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A dc-dc converter assembly

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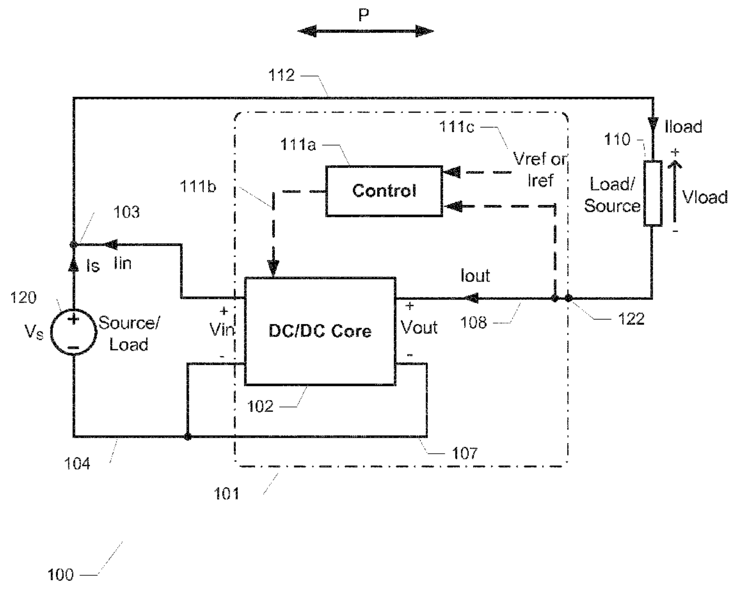

FIG. 1

(57) **Abstract:** The present invention relates to a DC-DC converter assembly which comprises a DC-DC converter. A converter load is electrically connected between a positive input and a positive output of the DC-DC converter such that a DC input voltage source of the assembly supplies load power directly to the converter load without passing through the DC-DC converter.

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A DC-DC CONVERTER ASSEMBLY

The present invention relates to a DC-DC converter assembly which comprises a DC-DC converter. A converter load is electrically connected between a positive input and a positive output of the DC-DC converter such that a DC input voltage source of the assembly supplies power directly to the converter load without passing through the DC-DC converter.

BACKGROUND OF THE INVENTION

Active and passive components of existing high power DC-DC converters are subjected to large voltage and current stresses and large heat dissipation caused by the flow of power through the converter and into the converter load. This reduces reliability and lifetime of high power DC-DC converters and requires costly active and passive components that can withstand the high currents and/or voltages. Hence, it is desirable to reduce the current stress and/or voltage stress of active and passive components of DC-DC converters of DC-DC converter assemblies for a given or nominal load power.

SUMMARY OF THE INVENTION

A first aspect of the invention relates to a DC-DC converter assembly which comprises a DC-DC converter. The DC-DC converter is configured to convert a DC input voltage into a DC output voltage and comprises:

- a positive input and a negative input for receipt of the DC input voltage from a DC input voltage source,
- a positive output and a negative output for supply of the DC output voltage to a converter load,
- a voltage regulation loop and/or a current regulation loop configured to adjust the DC output voltage or DC output current in accordance with a target DC voltage or a DC target current, respectively; and the converter load is electrically connected between the positive input and the positive output of the DC-DC converter such that the DC input voltage source supplies power directly to the converter load without passing through the DC-DC converter.

By connecting the converter load of the converter assembly between the positive input and the positive output of the DC-DC converter, the DC input voltage source may supply the majority of the power in the converter load, for example more than 50 %, or more than 66 %, or even the substantially entire load power, directly to the converter load. This feature serves to markedly reduce the amount of power that is converted or processed by, i.e. flowing through, the DC-DC converter for a given or power delivery to the converter load. The ratio between the power supplied directly to the converter load by the DC input voltage source and the power flowing through the DC-DC converter can be controlled or adjusted by selecting a value of the DC output voltage for a given DC input voltage. A step-down ratio or step-up of the DC-DC converter corresponds to the ratio between the DC output voltage and the DC input voltage depending on where the converter load and DC input voltage source is connected. The predetermined step-down ratio or step-up ratio of the DC-DC converter can also be expressed as a corresponding voltage gain as discussed below by numerical examples with reference to under the appended drawings.

For mains connected applications, the DC input voltage may lie between 320 V and 800 V - for example higher than 565 V. The DC output voltage may be smaller than one-fifth or one-tenth of the DC input voltage. The load power may be larger than 10 kW or larger than 50 kW.

Various types of DC-DC converters may be utilised in the present DC-DC converter assembly for example a high voltage gain DC-DC converter. The DC-DC converter may comprise a resonant converter topology or a non-resonant or hard-switched converter topology. The DC-DC converter may comprise one transformer or several separate transformers coupled in-between a primary side circuit and a secondary side circuit of the DC-DC converter to support a relatively high voltage gain of the DC-DC converter. However, the connection of the converter load between the positive input and the positive output of the DC-DC converter means that the converter assembly is without galvanic isolation because of the electrical connection between the primary side circuit and secondary side circuit of the DC-DC converter.

The DC-DC converter may comprise a resonant converter as mentioned above. The resonant converter may comprise a resonant network, e.g. an LC based circuit or resonator as discussed below, connected to an input driver or an output driver of the power converter. The input driver may therefore be configured to operate in so-called ZVS or ZCS mode to decrease power dissipation of one or more controllable semiconductor switches of the input driver. The input driver may comprise well-known driver topologies such as a half-bridge driver or an H-bridge driver. The input driver may comprise a plurality of appropriately arranged semiconductor switches such as IGBT switches or MOSFET switches to form well-known driver topologies.

The output voltage regulation loop ensures that the DC output voltage tracks the DC target voltage and the output current regulation loop likewise ensures the DC output current tracks the DC target current. The output voltage regulation loop ensures that the voltage drop across the converter load is relatively constant and well-defined as the difference between the DC input voltage and the DC output voltage. The output voltage or current regulation loop may include various known control mechanism such as pulse width modulation (PWM), phase shift modulation (PSM) or frequency modulation (FM) of a drive signal applied to an input driver or output driver of the DC-DC converter.

One embodiment of the DC-DC converter comprises an isolated or non-isolated Dual-Active-Bridge (DAB) converter since the latter topologies possess a number of beneficial properties in applications where a high voltage ratio between DC input voltage and DC output voltage is required. A high DC input voltage may for example be stepped down to a much smaller DC output voltage. Generally, a step-down ratio or step-up ratio may be at least 2, or more preferably at least 10, such as between 20 and 40. This corresponds to a voltage gain between the DC input voltage and DC output voltage from 0.5 down to 0.025. High input voltages are typically present in grid connected applications of the DC-DC converter assembly where the DC input voltage is derived from a grid connected DC input voltage source, for example through a single-phase or three-phase AC-DC converter, and this high input voltage must be stepped-down to a much lower output voltage level. The lower output voltage level may be one tenth or less of the input voltage. The DAB converter possesses numerous beneficial properties for high voltage and power applications due to its inherent zero voltage switching (ZVS) characteristics, simplified transformer design and high voltage gain as discussed below in additional detail with reference to the appended drawings. One embodiment of the Dual Active Bridge converter comprises:

- a first set of *n* transformers comprising respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores; said input windings being connected in series,
- a first resonant network connected in series with the series connected input windings or a first set of *n* resonant networks connected in series with respective ones of the output windings,
- a first set of *n* rectification circuits connected to respective ones of the output windings of the first set of *n* transformers to supply a first set of *n* rectified transformer voltages and currents to a first set of *n* rectification nodes,

a summing node configured to combine the first set of *n* rectified transformer voltages and currents to generate the DC output voltage;

- *n* being a positive integer number larger than or equal to 2 - for example between 2 and 6.

The individual transformers of the first set of *n* transformers are preferably nominally identical to facilitate equal voltage division between the input windings of individual transformers and facilitate equal current sharing between the output windings of the *n* transformers and other secondary side circuitry like the *n* rectification circuits. The first set of *n* transformers may comprise between 2 and 6 individual transformers.

Certain embodiments of the Dual Active Bridge converter comprises:

- a current balancing transformer comprising *n* transformer windings connected between respective ones of the first set of *n* rectification nodes and the summing node to force current balancing between individual windings of the first set of output winding. The *n* transformer windings of the current balancing transformer are preferably wound around a common magnetically permeable core to provide strong magnetic coupling between the *n* transformer windings. The *n* transformer windings of the current balancing transformer are preferably wound around a shared leg structure of the common magnetically permeable core to conduct equal amounts of magnetic flux through each transformer winding. Alternatively, the *n* transformer windings of the current balancing transformer may be implemented as *n* magnetically coupled inductors. The skilled person will appreciate that the current balancing transformer provides numerous benefits to DC-DC converters which comprises a plurality, such as two, three, four or more, parallelly coupled secondary side circuits. These benefits include elimination, or at least a significant reduction, of output current mismatches caused by practically occurring mismatches between electrical components and/or drive voltage waveform mismatches between the primary side circuits and secondary side circuits. The elimination of the output current mismatches allows parallel connection of numerous secondary side circuits and series connection of numerous input side circuits without inducing significant current imbalances between the individual secondary side circuits. Furthermore, each secondary side circuit and each primary side circuit can possess a much lower power rating compared to a single high-power secondary or primary side circuit. Hence, enabling utilization of relatively low cost active and passive components such as MOSFET and IGBT transistors. The thermal stress on the active and passive components of the DC-DC converter is also reduced and leads to significant increase the life time expectancy of the Dual Active Bridge DC-DC converters.

The DC output voltage, and hence also load power, of the Dual Active Bridge converter may be controlled in an efficient manner by adjusting a phase difference between the respective control signals or drive signals of the active rectification circuit and the input driver. In this embodiment, the output voltage or output current regulation loop may comprise: a DC target voltage or a DC target current,
- a first input driver for generating a first pulse width modulated drive signal at a first phase angle and applying the first pulse width modulated drive signal to the series connected input windings of the first set of *n* transformers;
- a first active rectification circuit configured to generate a second pulse width modulated drive signal at a second phase angle and apply the second pulse width modulated drive signal to respective control terminals of a plurality of controllable semiconductor switches of each rectification circuit of the first set of *n* rectification circuits; wherein the output voltage or output current regulation loop is configured to adaptively adjusting a phase difference between the first phase angle and the second phase angle to reach a desired DC output voltage, or a desired DC output current, of the dual active bridge DC-DC converter.

The skilled person will appreciate that some embodiments of the DC-DC converter may be unidirectional supporting only transfer of power/energy from the DC input voltage source to the converter load. Such unidirectional DC-DC converters may comprise one or more passive rectification circuit(s) on the secondary side. Alternative embodiments of the DC-DC converter may be bi-directional supporting the transfer of power/energy from the DC input voltage source to the converter load and vice versa. The reverse transfer of power from the converter load to the DC input voltage source may be enabled by active rectification circuits on the secondary side of the DC-DC converter and a control mechanism as discussed in additional detail below with reference to the appended drawings. Hence, according to certain embodiments of the DC-DC converter assembly, power may be transferred from the converter load directly to the DC input voltage source without passing through the DC-DC converter when operating in reverse mode. The skilled person will understand that the roles of the converter load and the DC input voltage source may be dynamically interchanged as needed during operation if the DC-DC converter supports bidirectional operation.

In grid-connected applications of the DC-DC converter assembly at least one of the converter load and the DC input voltage source may comprise an inverter, aka DC-AC converter, as discussed in additional detail below with reference to the appended drawings. The converter load may comprise a rechargeable battery pack and the DC input voltage source may comprise an inverter connectable to a single phase mains grid or a three phase mains grid. In this manner, the DC-DC converter assembly may charge the rechargeable battery pack through the mains voltage or alternatively, the DC-DC converter assembly may energize, drive or stabilize the mains grid using stored power/energy from the rechargeable battery pack.

Alternative embodiments of the DC-DC converter assembly, without grid connection, may operate without the inverter as part of the converter load or the DC input voltage source. The inverter may be eliminated where both the converter load and the DC input voltage source are native DC sources. For example, the DC input voltage may comprise photovoltaic cell(s) and/or rechargeable batteries and the converter load may comprise solid oxide fuel cells to produce hydrogen.

Certain DAB DC-DC converter embodiments may comprise a poly-phase DAB DC-DC converter as disclosed in the applicant's co-pending European application EP 16200247.1.

A second aspect of the invention relates to a method of supplying power to a converter load by a DC-DC converter, comprising:
- connecting a first terminal of the converter load to a positive input of the DC-DC converter,
- connecting a second terminal of the converter load to a positive output of the DC-DC converter,
- connecting a DC input voltage source to the positive input,
- adjusting a DC output voltage or a DC output current at the positive output of the DC-DC converter in accordance with a target DC voltage or target DC current, respectively.

The target DC voltage may be less than one-fifth, or even less than one-tenth, of the DC input voltage such that the DC input voltage source supplies a majority of the load power directly to the converter load compared to the power flowing through, i.e. processed by, the DC-DC converter. The DC input voltage source may for example supply more than 75 % of the load power, or more than 90 % of the load power such as substantially 100 % of the load power as discussed in the numerical examples below.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention will be described in more detail in connection with the appended drawings, in which:
FIG. 1 is a schematic diagram of an exemplary DC-DC converter assembly in accordance with a first embodiment of the invention,
FIG. 2 is a schematic diagram of a DC-DC converter assembly in accordance with a second embodiment of the invention,
FIG. 3 is a schematic diagram of a DC-DC converter assembly in accordance with a third embodiment of the invention,
FIG. 4 is a schematic diagram of a DC-DC converter assembly in accordance with a fourth embodiment of the invention,

FIG. 5 is a schematic diagram of a DC-DC converter assembly in accordance with a fifth embodiment of the invention,

FIG. 6 shows schematic diagram of a DC-DC converter assembly is a schematic diagram of an exemplary DC-DC converter assembly with a regenerative fuel cell load (RFC) in accordance with a sixth embodiment of the invention,

FIG. 7 is a plot of current-voltage characteristics of a RFC based converter load,

FIG. 8 is a plot of voltage-power characteristics of a RFC based converter load,

FIG. 9 is a plot of power requirements Pdcdc of the DC-DC converter, of the sixth embodiment of DC-DC converter assembly, relative to the operating power P_{ESS} of the RFC based converter load,

FIG. 10 is a plot of the converter load power Pload flowing into a battery pack load versus input power Pin processed by the DC-DC converter, of the sixth embodiment of DC-DC converter assembly, at different converter load powers,

FIG. 11 shows respective measured efficiency figures of the DC-DC converter assembly and the DC-DC converter at different levels of operating power Pload of a battery pack converter load,

FIG. 12 shows a plot of the power conversion efficiency of the DC-DC converter assembly according to the sixth embodiment versus converter load power,

FIG. 13 is a circuit diagram of various exemplary resonant networks for use in certain embodiments of the DC-DC converter,

FIG. 14 is a plot of experimentally measured voltage and current waveforms of the DC-DC converter assembly in accordance with the first embodiment of the invention; and

FIG. 15 shows a schematic diagram of a DC-DC converter assembly based on a single-phase dual active bridge (DAB) DC-DC converter in accordance with a sixth embodiment of the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

In the following, various exemplary embodiments of the present DC-DC converter assembly are described with reference to the appended drawings. The skilled person will understand that the accompanying drawings are schematic and simplified for clarity and therefore merely show details which are essential to the understanding of the invention, while other details have been left out. Like reference numerals refer to like elements or components throughout. Like elements or components will therefore not necessarily be described in detail with respect to each figure. It will further be appreciated that certain actions and/or steps may be described or depicted in a particular order of occurrence while those skilled in the art will understand that such specificity with respect to sequence is not actually required.

FIG. 1 shows a schematic diagram of an exemplary DC-DC converter assembly 100 in accordance with a first embodiment of the invention. The DC-DC converter assembly 100 comprises a DC-DC converter 101 which converts a first fraction of a load power of the converter load 110 (Load/Source), while a DC input voltage source or current source 120 (Source/Load) supplies a second fraction of the load power directly to the converter load 110 without passing through the DC-DC converter 101. The direct supply of load power to the converter load 110 is achieved because the converter load 110 is connected between a positive input 103 and positive output 108 of the DC-DC converter 101 - for example via an electrical wire or conductor 112. This load connection arrangement connects the converter load 110 in series with the DC-DC converter 101 instead of the traditional parallel output connection of the converter load. In some embodiments of the DC-DC converter assembly 100, the second fraction of the load power may be markedly larger than the first fraction - for example at least 3, 5 or 10 times larger depending on design details, voltage specifications of the converter load and DC input source and performance requirement of the DC-DC converter assembly 100. The reduced power delivery of the DC-DC converter 101 leads to a considerable reduction in size and costs of the DAB DC-DC converter 101 at any given load power in combination with increased reliability, since voltage stress and heat dissipation of active and passive components of the DC-DC core 102 are reduced. The overall energy/power efficiency of the DC-DC converter assembly 100 also increases because the DC-DC converter 102 converts less power which reduces power losses within the converter 102.

The DC input voltage source 120 is connected between a positive input 103 and negative input 104 of the DC-DC converter 101. The negative input 104 may for example be connected to a ground potential of the DC converter assembly 100 and a negative output 107 also connected to the ground potential.

The DC-DC converter 101 additionally comprises a voltage or current regulation loop 111a, 111b, 111c configured to adjust the DC output voltage at the output terminal 122 in accordance with a target DC voltage or equivalent adjusting a DC output current flowing through the output terminal 122 in accordance with a target DC current. The voltage or current regulation loop 111a, 111b, 111c may comprise a feedback mechanism. The regulation mechanism of the voltage or current regulation loop may comprise a modulation strategy such a PWM, PSM or FM of a drive signal applied to an input driver and/or an output driver of the DC-DC converter 101 as discussed in additional detail below. The skilled person will appreciate that some embodiments of the DC-DC converter 101 may be unidirectional where power only can be transferred from the source 120 to the load 110. Such unidirectional DC-DC converters may comprise a passive rectification circuit on the secondary side. Alternative embodiments of the DC-DC converter 101 may be bi-directional enabling power transfer from the source 120 to the load 110 and vice versa depending on a suitable control mechanism applied to an active rectification circuit on the secondary side. In the latter embodiments, the skilled person will understand that the role of the DC input voltage source 120 and the converter load 110 may be interchanged when the DC-DC converter 101 operates in reverse mode and hence the DC input voltage source 120 is also indicated as Load while the converter load 110 is also indicated as Source.

The DC output voltage, as set by the voltage or current regulation loop, may be significant smaller than the DC input voltage supplied by the DC input source 120 at the positive and negative inputs of the DC-DC converter 101. This feature ensures that the majority of the load power is supplied by the DC input source 120 as illustrated by the quantitative example below.

A first exemplary embodiment of the DC-DC converter assembly 100 may be designed using the following constraints and target performance:

DC input voltage = Vs= 565 V – corresponding to a three-phase rectified mains voltage.

Iload = 100 A.

Pload = 54 kW.

Vload = Pload/Iload = 540 V.
Vout = Vs-Vload = 565 V - 540 V = 25 V.
Iout = Iload, due to the series connection of the load and the output of the DC-DC converter.

Using the above design and performance targets for the DC-DC converter assembly 100 and for simplicity assuming 100 % efficiency of the DC-DC converter eff=100/100 reveals that:
Converter power at Vout terminals = P1= 25 V * 100 A = 2.5 kW.
Converter power at Vin terminals = P2 = P1*eff = 2.5 kW *1 = 2.5 kW
Iin = P2 / Vs = 4.4248 A
Is = Iload – Iin = 95.5752 A
Ps = Vs * Is = 54 kW

Consequently, in the above scenario the DC input voltage source supplies 100 % of the 54 kW of load power directly to the converter load 110, i.e. without passing through the DC-DC converter. Furthermore, the DC-DC converter 101 converts 2.5 kW of circulating power flowing through the DC-DC converter 101.
Assuming an efficiency of the DC-DC converter 95% eff=95/100 reveals using the same target specifications as above reveals that:
Converter power at Vout terminals = P1= 25 V * 100 A = 2.5 kW.
Converter power at Vin terminals = P2 = P1*eff = 2.5 kW * 0.95 = 2.375 kW
The DC-DC converter losses = P1 – P2 = 2.5 kW – 2.375 kW = 125 W
Iin = P2 / Vs = 4.2035 A
Is = Iload – Iin = 95.7965 A
Ps = Vs * Is = 54.125 kW

Accordingly, the efficiency of the DC-DC converter assembly Passembly:
Passembly =100*(Pload / Ps) =100*(54 kW / 54.125 kW) = 99.77%

Consequently, the DC input voltage source supplies 54.125 kW of power of which 54 kW is the power supplied directly to the converter load 110 and an additional fraction of power related to the DC-DC converter 101 losses of 125 W. This leads to a total efficiency of the DC-DC converter assembly of 99.77%.

The skilled person will understand that the voltage regulation loop 111a, 111b, 111c may be adapted to set a higher DC output voltage of the converter 101 than the above-specified 25 V or an even smaller DC output voltage of the converter 101. Hence, a smaller fraction or an even larger fraction of the load power may be converted by, or supplied through, the DC-DC converter 101. The lower the DC output voltage will lead to a lower circulating power converted by the DC-DC converter. However, the lower DC output voltage will generally lead to a larger voltage gain of the DC-DC converter 101 which may present practical problems for passive components, like transformers, of the DC-DC converter 101.

However, a large voltage gain can be accommodated in an advantageous manner by utilizing a DC-DC converter topology which comprises a plurality of transformers with their primary side windings connected in series to the DC input voltage. The series connected primary side windings lead to a smaller voltage drop across each primary winding and a reduced requirement to the voltage gain between the primary winding and secondary winding of each transformer. The DC-DC converter may for example comprise a Dual-Active-Bridge (DAB) converter since the latter converter topology possesses a number of beneficial properties when exploited in the present DC-DC converter 101 where a high input voltage often arises from a grid connected input source. This high voltage must be transformed down to a much lower output voltage level e.g. one tenth or less of the input voltage. The (DAB) converter possesses numerous beneficial properties for high power applications due to its inherent zero voltage switching (ZVS) characteristics, simplified transformer design and high voltage gain [1], [2], [3]. The DAB converter is preferably configured with parallelly connected secondary side circuits (i.e. low voltage side) while the primary side circuits (i.e. high voltage side) are series connected to achieve a high voltage gain or step-down ratio as discussed below in additional detail with reference to FIG. 15.

FIG. 2 shows a schematic diagram of a DC-DC converter assembly 200 in accordance with a second embodiment of the invention. The DC-DC converter assembly 100 comprises a DC-DC converter 201 which may be identical to any of the previously discussed exemplary DC-DC converters. The present DC-DC converter 201 may be unidirectional and transfer power from a DC input voltage source which comprises a two-phase or three-phase grid-connected inverter 222, 220. The load 210 may comprise an energy storage unit such as a rechargeable battery stack or package comprising a plurality of series connected rechargeable battery cells or a fuel cell etc.

FIG. 3 shows a schematic diagram of a DC-DC converter assembly 300 in accordance with a third embodiment of the invention. The DC-DC converter assembly 300 comprises a DC-DC converter 301 which may be identical to any of the previously discussed exemplary DC-DC converters. The present DC-DC converter 301 may be unidirectional and transfer power from a DC input voltage source 320 which comprises an energy storage unit such as a rechargeable battery stack or package comprising a plurality of series connected rechargeable battery cells or a fuel cell etc. The load 310 may comprise a grid-connected inverter 310. In this manner, the grid acts as a converter load and the energy storage unit may deliver power/energy to the grid for example for grid stabilization purposes or deliver power/energy to AC loads such as dishwashers or washing machines.

FIG. 4 shows a schematic diagram of a DC-DC converter assembly 400 in accordance with a fourth embodiment of the invention. The DC-DC converter assembly 400 comprises a DC-DC converter 401 which may be identical to any of the previously discussed exemplary DC-DC converters. The present DC-DC converter 401 may be bi-directional and in a reverse mode of operation transfer power from a load connected DC source 410 to a two-phase or three-phase grid-connected inverter 420. The load connected DC source 410 may comprise an energy storage unit such as a rechargeable battery stack or package comprising a plurality of series connected rechargeable battery cells or a fuel cell etc.

FIG. 5 shows a schematic diagram of a DC-DC converter assembly 500 in accordance with a fifth embodiment of the invention. The DC-DC converter assembly 500 comprises a DC-DC converter 501 which may be identical to any of the previously discussed exemplary DC-DC converters. The present DC-DC converter 501 may be adapted for bidirectional operation and, in a reverse mode of operation, transfer power from a grid-connected inverter 510, which is connected to the load terminals of the converter, to a DC source 520. The load connected DC source 520 may comprise an energy storage unit such as a rechargeable battery stack or package 525 comprising a plurality of series connected rechargeable battery cells or a fuel cell etc. Hence, the roles of the load and source have been interchanged compared with the DC-DC converter assembly 400 discussed above.

FIG. 6 shows schematic diagram of a DC-DC converter assembly 600 with a regenerative fuel cell load 610 in accordance with a sixth embodiment of the invention. This embodiment brings significant advantages to power applications that need to operate with wide input voltage range and/or output voltage range such as the illustrated regenerative fuel cell (RFC). An exemplary embodiment of the DC-DC converter assembly 600 may be configured to operate with the following specifications: DC input voltage, V_s = 600 V. The DC converter assembly 600 is configured for bidirectional operation. The converter load is a RFC with current-voltage characteristics as given on FIG.7 and the voltage-power characteristics given in FIG. 8, where V_{ESS} refers to the load voltage, the operating voltage, of the RFC. I_{ESS} is the operating current of the RFC, and therefore corresponds to the previously discussed load current Iload, albeit with opposite sign. V_{ESS} is the voltage across the converter load 610 and therefore corresponding to the previously discussed load voltage Vload. P_{ESS} refers to the operating power of the RFC and therefore corresponds to the previously discussed load power Pload.

The output voltage Vou of the DC-DC converter 601 at its output terminals 622, 607 can be calculated as Vout = Vs-V_{ESS} in a charging mode and a discharging mode by:

<u>In charging mode</u> where power is flowing from the DC input voltage source 620 or Vs to RFC:

- The input power of the DC-DC converter at Vout terminals, because the current flows from the DC input voltage source 620 to the RFC, is calculated by
  Pin=Vout*I_{ESS}
- Assuming an efficiency of the DC-DC converter 601 of eff=0.95, the output power of the DC-DC converter at the Vin terminals, can be calculated by: Pout=Pin*eff

- And the DC-DC converter losses are calculated
  Ploss=Pout - Pin
- The current delivered by from the DC input voltage source 620 can then be calculated by: Is=(Pout/Vs) - I_{ESS}
- Then, the power supplied by DC input voltage source 620 is calculated by Ps=Is*Vs
- Finally, the DC-DC converter assembly efficiency in charging mode is calculated with: Eff_assembly=100*(Ps-Ploss)/Ps.

<u>In discharging mode</u> where power is flowing to the DC input voltage source 620 from the RFC 610:

- The output power of the DC-DC converter 601 at the Vout terminals, because current flows from the RFC to the DC input voltage source 620 is calculated by:
  Pout= Vout*I_{ESS}
- Assuming an efficiency of the DC-DC converter of eff=0.95, the input power of the DC-DC converter at the Vin terminals, can be calculated by: Pin=Pout/eff
- And the DC-DC converter losses are calculated
  Ploss=Pout-Pin
- Finally, the DC-DC converter assembly efficiency in discharging mode is calculated with: Eff_assembly=100*(P_{ESS} -Ploss)/ P_{ESS}.

According to the above-outlined analysis the power requirements Pdcdc of the DC-DC converter 601 are plotted in FIG. 9 in terms of the operating power P_{ESS} of the RFC 610. Finally, FIG. 12 shows a plot of the power conversion efficiency of the DC-DC converter assembly 600 versus converter load power P_{ESS}.

<u>Experimental validation:</u>

The inventors have in the laboratory experimentally validated the performance of the previously discussed exemplary DC-DC converter assembly 100 where FIG. 14 shows experimentally measured voltage and current waveforms. The converter load 110 comprises a rechargeable battery stack or package as discussed before. In FIG.14 Vin and Vout refer to the voltage across the input terminals and output terminals, respectively, of the DC-DC converter 102 where Is indicates the current supplied by the DC input voltage source 120 and Iload is the current flowing through the converter load 110.

Therefore, the voltage across the load Vload and the power Pload stored by the rechargeable battery pack 110 can be calculated as:
Vload=Vin-Vout=317.02 V - 50.35 V = 266.67 V
Pload=Vload*Iload=266.67 V * 1.819 A = 485.07 W.

The input power of the DC-DC converter 102 at the input terminals Vout can be calculated by: Pin=Vout*Iload = 50.35 V * 1.819 A = 91.58 W.

And the output power of the DC-DC converter 102 at the input terminals Vin can be calculated by:
Pout = Vin * Iin = Vin * (Iload-Is) = 317.02 V * (1.819 A – 1.582 A) = 75.13 W

Therefore the DC-DC converter losses can be calculated by:
Plosses= Pin-Pout = 91.58 W – 75.13 W = 16.45 W

This results in a conversion efficiency of eff= 100*Pout/Pin=82% of the DC-DC converter power 102.

The power supplied by the DC input voltage source 120 can be calculated by:
Ps= Vs* Is = Vin * Is = 317.02 V * 1.582 A = 501.52 W.

The power conversion efficiency, Eff_assembly, of the DC-DC converter assembly 100 can be calculated by:
Eff_assembly = 100* (Ps-Plosses)/Ps= 100* (501.52 W – 16.45 W) / 501.52 W = 96.72 %.

From the experimental results above it is evident that the following observations can be made:

1) A DC-DC converter operating at, or processing, an input power Pin=91.58W drives a converter load consuming Pload=485.07W

2) The present embodiment of the DC-DC converter assembly 100 may utilize a DC-DC converter 102 with an power conversion efficiency of eff = 82% while the overall efficiency of the DC-DC converter assembly 100 is boosted or increased to a remarkable value of up to Eff_assembly = 96.72%.

FIG. 10 shows the experimentally measured power Pload flowing into, i.e. stored by, the battery pack load 110 versus the input power Pin processed by the DC-DC converter 102 at different operating power of Pload. The different values of load power Pload are obtained by changing the load current Iload.

FIG. 11 shows respective measured efficiency figures of the DC-DC converter 101and the DC-DC converter assembly 600 obtained under the same test conditions at different operating power Pload of the battery pack load 110.

The above-outlined results verifies that a DC-DC converter assembly in accordance with the present invention can utilize a DC-DC converter or converter core with a significantly lower power rating than a target load power of the DC-DC converter assembly 100. As illustrated above, the power rating of the DC-DC converter may in exemplary embodiments may be less than 30 %, or less than 25 %, or even less than 20 %, of the target load power of the DC-DC converter assembly. Another significant advantage of the invention is that the achieved power rating reduction of the DC-DC converter leads to a marked increase of the overall power conversion efficiency of the DC-DC converter assembly.

FIG. 15 shows a schematic electrical diagram of an exemplary embodiment of the previously discussed DAB embodiment of the DC-DC converters 101, 201, 301, 601. The depicted DAB converter 602 may be viewed as a single-phase embodiment of a range of DAB converter topologies that additional comprises poly-phase embodiments as those discussed in the applicant’s co-pending European application EP 16200247.1. The DAB converter 1502 comprises a positive input 603 for receipt of a DC input voltage produced by a DC input voltage or current source 620. The skilled person will understand that a DC input voltage source 620 may comprise an inverter, i.e. AC-DC converter, supplying a rectified mains voltage from a single phase mains voltage or a three-phase mains voltage. Hence, the DC input voltage may lie between 380 V and 565 V in grid connected embodiments of the DC-DC converter assembly. The converter load/source 1510 is electrically connected between an output node or terminal 1530 of the DAB converter 1502 and the positive input 1503 receiving the DC input voltage leading to the previously discussed benefits on the performance and reliability of the present DC-DC converter assembly because the load power is supplied directly by the DC input voltage or current source 1520 without passing through the DAB DC-DC converter 1502. Consequently, the DAB DC-DC converter 1502 merely converts a certain fraction of the load power, and this fraction may be markedly smaller than the load power, which leads to a considerable reduction in size and costs of the DAB DC-DC converter 1502 and increased reliability since voltage stress and heat dissipation in active and passive components are reduced. The electrical connection, e.g. by suitable wire or cable, of the converter load 1510 from the converter output 1530 back to the positive input of the DAB converter 1502 breaks galvanic isolation between the primary side circuit and secondary side circuit otherwise provided for by the first and second transformers T1-1 and T1-2. Hence, the converter assembly is not galvanically isolated.

The DAB DC-DC converter 1502 may as illustrated comprise an H-bridge input driver comprising four controllable semiconductor switches SP1, SP2, SP3 and SP4 generating a first pulse width modulated drive signal (not shown) at a first phase angle φ1. The skilled person will understand that the first pulse width modulated drive signal may be generated by a voltage or current regulation loop (not shown) configured to generate or supply an appropriate drive signal to respective control terminals (not shown) of the four controllable semiconductor switches SP1, SP2, SP3 and SP4 of the H-bridge input driver. Each of the four controllable semiconductor switches SP1, SP2, SP3 and SP4 may for example comprise a MOSFET or an IGBT with a gate terminal acting as control terminal. The control terminals are utilised to control state switching of the MOSFET or an IGBT devices between a conducting state (on-state) and a non-conducting state (off-state). The DAB DC-DC converter 1520 comprises a set of transformers where each transformer preferably is configured to deliver a substantial voltage gain between voltages of the primary side winding and secondary side winding of the transformer. The present embodiment of the DAB DC-DC converter 1520 utilizes merely two separate transformers T1-1 and T1-2, but the skilled person will understand that alternatively embodiments may comprise one or more additional transformers having their primary winding(s) connected in series with the primary side windings of T1-1 and T1-2, and the secondary side winding(s) connected to a separate rectification circuit such that all rectification circuits are coupled in parallel to a common DC output voltage node 1513.

The input/primary winding and output/secondary winding of each of the first and second transformers T1-1 and T1-2 are magnetically coupled to each other through respective magnetically permeable cores e.g. an E-core or toroidal core. The winding ratio of each of the first and second transformers T1-1 and T1-2 may vary depending on factors like the DC input voltage, number of transformers and a desired DC output voltage, or voltage range, of the converter 1502. In some embodiments, a winding ratio between 4 and 20 such as about 9 has proven useful. The first and second transformers T1-1 and T1-2 are preferably nominally identical to facilitate equal voltage division between the respective input windings of first and second transformers and facilitate equal current sharing between the output windings and other secondary side circuitry. The first pulse width modulated drive signal generated by the H-bridge input driver is applied to the series connected input windings of first and second transformers T1-1 and T1-2 either through a resonant network 1335, as illustrated in the present embodiment, or directly (without intermediate electric components like inductors and capacitors, to the series connected input windings. In the latter embodiment, the resonant network 1335 is moved from the primary side of each transformer to the secondary side of the converter 1502, more specifically to each of the output windings of the first and second transformers T1-1 and T1-2 on the secondary side of the DAB DC-DC converter 1502. In the latter case, appropriately modified first and second resonant networks (not shown) are connected in series with respective ones of the output windings of the first and second transformers T1-1 and T1-2 by taken into account the impedance transformation caused by the winding ratios of the first and second transformers T1-1 and T1-2 and the number of parallelly connected output windings.

Three exemplary embodiments of the resonant network 1335 are schematically illustrated on FIG.13. The resonant network 1335 may comprise a single series connected inductor L_{AC} connected in series with the series connected input windings of first and second transformers T1-1 and T1-2 or a series connected combination of an inductor L_{AC} and capacitor C_{AC}. The resonant network 1335 may alternative comprise a pair of series connected inductors L_{AC1}, L_{AC2} and with a midpoint between these connected to a first terminal of a capacitor C_{AC} where the series connected inductors are inserted in series with input windings of the first and second transformers T1-1 and T1-2 and the other end of C_{AC} is connected to an ac ground potential.

The duty cycle of the first pulse width modulated drive signal may be 50 % and the first phase angle is an arbitrary value which is used to define respective phase shifts to additional pulse width modulated drive signal(s) and certain pulse width modulated rectification signals as discussed in additional detail below. The first pulse width modulated drive signal may have a frequency between 1 kHz and 1 MHz depending on numerous performance requirements of a specific design of the present DAB DC-DC converter 1502 such as a desired maximum power output, properties of the first and second transformers and properties of the resonant network 1335 or networks.

The DAB DC-DC converter 1502 additionally comprises a set of rectification circuits comprising first and second active rectification circuits 1507, 1509 in the present embodiment but may comprise one or more additional active rectification circuits in other embodiments as mentioned above. The first and second active rectification circuits 607, 609 are connected to respective ones of the output windings of the first and second transformers T1-1 and T1-2 to supply respective rectified transformer voltages to first and second rectification nodes 1507, 1509 of the converter. Each of the first and second active rectification circuits comprises a full-wave rectifier in the present embodiment. The first active rectification circuit 1532 comprises four controllable semiconductor switches, i.e. SS5, SS6, SS7 and SS8, connected to respective ends of the first output winding for receipt of the ac voltage induced in the first output winding. The second active rectification circuit 1540 likewise comprises four controllable semiconductor switches, i.e. SS9, SS10, SS11 and SS12, connected to respective ends of the second output winding (of transformer T1-2) for receipt of the ac voltage induced in the second output winding. Each of the controllable semiconductor switches SS5, SS6, SS7, SS8, SS9, SS10, SS11 and SS12 of these rectification circuits may for example comprise a MOSFET or an IGBT with a gate terminal. The latter terminals are utilised to control state switching of the MOSFET or an IGBT devices between a conducting state (on-state) and a non-conducting state (off-state).

Hence, the term “active” in “active rectification circuit” means that the latter is based on controllable semiconductor switches, e.g. transistors, where the switching time instant can be controlled via the respective control terminals of the switches by an appropriately timed control signal as opposed to a passive rectification circuit based on diodes. The latter control signal may in particular comprise a second pulse width modulated drive signal (not shown) that is off-set with a fixed or adjustable phase angle relative to the first pulse width modulated drive signal driving the input windings. The phase difference between the first and second pulse width modulated drive signals may be used to control load power to a converter load 1510 connected to a DC output terminal or node 1530 of the converter 1502. Hence, this method of adjusting the load power supplied to the converter load 1510 by the DC-DC converter 1502 preferably comprising:
- applying the first pulse width modulated drive signal at a first phase angle to the series connected input windings of the first set of transformers,
- applying the second pulse width modulated drive signal at a second phase angle to respective control terminals of a plurality of controllable semiconductor switches of each rectifier of the first set of rectifiers,
- adaptively adjusting a phase difference between the first phase angle and the second phase angle to reach a desired DC output voltage of the dual active bridge DC-DC converter. The skilled person will understand that the adaptive adjustment of the phase difference may be carried out by a suitable voltage or current regulation loop sensing the instantaneous DC output voltage and comparing the latter with a certain DC reference/set-point voltage indicating a desired DC output voltage of the DC-DC converter 1502.

The DAB DC-DC converter 1502 may comprise an optional current balancing transformer 1525 which comprises first and second transformer windings wound around a common magnetically permeable core (not shown). The number of turns of the first transformer winding is preferably identical to the number of turns of the second transformer winding in the present embodiment which comprises an even number of parallel secondary side circuits, i.e. two parallel secondary side circuits. One end of each of the first and second transformer windings of the current balancing transformer 1525 is interconnected to form a common DC output voltage node 1513 while the opposite ends of the first and second transformer windings are connected to respective ones of the first and second rectification nodes 1532, 1540. Hence, each transformer winding is connected between a rectification nodes and the common DC output voltage node 613 and thereby forces current balancing between the output/secondary windings of the first and second transformers T1-1 and T1-2. The current balancing effect on currents flowing through first and second active rectification circuits 1507, 1509 and their associated output winding can be understood by noting the transformer 625 exhibits a high impedance against differential components of the first and second output currents *i1 and i2* and a low impedance in respect of common mode current components of the first and second output currents *i1* and *i2*. Construction details of the current balancing transformer 1525 are discussed in detail in the applicant's co-pending application EP 16200247.1. The skilled person will appreciate that the current balancing transformer 1525 provides numerous benefits to DAB DC-DC converter topologies comprising a plurality of parallelly coupled secondary side circuits. These benefits include the elimination, or at least a significant reduction, of output current mismatches, such as i1 and i2 discussed above, caused by practically occurring mismatches between electrical components and/or drive voltage waveform mismatches between the primary side circuits and secondary side circuits. The elimination of the output current mismatches allows numerous secondary side circuits to be coupled in parallel and numerous input side circuits coupled in series as discussed above, without inducing significant current imbalances between the individual secondary side circuits. The skilled person will appreciate that the series connection of the respective input windings of the set of transformers, e.g. the first and second transformers T1-1 and T1-2, provides numerous benefits to DAB DC-DC converter topologies comprising a plurality of series connected primary side circuits to achieve a high voltage gain in a grid-connected power converter. The transformer for each of the stages can be realized with a lower turns ratio for the input and output windings thereby significantly easing the transformer design process and enabling a modular design approach of simplified transformers.

The skilled person will appreciate that the controllable semiconductor switches SS5, SS6, SS7 SS8, SS9, SS10, SS11 and SS12 of first active rectification circuit 1507 and the second active rectification circuit 1509 may be replaced by diodes in alternative embodiments of the DAB DC-DC converter 1502. Such a variant of the DAB DC-DC converter 1502 is merely capable of supporting unidirectional power flow from the DC input voltage or energy source 1520 to the converter load 1510.

REFERENCES

[1] Power conversion apparatus for DC/DC conversion using dual active bridges, US 5027264 A.

[2] R. W. A. A. De Doncker, D. M. Divan and M. H. Kheraluwala, "A three-phase soft-switched high-power-density DC/DC converter for high-power applications," in IEEE Transactions on Industry Applications, vol. 27, no. 1, pp. 63-73, Jan/Feb 1991 .doi: 10.1109/28.67533.

[3] B. Zhao, Q. Song, W. Liu and Y. Sun, "Overview of Dual-Active-Bridge Isolated Bidirectional DC-DC Converter for High-Frequency-Link Power-Conversion System," in IEEE Transactions on Power Electronics, vol. 29, no. 8, pp. 4091-4106, Aug. 2014.doi: 10.1109/TPEL.2013.2289913.

CLAIMS

1. A DC-DC converter assembly comprising:

a DC-DC converter configured to convert a DC input voltage into a DC output voltage at a predetermined step-down ratio or step-up ratio, comprising:

- a positive input and a negative input for receipt of the DC input voltage from a DC input voltage source,
- a positive output and a negative output for supply of the DC output voltage to a converter load,
- a voltage regulation loop and/or a current regulation loop configured to adjust the DC output voltage or DC output current in accordance with a target DC voltage or a DC target current, respectively; and

wherein the converter load is electrically connected between the positive input and the positive output of the DC-DC converter such that the DC input voltage source supplies power directly to the converter load without passing through the DC-DC converter.

2. A DC-DC converter assembly according to claim 1, wherein the predetermined step-down ratio is at least 2, or more preferably at least 10, such as between 20 and 40 or the predetermined step-up ratio is at least 2, or more preferably at least 10, such as between 20 and 40.

3. A DC-DC converter assembly according to claim 1 or 2, wherein the DC-DC converter comprises a resonant network connected to an input driver of the power converter.

4. A DC-DC converter assembly according to claim 3, wherein the DC-DC converter comprises a Dual Active Bridge (DAB) converter.

5. A DC-DC converter assembly according to claim 4, wherein the Dual Active Bridge (DAB) converter comprises:

- a first set of *n* transformers comprising respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores; said input windings being connected in series,

- a first resonant network connected in series with the series connected input windings or a first set of *n* resonant networks connected in series with respective ones of the output windings,
- a first set of *n* rectification circuits connected to respective ones of the output windings of the first set of *n* transformers to supply a first set of *n* rectified transformer voltages and currents to a first set of *n* rectification nodes,

a summing node configured to combine the first set of *n* rectified transformer voltages and currents to generate the DC output voltage;
- *n* being a positive integer number larger than or equal to 2.

6. A DC-DC converter assembly according to claim 5, wherein the Dual Active Bridge (DAB) converter additionally comprises:
- a current balancing transformer comprising *n* transformer windings connected between respective ones of the first set of *n* rectification nodes and the summing node to force current balancing between individual windings of the first set of output windings.

7. A DC-DC converter assembly according to claim 5 or 6, wherein the first set of *n* transformers of the Dual Active Bridge (DAB) converter comprises of the between 2 and 6 individual transformers.

8. A DC-DC converter assembly according to any of claims 5 - 7, wherein the output voltage or output current regulation loop comprises:
- a first input driver for generating a first pulse width modulated drive signal at a first phase angle and applying the first pulse width modulated drive signal to the series connected input windings of the first set of *n* transformers;
- a first active rectification circuit configured to generate a second pulse width modulated drive signal at a second phase angle and apply the second pulse width modulated drive signal to respective control terminals of a plurality of controllable semiconductor switches of each rectification circuit of the first set of *n* rectification circuits; wherein the output voltage or output current regulation loop is configured to adaptively adjusting a phase difference between the first phase angle and the second phase angle to reach a desired DC output voltage or a desired DC output current of the dual active bridge DC-DC converter.

9. A DC-DC converter assembly according to any of the preceding claims, wherein at least one of the converter load and the DC input voltage source comprises an inverter, aka DC-AC converter.

10. A DC-DC converter assembly according to any of the preceding claims, wherein the DC-DC converter is configured for bidirectional operation to additionally transfer power from the converter load directly to the DC input voltage source without passing through the DC-DC converter.

11. A DC-DC converter assembly according to claim 10, wherein the converter load comprises a rechargeable battery pack and the DC input voltage source comprises an inverter, aka DC-AC converter, connectable to a single phase mains grid or a three phase mains grid.

12. A method of supplying power to a converter load by a DC-DC converter, comprising:
- connecting a first terminal of the converter load to a positive input of the DC-DC converter,
- connecting a second terminal of the converter load to a positive output of the DC-DC converter,
- connecting a DC input voltage source to the positive input,
- adjusting a DC output voltage or a DC output current at the positive output of the DC-DC converter in accordance with a target DC voltage or target DC current, respectively.

13. A method of supplying power to a converter load by a DC-DC converter according to a claim 12, wherein the target DC voltage is less than one-fifth of the DC input voltage such that the DC input voltage source supplies power directly to the converter load without passing through the DC-DC converter.

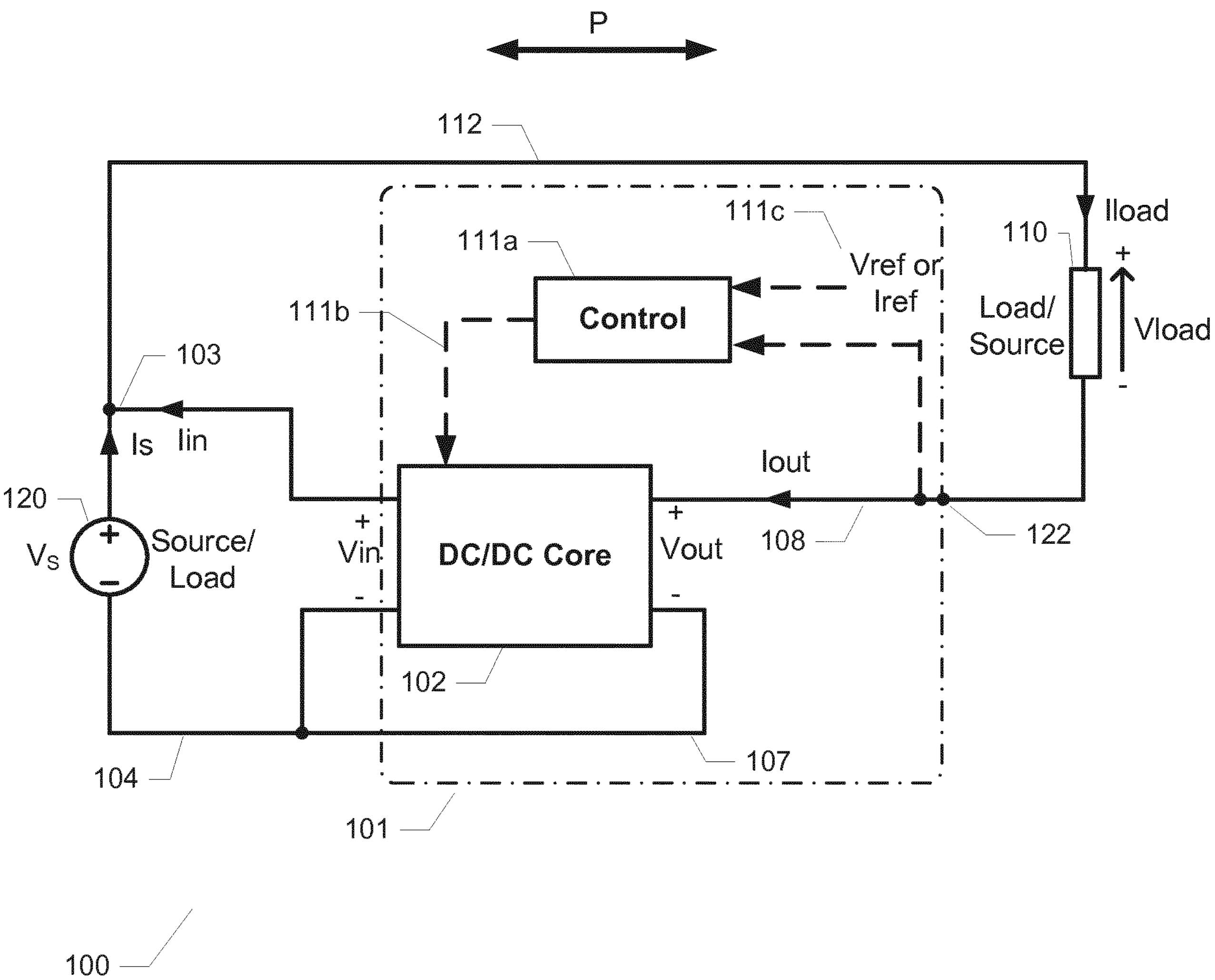
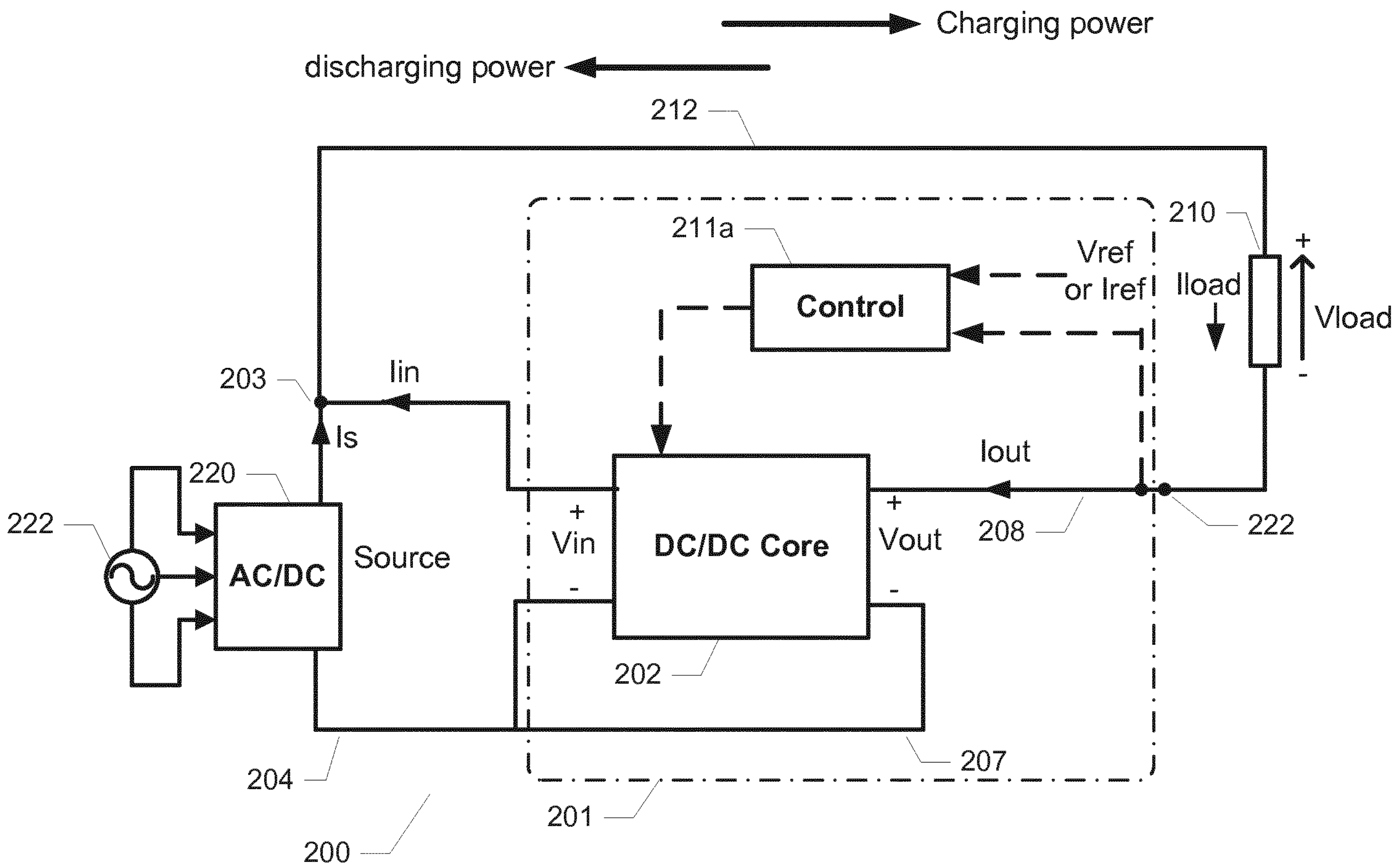

P
112
111c
111a
Vref or
Iref
110
Iload
+
Control
Load/
Source
Vload
111b
103
-
Is
Iin
Iout
120
+
Vs
+
Source/
Load
Vin
-
DC/DC Core
+
Vout
-
108
122
102
104
107
101
100

FIG. 1



Charging power
discharging power
212
210
211a
Vref
or Iref
Iload
Vload
Control
203
Iin
Is
220
222
AC/DC
Source
+
Vin
-
DC/DC Core
+
Vout
-
Iout
208
222
202
204
207
201
200

FIG. 2

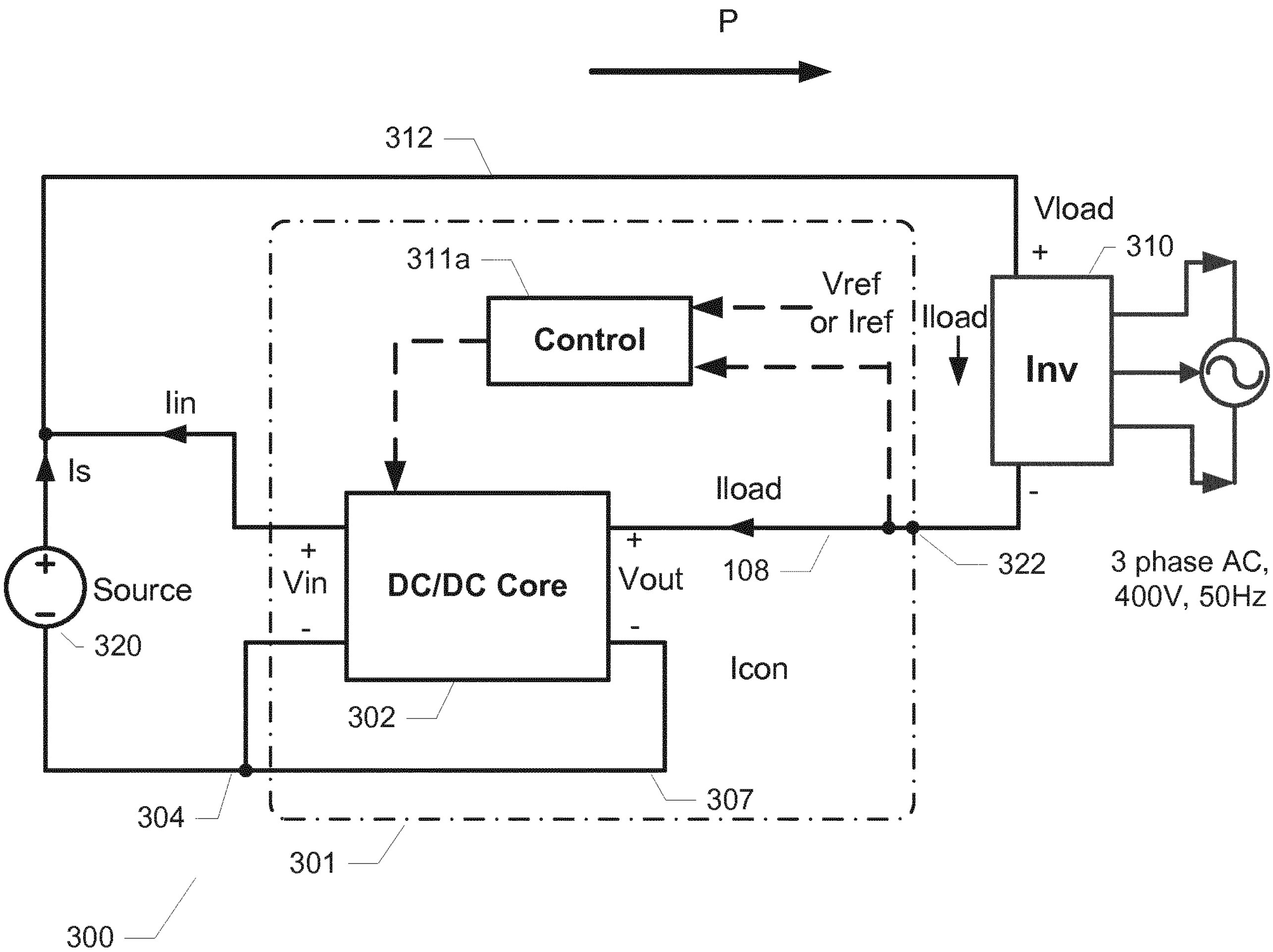

P
312
Vload
311a
+
310
Vref
or Iref
Control
Iload
Inv
Iin
Is
Iload
+
-
+
Vin
DC/DC Core
+
Vout
108
322
3 phase AC,
400V, 50Hz
Source
-
-
320
Icon
302
307
304
301
300

FIG. 3

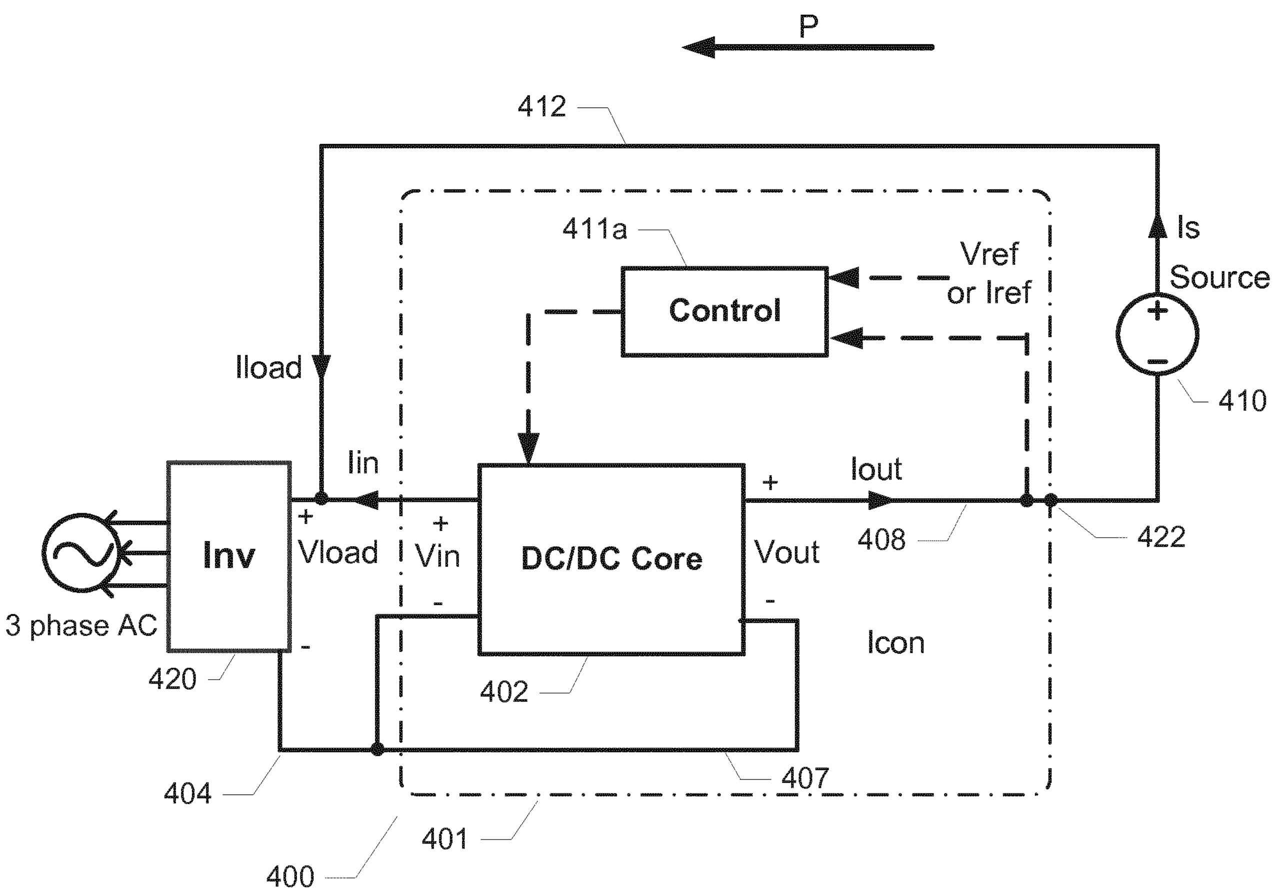

P
412
411a
Control
Vref
or Iref
Is
Source
410
Iload
Iin
Iout
Inv
+
Vload
+
Vin
DC/DC Core
+
Vout
408
422
3 phase AC
420
-
-
-
Icon
402
404
407
401
400

FIG. 4

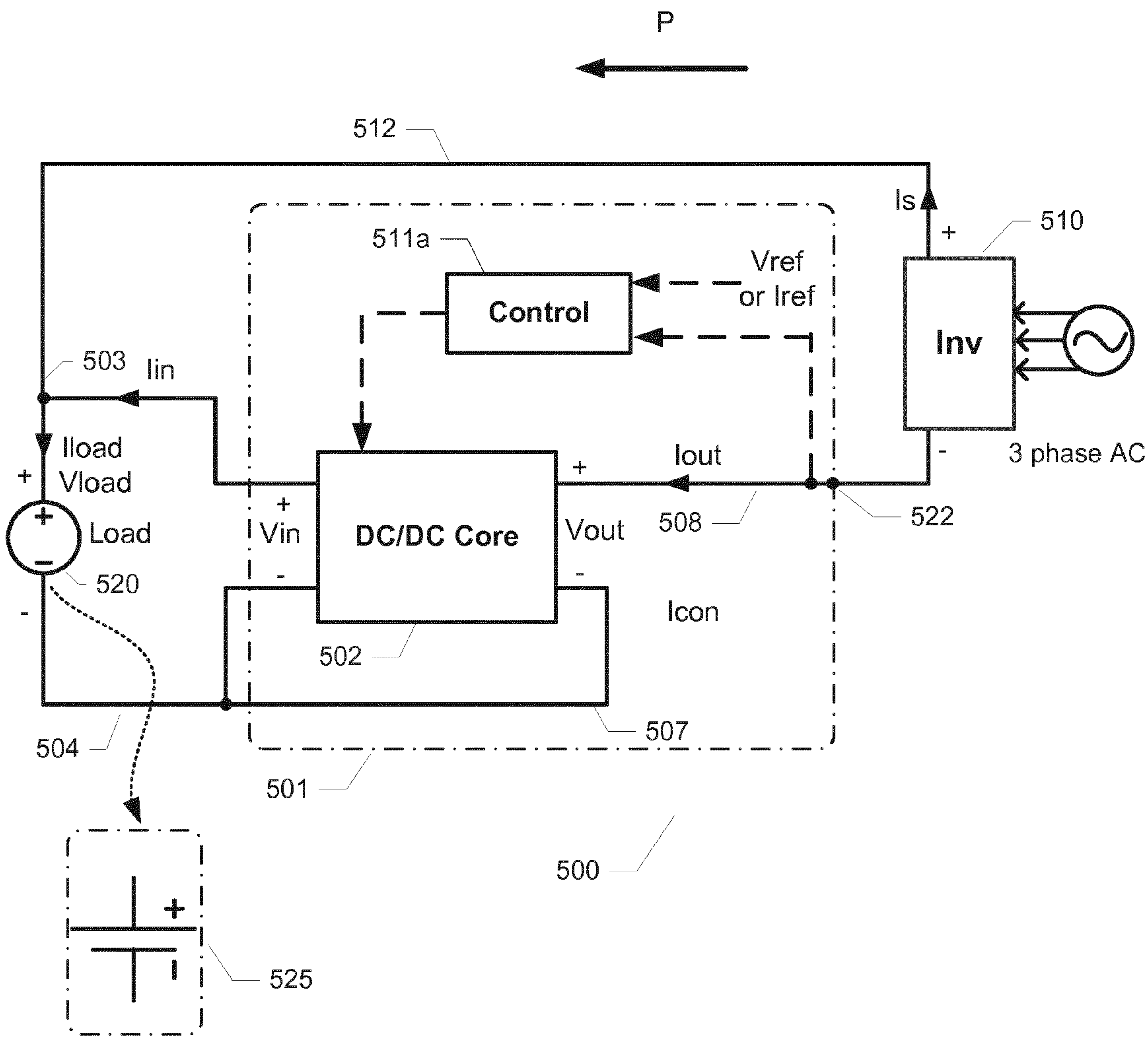

P
512
Is
+
510
511a
Vref
or Iref
Control
Inv
503
Iin
Iload
Vload
+
+
Load
Iout
+
-
3 phase AC
+
Vin
DC/DC Core
Vout
508
522
520
-
-
-
Icon
502
504
507
501
500
+
525

FIG. 5

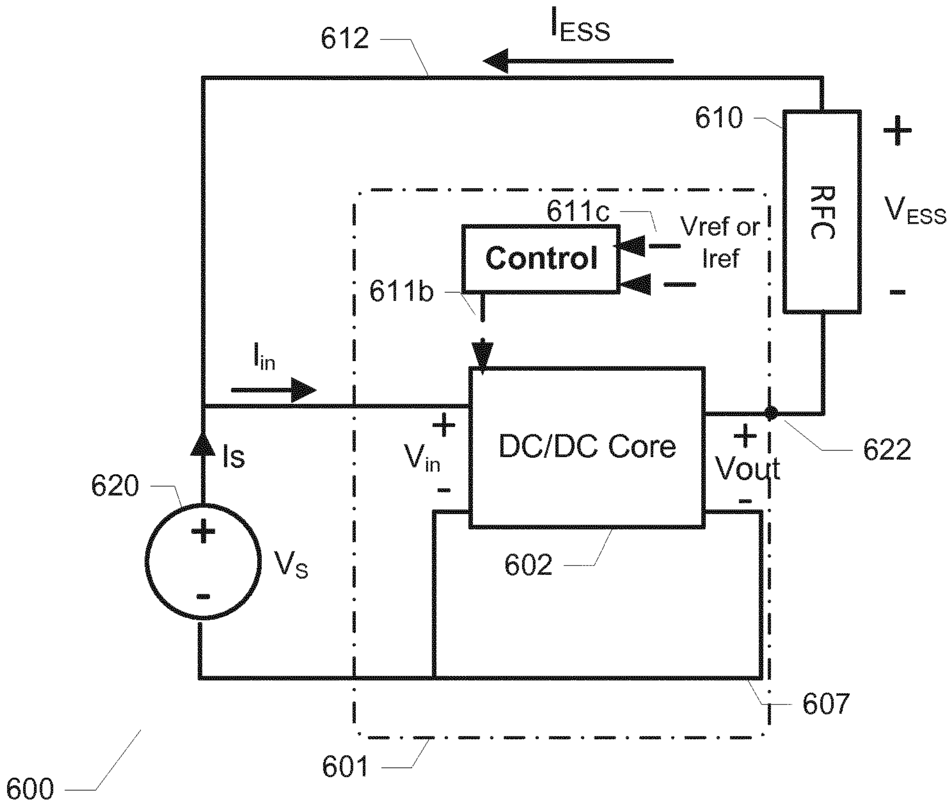

612
I_ESS
610
+
RFC
V_ESS
-
611c
Vref or
Iref
Control
611b
I_in
DC/DC Core
+
V_in
-
+
Vout
-
622
Is
620
+
V_S
-
602
607
601
600

FIG. 6

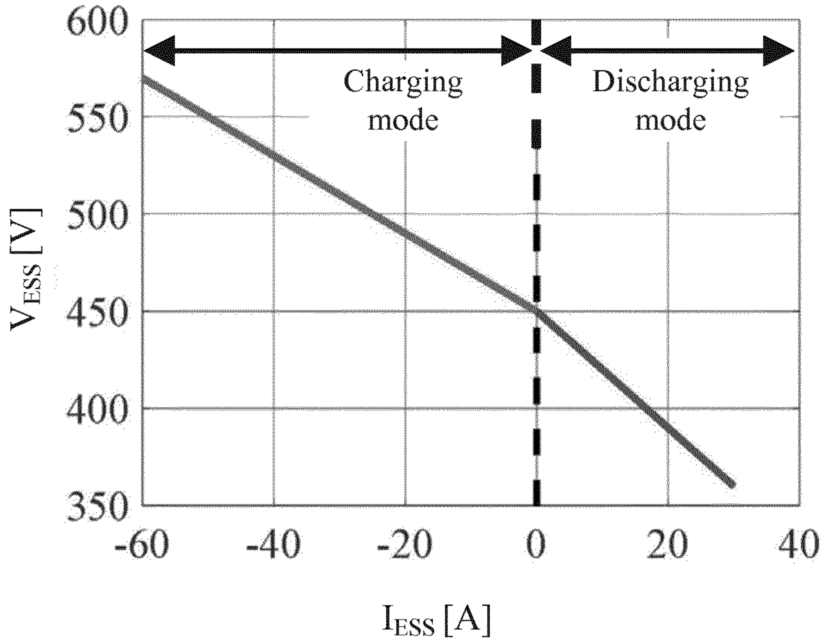

600
550
500
450
400
350
V_{ESS} [V]
Charging mode
Discharging mode
-60
-40
-20
0
20
40
I_{ESS} [A]

FIG. 7

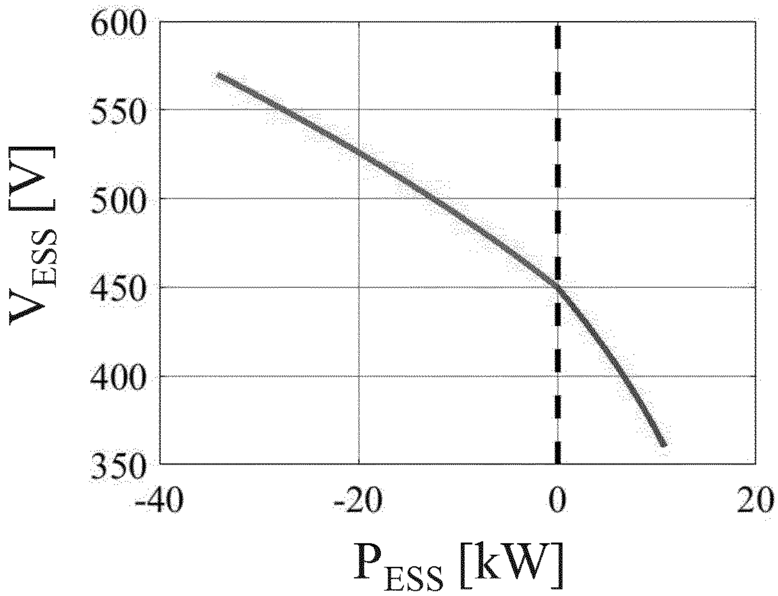

600
550
500
450
400
350
V_{ESS} [V]
-40
-20
0
20
P_{ESS} [kW]

FIG. 8

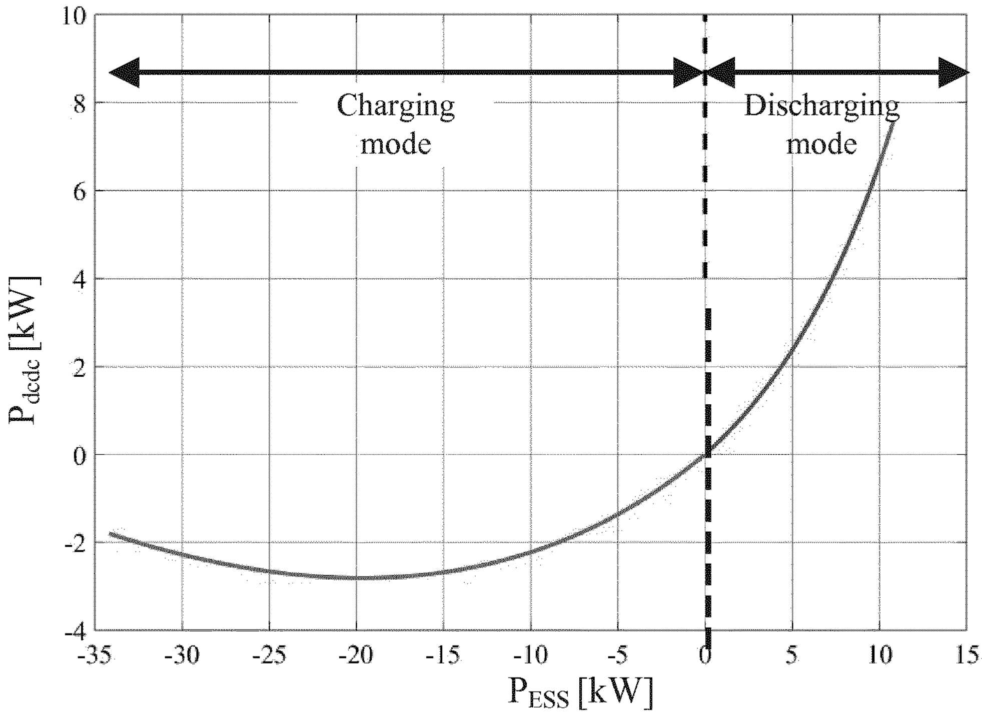

10
8
6
4
2
0
-2
-4
-35 -30 -25 -20 -15 -10 -5 0 5 10 15
Charging mode
Discharging mode
P_{dcdc} [kW]
P_{ESS} [kW]

FIG. 9

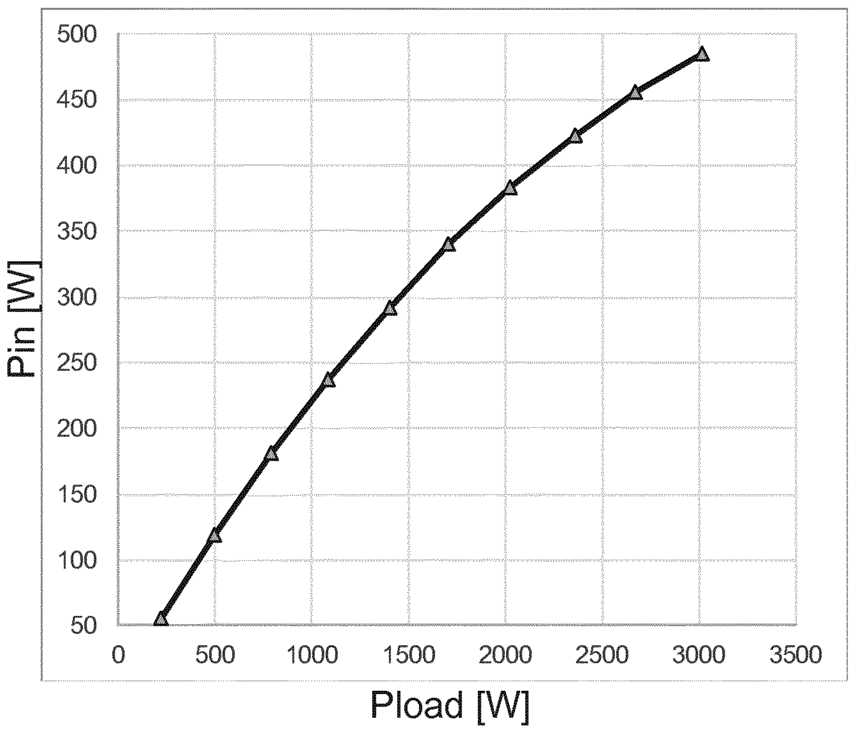

500
450
400
350
300
250
200
150
100
50
0 500 1000 1500 2000 2500 3000 3500
Pin [W]
Pload [W]

FIG. 10

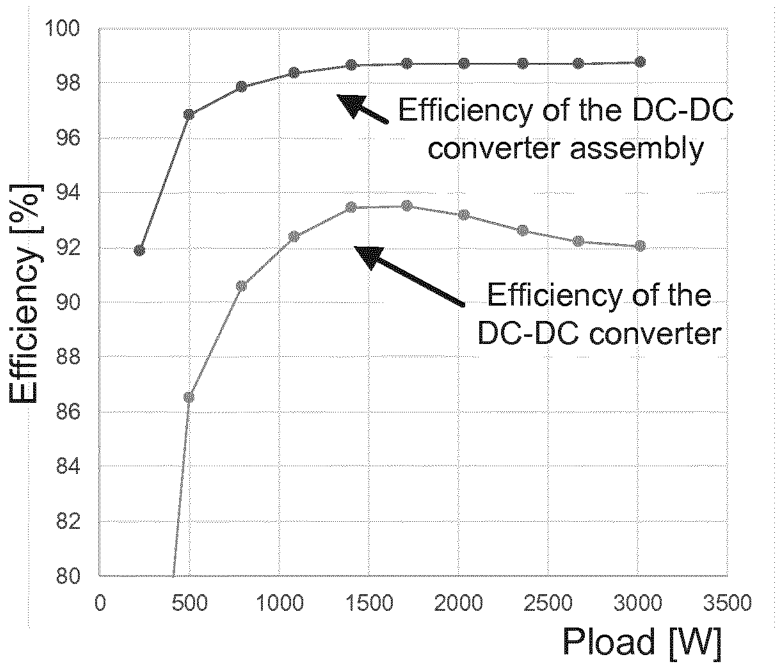

100
98
96
94
92
90
88
86
84
82
80
Efficiency [%]
Efficiency of the DC-DC converter assembly
Efficiency of the DC-DC converter
0
500
1000
1500
2000
2500
3000
3500
Pload [W]

FIG. 11

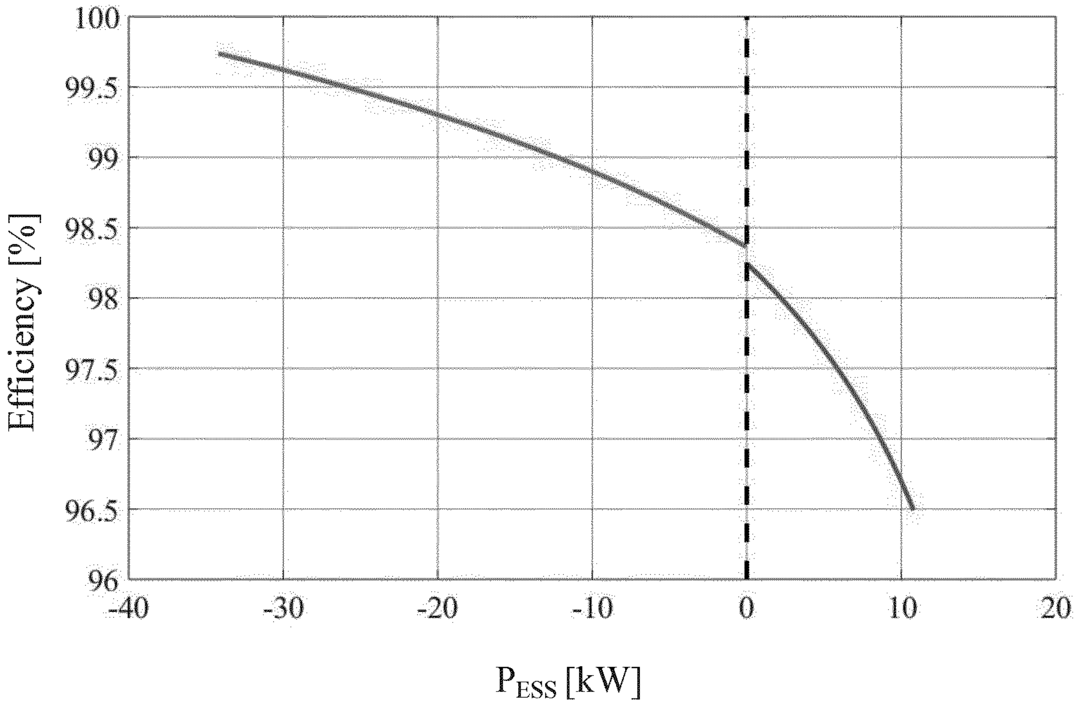

100
99.5
99
98.5
98
97.5
97
96.5
96
Efficiency [%]
-40
-30
-20
-10
0
10
20
P_{ESS} [kW]

FIG. 12

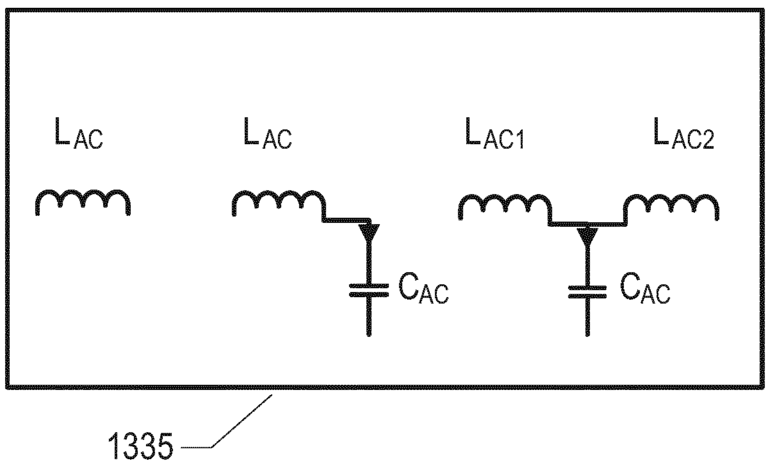

L_AC
L_AC
L_AC1
L_AC2
C_AC
C_AC
1335

Fig. 13

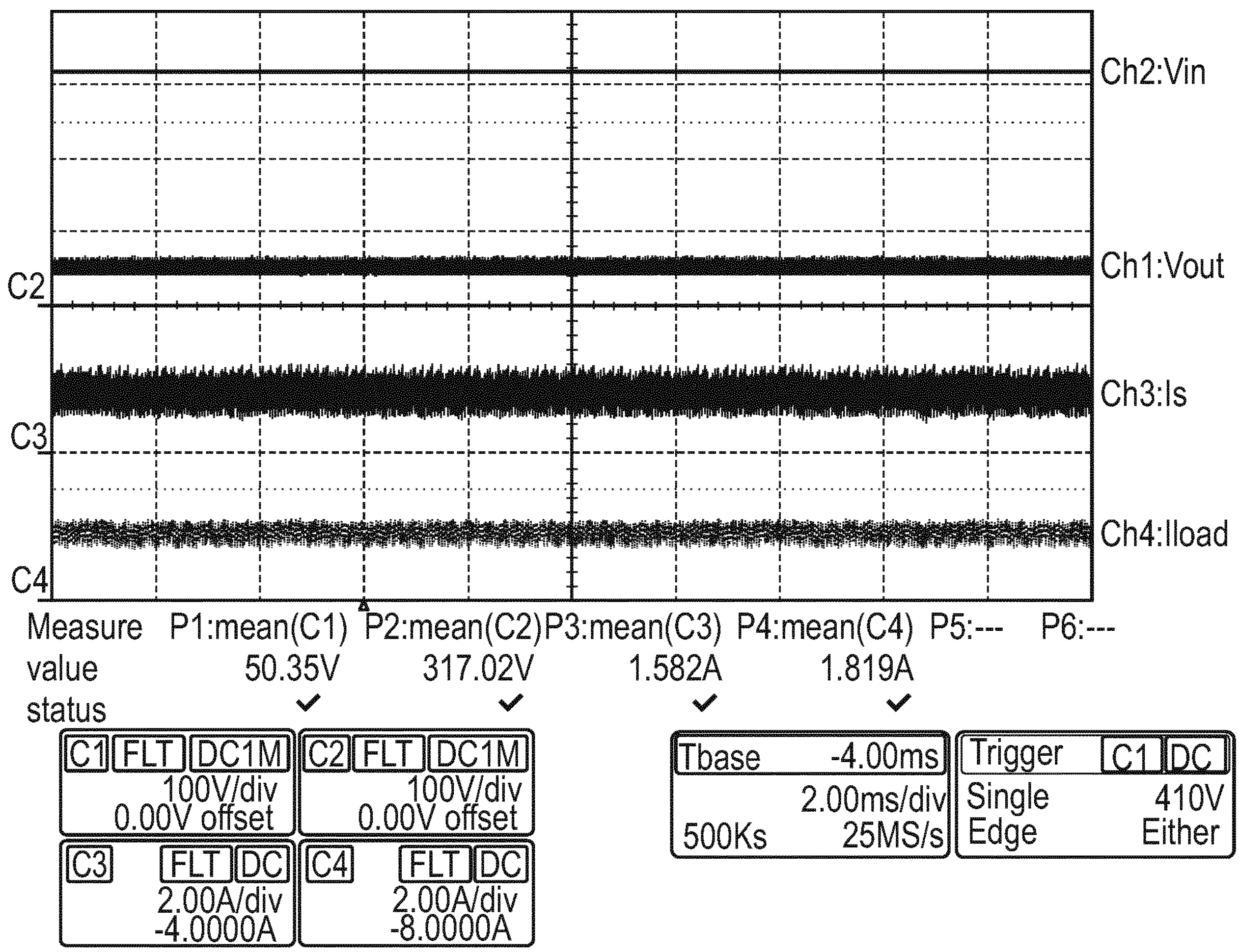
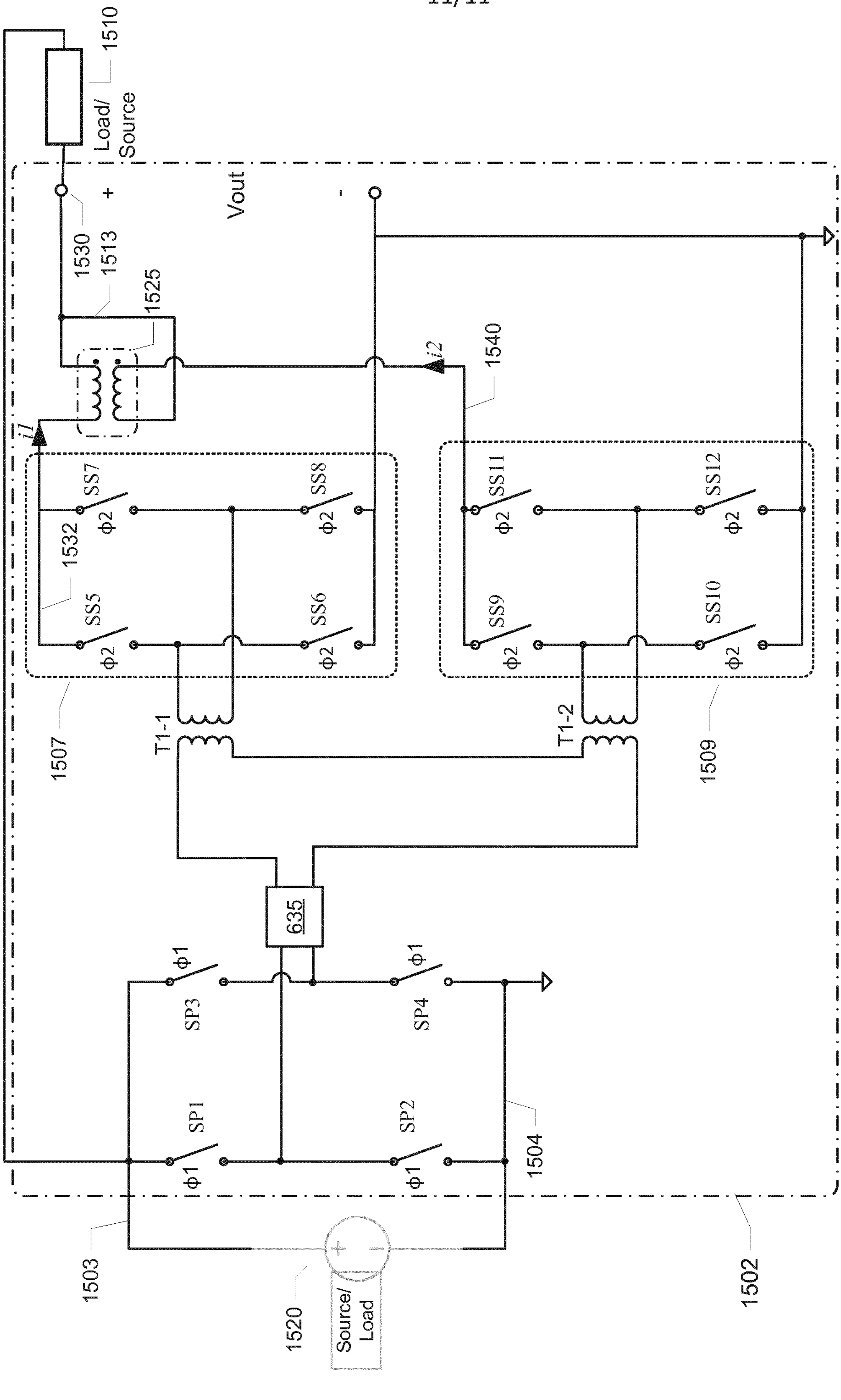

Ch2:Vin
Ch1:Vout
Ch3:Is
Ch4:Iload
C2
C3
C4
Measure P1:mean(C1) P2:mean(C2) P3:mean(C3) P4:mean(C4) P5:--- P6:---
value 50.35V 317.02V 1.582A 1.819A
status
C1 FLT DC1M 100V/div 0.00V offset
C2 FLT DC1M 100V/div 0.00V offset
C3 FLT DC 2.00A/div -4.0000A
C4 FLT DC 2.00A/div -8.0000A
Tbase -4.00ms 2.00ms/div 500Ks 25MS/s
Trigger C1 DC Single 410V Edge Either

Fig. 14



Load/ Source
1510
1530
1513
1525
+
Vout
-
i1
i2
1540
SS5
SS6
SS7
SS8
SS9
SS10
SS11
SS12
ϕ2
1532
T1-1
T1-2
1507
1509
635
SP1
SP2
SP3
SP4
ϕ1
1504
1503
1520
Source/ Load
1502

FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/078202

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02M3/335 H02M3/337
ADD. H02M1/00

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)
H02M

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 2 819 291 A1 (NISSAN MOTOR [JP]; KAWAMURA ATSUO [JP]) 31 December 2014 (2014-12-31) paragraphs [0012] - [0014] paragraphs [0018], [0019] paragraphs [0022] - [0047]; figures 1,3 -----	1-13
A	EP 2 833 532 A1 (HUAWEI TECH CO LTD [CN]) 4 February 2015 (2015-02-04) paragraphs [0015], [0036], [0037] claim 1 figure 5 -----	1-13
A	US 2014/153290 A1 (LI YUEHUI [CN] ET AL) 5 June 2014 (2014-06-05) the whole document -----	2-4
	-/--	

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

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
2 January 2019	15/01/2019

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Standaert, Frans

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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