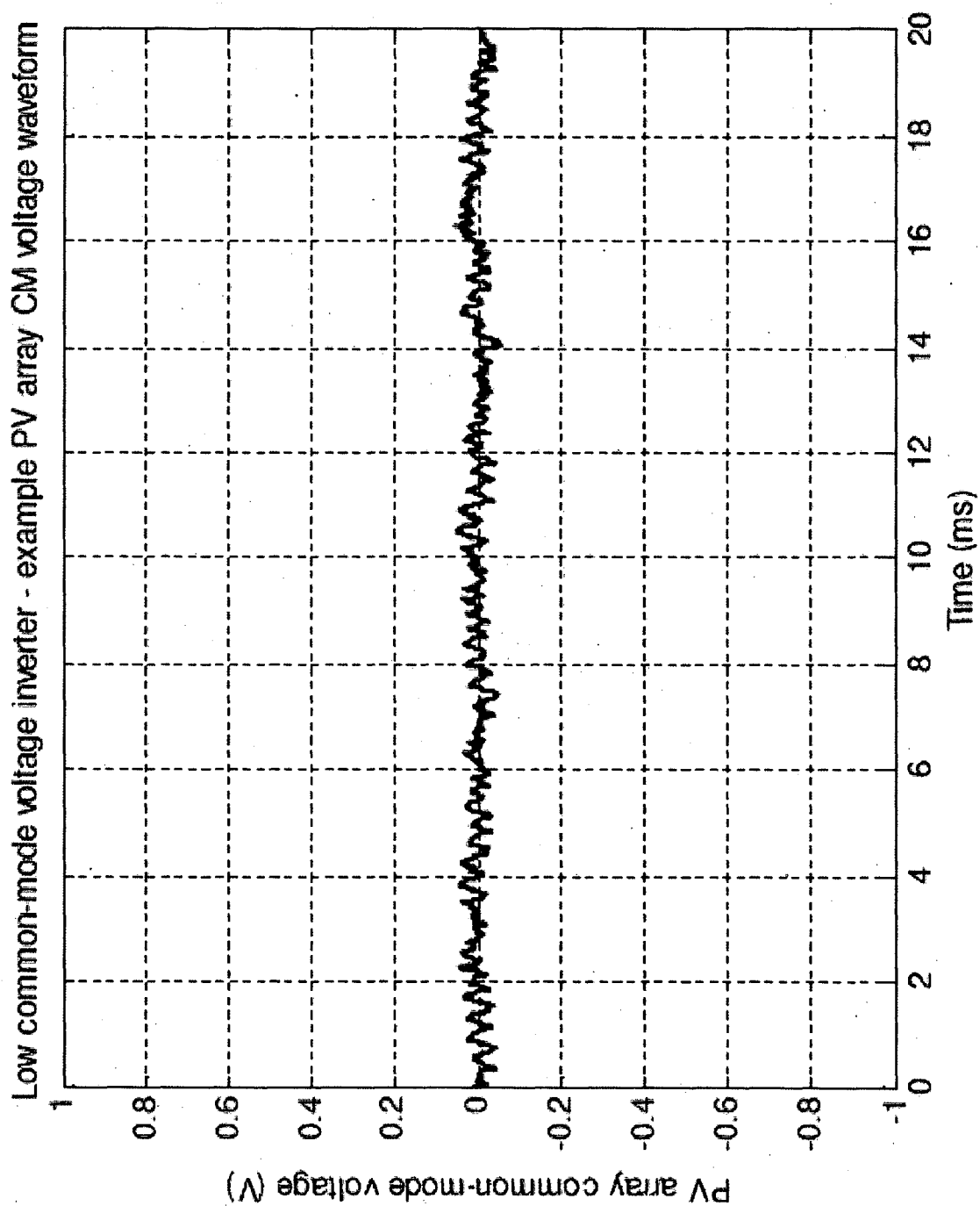


FIGURE 16

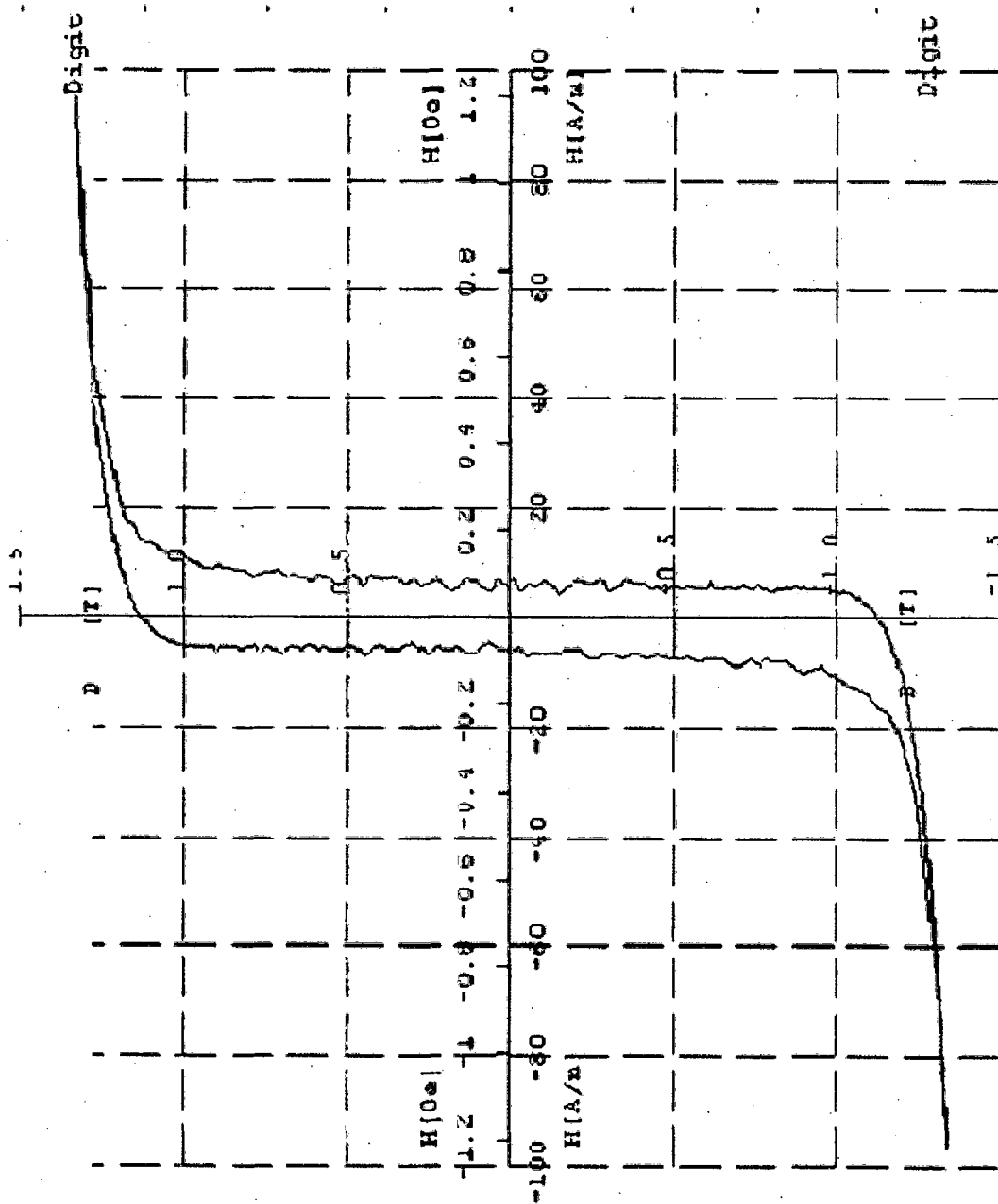


FIGURE 17

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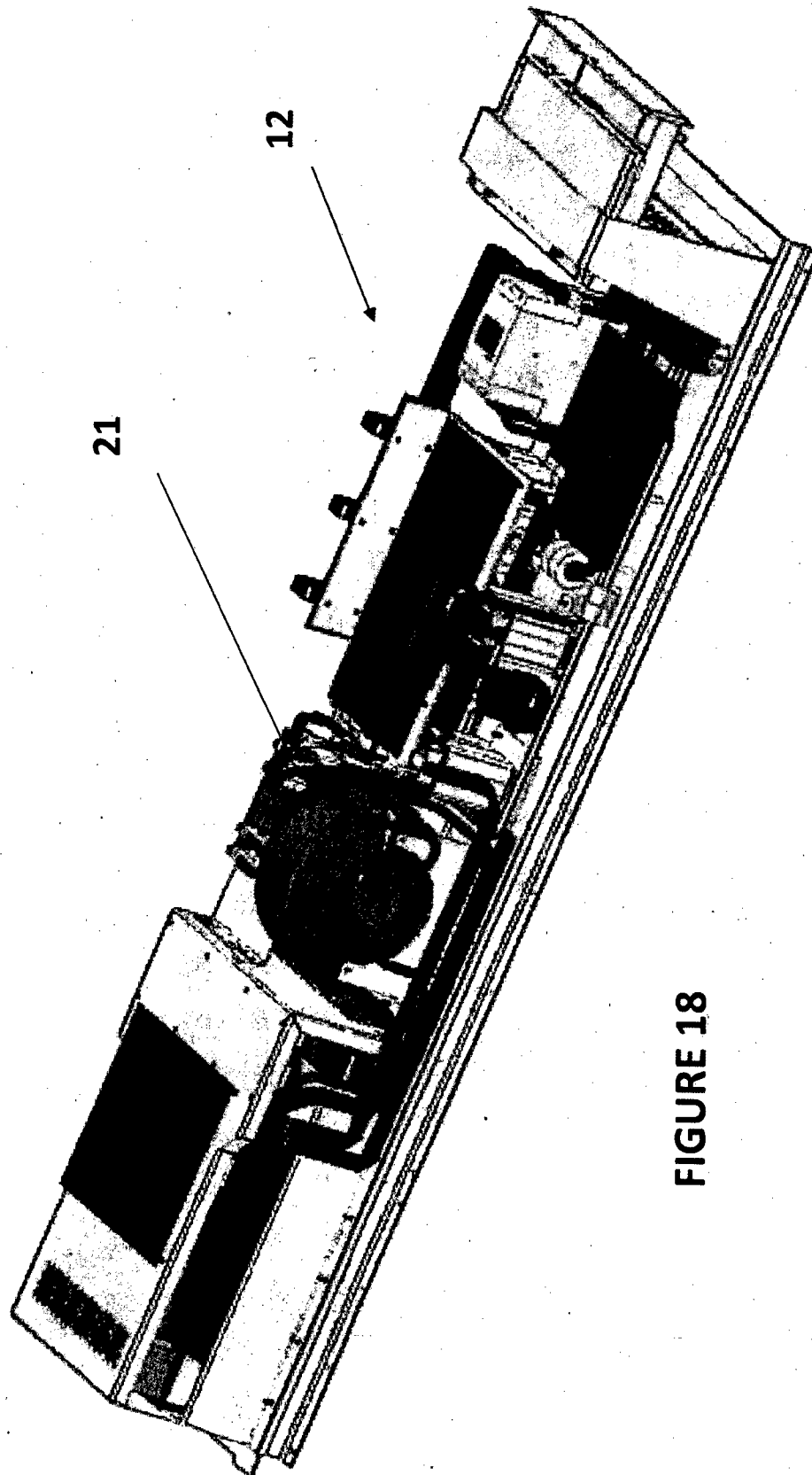


FIGURE 18

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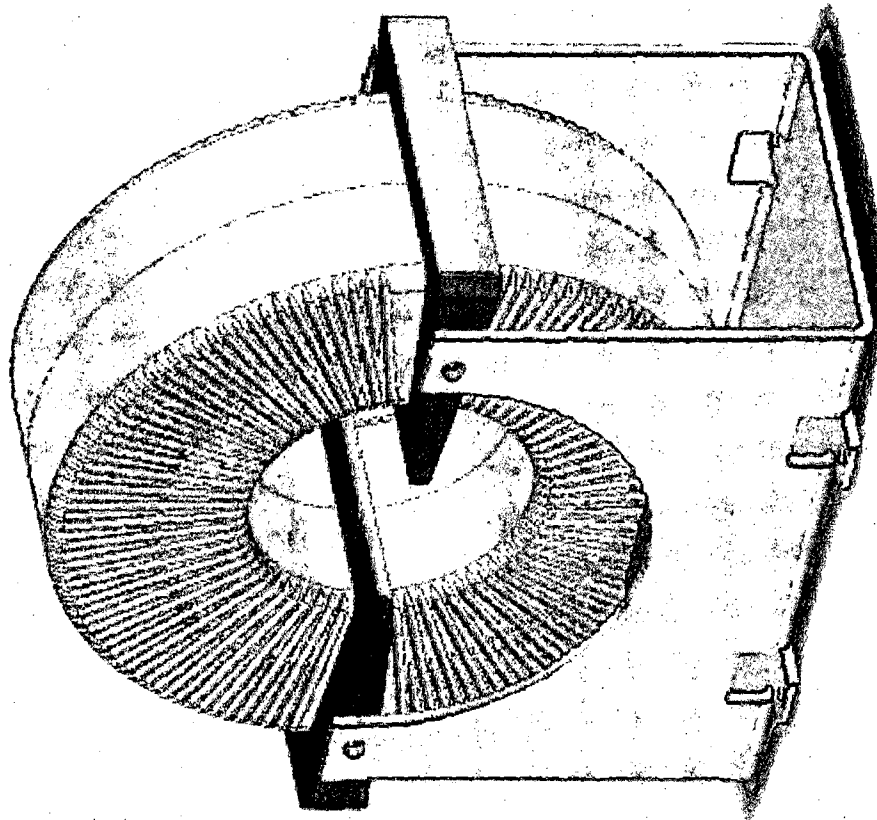


FIGURE 19

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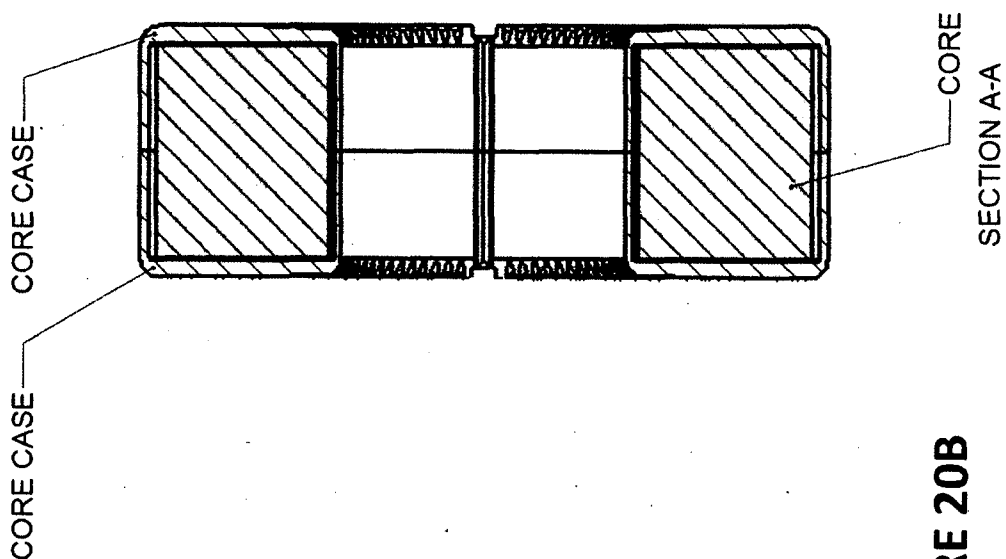


FIGURE 20B

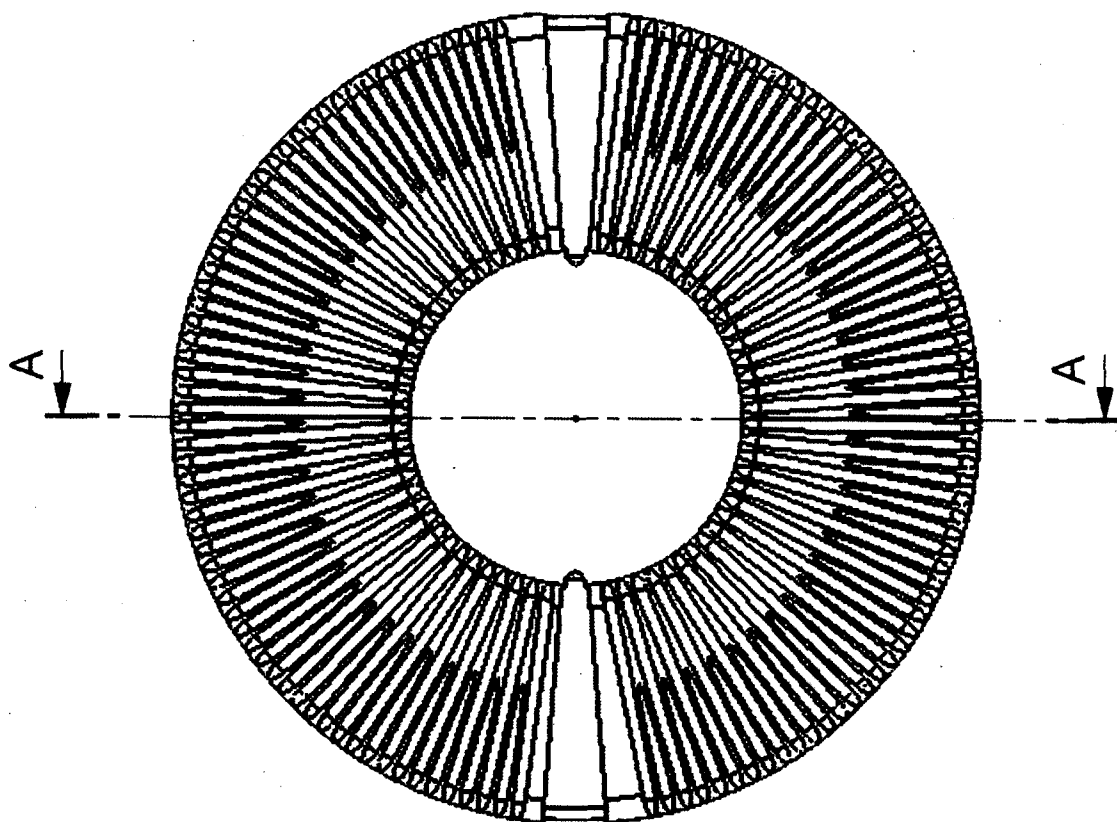


FIGURE 20A

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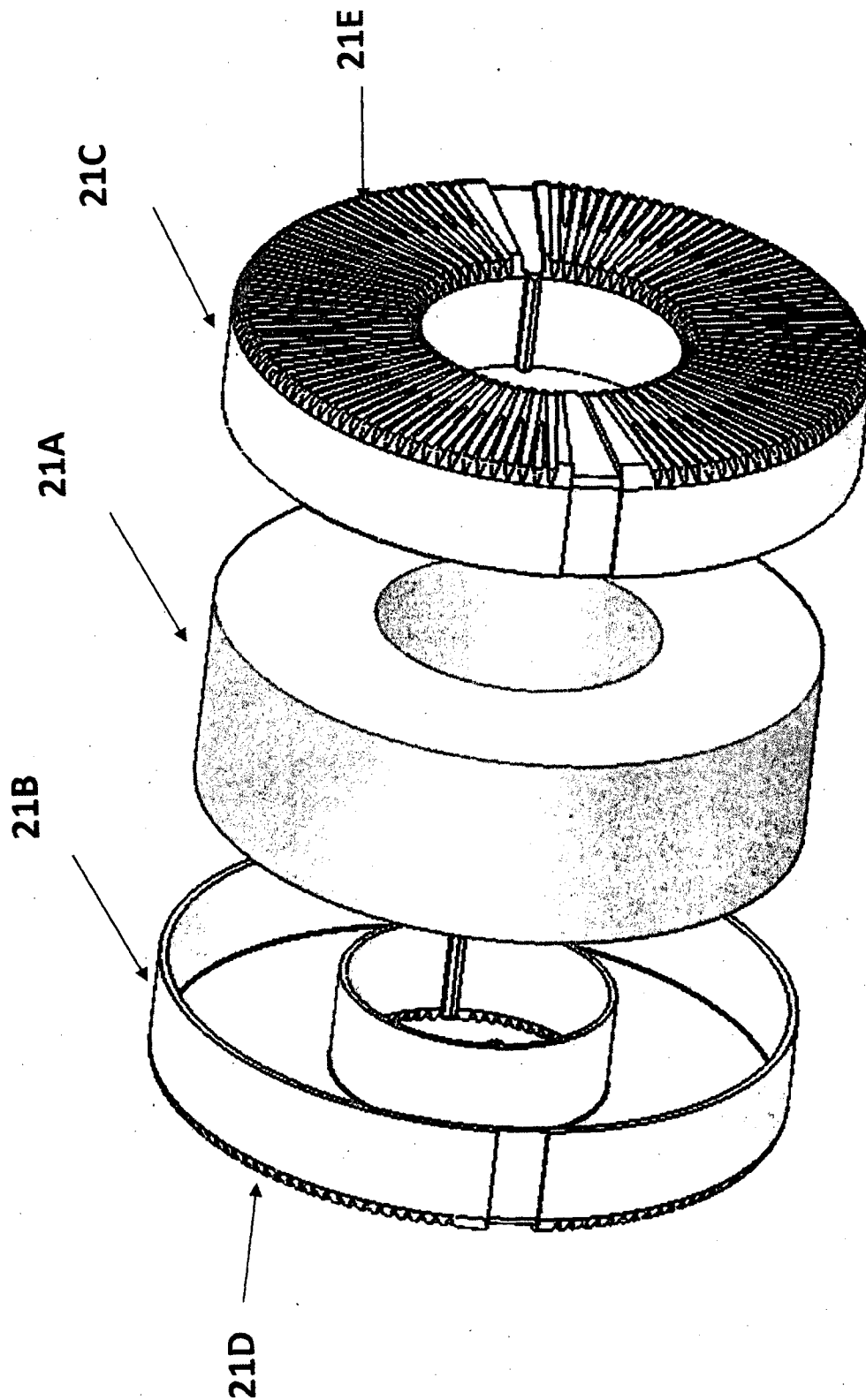


FIGURE 20C

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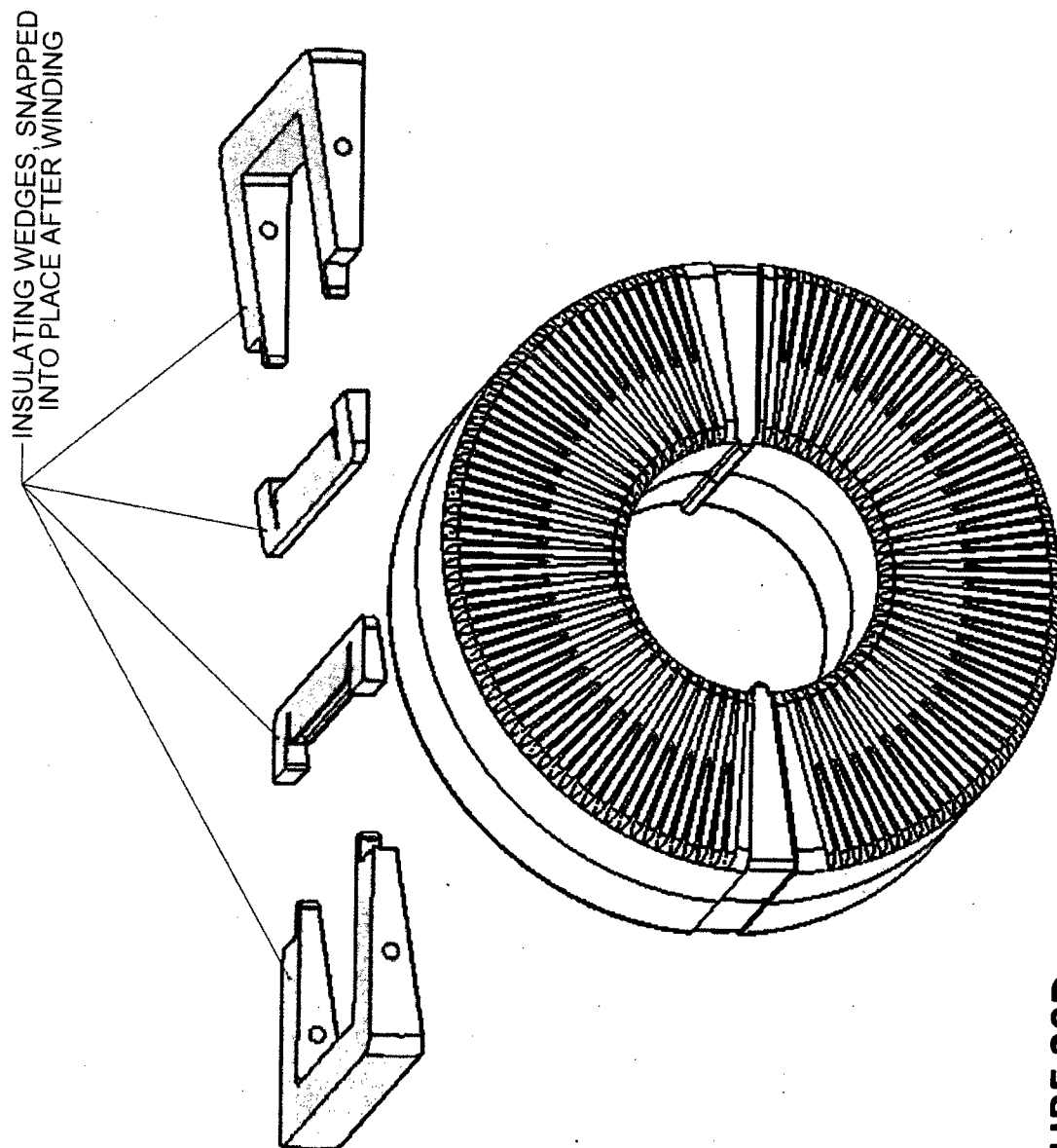


FIGURE 20D

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FIGURE 21A

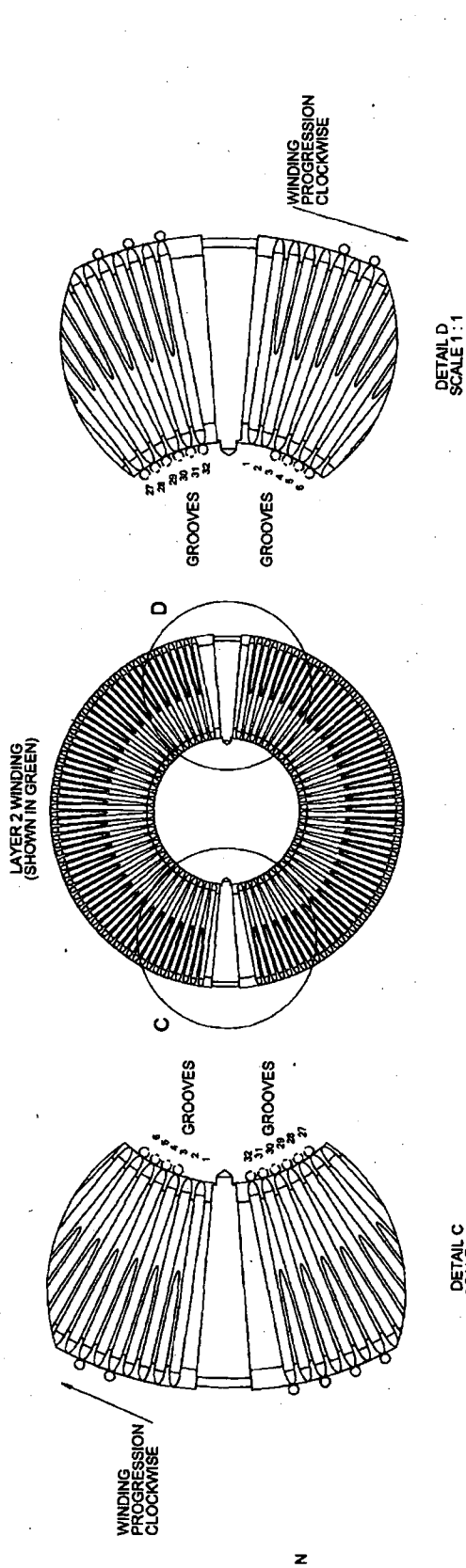


FIGURE 21B

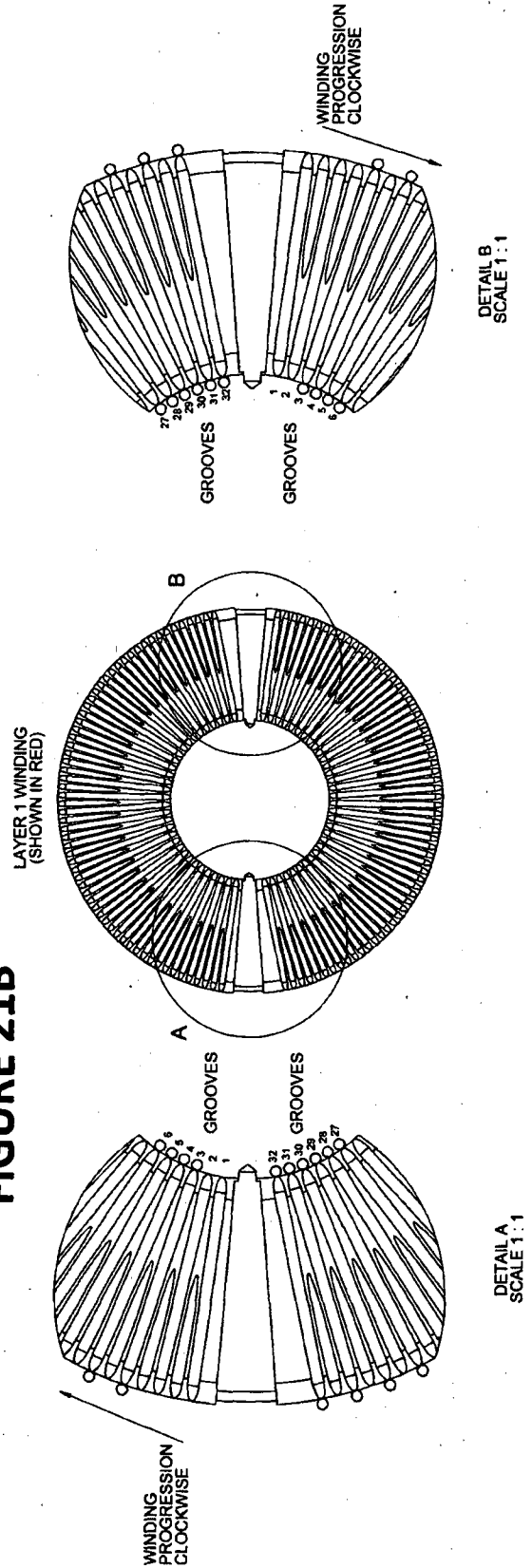


FIGURE 21C

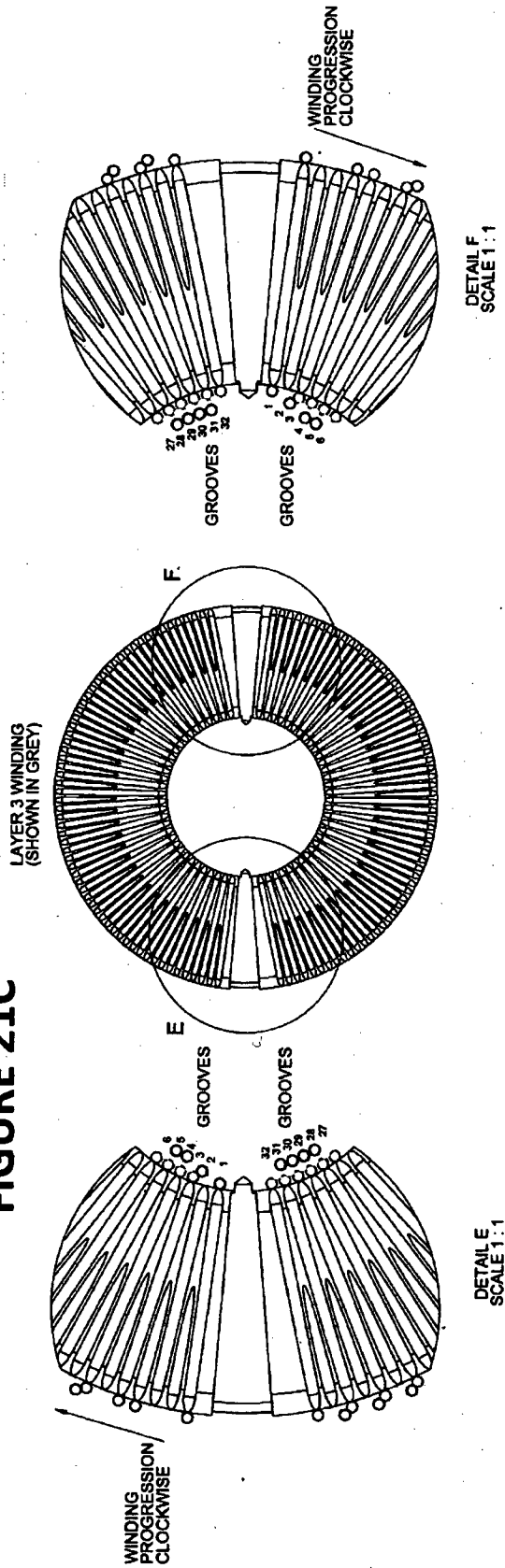
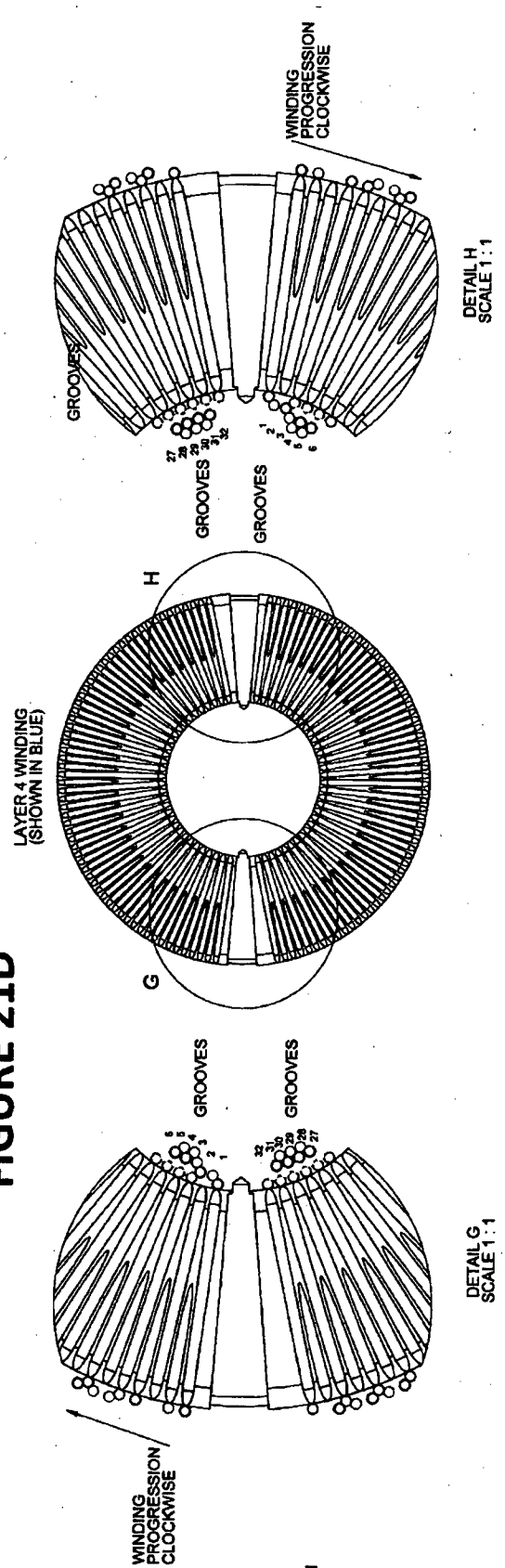


FIGURE 21D



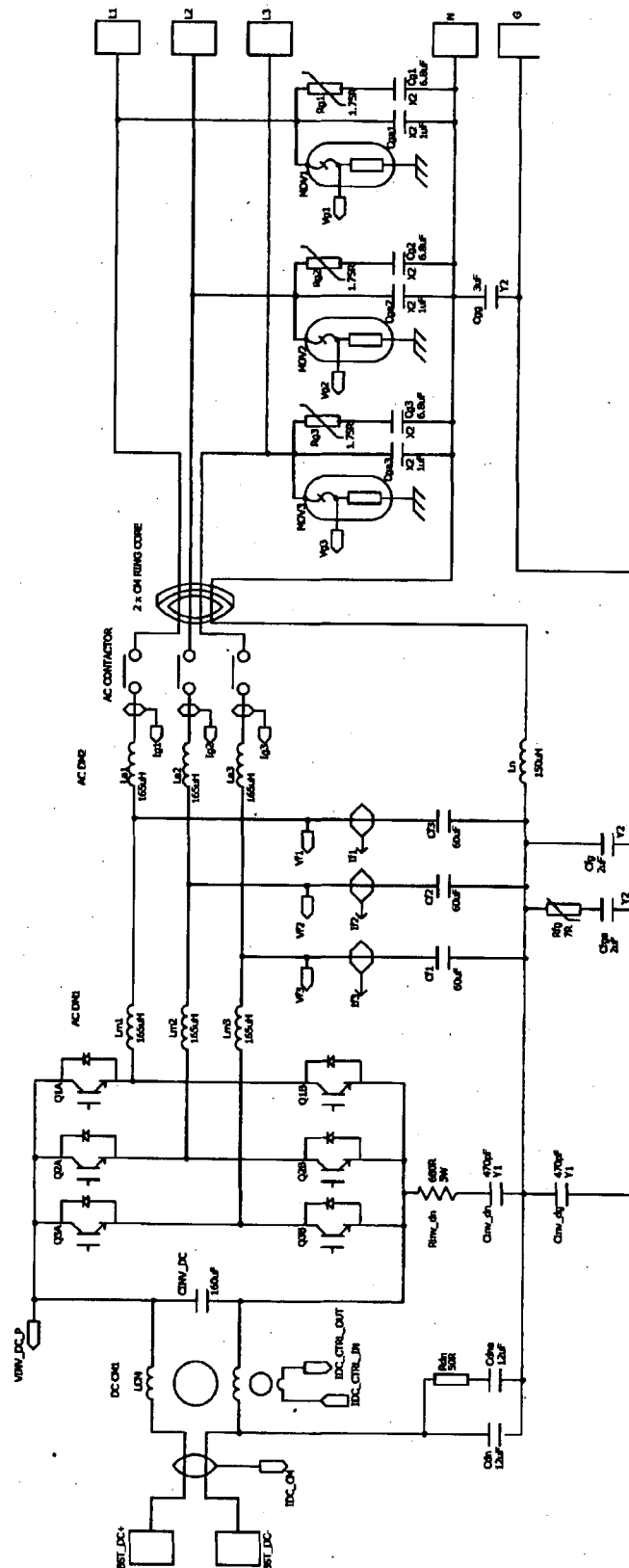
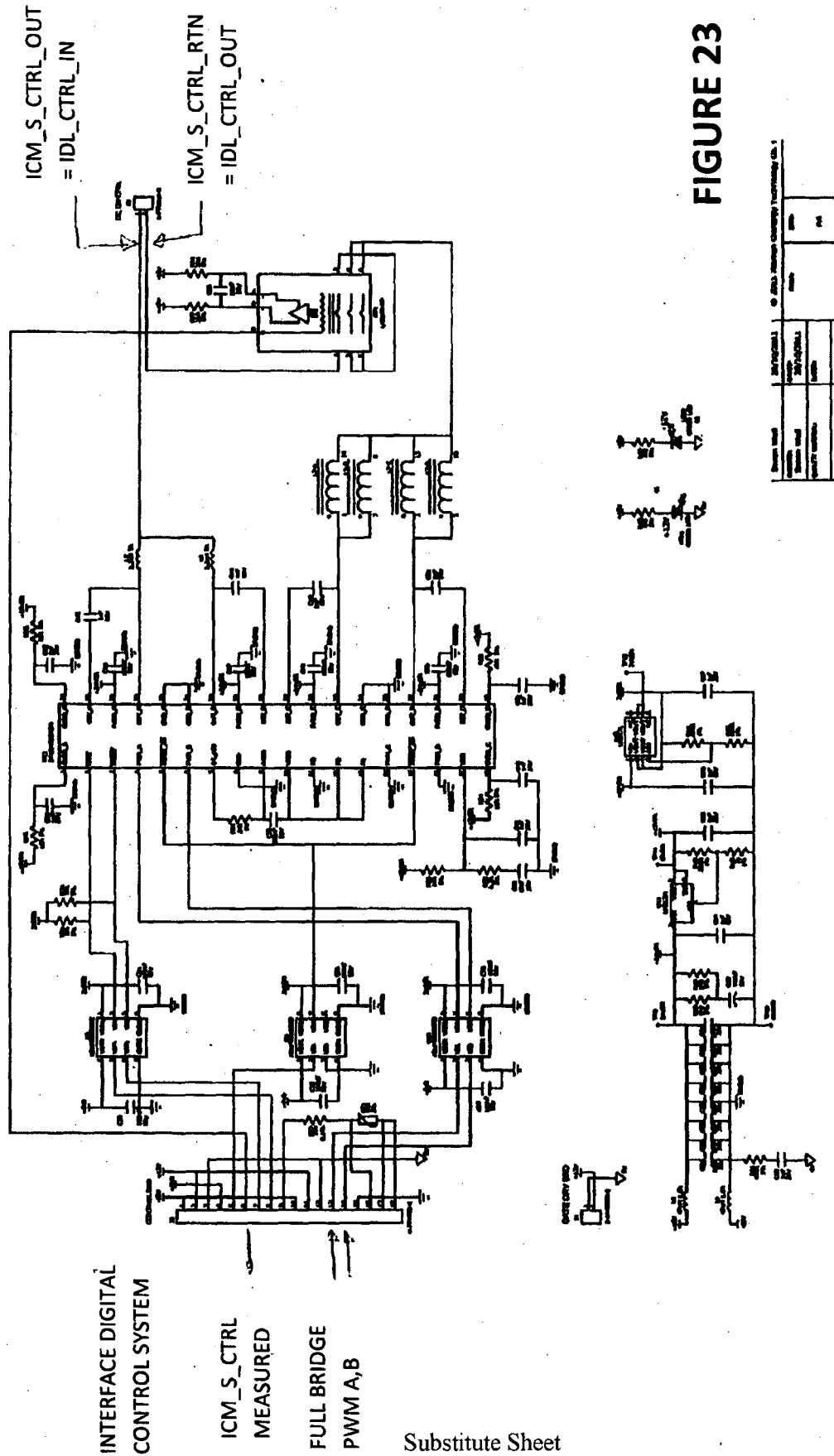


FIGURE 22

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2012/000141

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

H02M 1/12 (2006.01)*H02M 1/14* (2006.01)*H02J 3/01* (2006.01)*H03H 11/00* (2006.01)

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)

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)

EPODOC, WPI (abstracts); GOOGLE keywords: COMMON MODE, REJECT, FILTER, TRANSFORMER, INVERTER, HARMONIC, SERIES, SOLAR and other terms and phrases..

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	FUJITA, H: "A High-Efficiency Solar Power Conditioner Using a Zigzag-Connected Chopper Converter", The 2010 International Power Electronics Conference, IEEE, 21-24 June 2010, pages 1681 – 1687. Abstract, sections II-V, Figs. 1, 2, 4, 10-12.	1-6, 13-19, 30, 44-47, 53
X	US 5831842 A (OGASAWARA et al.) 3 November 1998 Abstract, column 1 line 59 – column 3 line 4, column 3 line 50 – column 5 line 17, column 6 lines 34-44, Figs. 1, 2, 5-8.	1-53



Further documents are listed in the continuation of Box C



See patent family annex

* Special categories of cited documents:

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

"T"

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

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

"X"

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

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

"Y"

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

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

"&"

document member of the same patent family

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

Date of the actual completion of the international search

03 April 2012

Date of mailing of the international search report

24 April 2012

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2012/000141**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☒ Claims Nos.: **54, 55**
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
The claims 54 and 55 do not comply with Rule 6.2(a) because they rely on references to the description and/or drawings.
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/AU2012/000141

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member	
US	5831842	JP	10094244
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			
END OF ANNEX			