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(54) Title: THREE-PHASE AC TO DC POWER CONVERTER

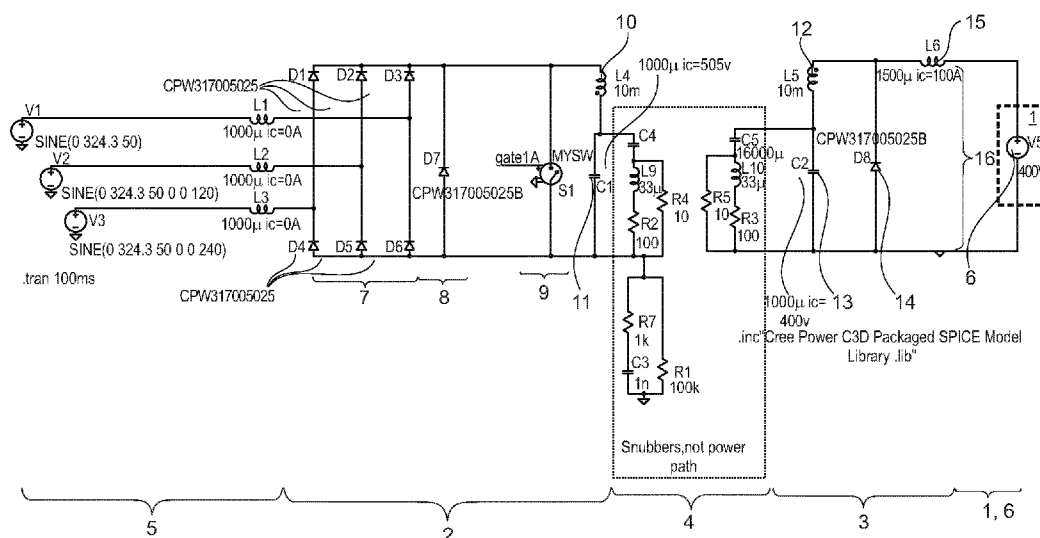


Fig. 1

(57) Abstract: The invention relates to a three-phase alternating current, AC, to direct current, DC, power converter, comprising a boost power factor correction, PFC, circuit (2) comprising a low frequency diode-based converter (7) configured for connecting a PFC input of the converter (7) to an AC source (5), and a PFC inductor (10) and a PFC capacitor (11) connected in series together and in parallel to a PFC output of the converter (7), further comprising either a high frequency PFC diode (8) and a high frequency PFC switch (9) connected in parallel to the PFC output of the converter (7) or comprising a plurality of high frequency PFC switches (9) each connected in parallel to one of the diodes of the converter (7), a Čuk converter (3) comprising a first Čuk inductor (12) and a Čuk capacitor (13) connected in series, a second Čuk inductor (15) and a high frequency Čuk diode (14) connected in parallel to the series connection and forming, via a series connection with the second Čuk inductor (15), a Čuk output (16) to which a DC load (6) can be connected, and a transformer (4) having a primary side connected in parallel to the PFC capacitor (11) and a secondary side connected in parallel to the Čuk capacitor (13).

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Description**Three-phase AC to DC power converter****Technical Field**

[0001] The invention relates to a three-phase alternating current, AC, to direct current, DC, power converter in particular for charging an electrical vehicle, comprising a low frequency diode-based converter.

Background Art

[0002] Power converters for charging electrical vehicles are known from prior art and are often referred to as electric vehicle charging station, also called EV charging station, electric recharging point, charging point, charge point, ECS, electronic charging station, or in recent days as EVSE, electric vehicle supply equipment. Generally, an EVSE is an element in an infrastructure that supplies electric energy for the recharging of electric vehicles, such as plug-in electric vehicles, including electric cars, neighbourhood electric vehicles and plug-in hybrids, either at home, at public spaces or work. Some electric vehicles have on board converters that can plug into a standard electrical outlet or a high-capacity appliance outlet. Other electrical vehicles either require or can use a charging station that provides electrical conversion, monitoring, or safety functionality.

[0003] These charging stations are also needed when traveling, and many support faster charging at higher voltages and currents than are available from residential EVSEs. Public charging stations are typically on-street facilities provided by electric utility companies or located at retail shopping centres, restaurants and parkings, and operated by many private companies. Charging standards encompass Combined Charging System, CCS, which is becoming the universal standard or CHAdeMO besides others.

[0004] There is general aim to constantly provide better power converter topologies that are cheap, provide a large output voltage range, are

characterized by a high efficient power conversion, a good power factor, THD, total harmonic distortion, on alternating current, AC and/or a good output ripple on direct current, DC.

Summary of invention

[0005] It is therefore an object of the invention to provide an improved power converter for charging an electrical vehicle.

[0006] The object of the invention is solved by the features of the independent claims. Preferred embodiments are detailed in the dependent claims.

[0007] Thus, the object is solved by a three-phase alternating current, AC, to direct current, DC, power converter in particular for charging an electrical vehicle, comprising

- a boost power factor correction, PFC, circuit comprising a low frequency diode-based converter configured for connecting a PFC input of the converter to an AC source, and a PFC inductor and a PFC capacitor connected in series together and in parallel to a PFC output of the converter, further comprising either a high frequency PFC diode and a high frequency PFC switch connected in parallel to the PFC output of the converter or comprising a plurality of high frequency PFC switches each connected in parallel to one of the diodes of the converter,

- a Ćuk converter comprising a Ćuk inductor and a first Ćuk capacitor connected in series, a second Ćuk capacitor and a high frequency Ćuk diode connected in parallel to the series connection and forming, via a series connection with the second Ćuk capacitor, a Ćuk output in particular to which the electrical vehicle can be connected as DC load, and

- a transformer having a primary side connected in parallel to the PFC capacitor and a secondary side connected in parallel to the Ćuk capacitor.

[0008] It is therefore a key aspect of the invention to combine a three phase boost PFC circuit with a Ćuk converter. A power factor correction, PFC circuit generally increases the power factor of a load thereby improving overall conversion efficiency. The power factor of an AC electrical power system is defined as the ratio of the real power absorbed by the load to

the apparent power flowing in the circuit, and is a dimensionless number in the closed interval of -1 to 1 . A Ćuk converter, sometimes incorrectly spelled Cuk, Ćuk or Cúk, is a type of DC/DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. The Ćuk converter is essentially a boost converter followed by a buck converter with a capacitor i.e. the first Ćuk capacitor to couple the energy. The Ćuk converter is named after Slobodan Ćuk of the California Institute of Technology, who first presented the design. The Ćuk converter is preferably provided as an isolated Ćuk converter. Switching frequency for the switches is for example 10kHz.

[0009] The proposed converter provides the advantage of a constant input current and constant output current, with inductor current ripple. Even that hard switching may be applied to the switch, the proposed solution helps to improve EMC, electromagnetic compatibility, and input/output ripple requirements. The proposed converter advantageously provides a wide range of output voltages. Possible inductors on the AC side see three levels, thereby reducing the input voltage ripple. Due to using the Ćuk respectively boost-buck converter, a wide output voltage range independent of the input voltage can be achieved. Thus, power conversion efficiency is very high as there is no input rectification or output rectification. The proposed solution is particularly suited for SiC, silicon carbide, and IGBTs as switches and can be implemented by using only one "high" frequency switch and each one "high" frequency diode on the primary and on the secondary side. Thus, as component count is in addition very low, the proposed converter can be implemented at very low cost but thereby providing high efficiency in conversion.

[0010] In case the high frequency PFC diode and the high frequency PFC switch are connected in parallel to the PFC output of the converter the power path only requires one high frequency PFC switch, one high frequency PFC diode, one high frequency Ćuk diode, six low frequency diodes of the diode-based converter, mains frequency, four inductors, PFC and Ćuk, as well as two capacitors, PFC and Ćuk. The proposed topology does not need any AC voltage or current measurement while only output voltage and current would be sufficient. Control of the switching can very easily done,

as it is naturally stable, works with a fixed PWM, pulse width modulation, or slight corrections in case of unclean AC sources. For such 'single' switch version the PFC inductor can be used in discontinuous mode resulting in a good power factor.

- [0011] In case the plurality of high frequency PFC switches are each connected in parallel to one of the diodes of the converter such solution either provides a good power factor, while it can be uni- or bi directional, with the addition of one extra Ćuk switch, as described later. In such case the diodes of the converter are preferably provided as high frequency diodes as well. The term high frequency means in terms of the present application that, for example for a switch, the switch provide faster switching frequency than of overall system frequency, for example of the AC network. In such topology a single high frequency PFC switch can be overtaken by the plurality of high frequency PFC switches using some smart switching strategies. In other words, the single high frequency PFC switch is replaced by switching on all the plurality of high frequency PFC switches on the AC side of the diode-based converter. Any remaining duty cycle can be used to perform the PFC function on the AC side by switching the corresponding top and bottom high frequency PFC switches. Depending on the direction of the current, after all high frequency PFC switches are on, preferably the top or bottom high frequency PFC switches can be left on, and switched over in between, after which all high frequency PFC switches are switched on again. Such switching results in a good PFC on the AC side and constant current on the DC side. Besides that soft-switching techniques that have been used before in Ćuk and boost PFC converters can be applied to the proposed topologies. With such version with six high frequency PFC switches on the primary and a high frequency Ćuk switch switch on the secondary side, as discussed later, the converter can work bi-directionally.
- [0012] The following implementations allow for further improving PFC and/or THD, total harmonic distortion, by using additional passive trap filter elements and/or passive PFC, additional parallel active harmonic compensation/PFC and/or harmonic compensation by replacing low frequency diodes with active switches. First two options are in particular advantageous depending on the power level and requirements. The latter

option uses same power inductors. Therefore, extra costs only occur due to switches and their drivers compared to an additional active filter which would require extra inductors and a capacitor buffer.

- [0013] According to a further preferred implementation the PFC capacitor, via the transformer, and the Ćuk capacitor are connected to the negative potential of the Ćuk output and the PFC inductor is connected, via the transformer, the first Ćuk inductor and the second Ćuk inductor, to the positive potential of the Ćuk output.
- [0014] In another preferred implementation the anode of the high frequency Ćuk diode is connected to the negative potential of the Ćuk output.
- [0015] According to a further preferred implementation the second Ćuk inductor is connected to the positive potential of the Ćuk output and in series with the first Ćuk inductor.
- [0016] According to a further preferred implementation the converter comprises a high frequency Ćuk switch connected in parallel to the high frequency Ćuk diode.
- [0017] According to another preferred implementation the converter comprises three phase inductors each arranged in a respective current path between the PFC input and the low frequency diode-based converter.
- [0018] According to a further preferred implementation the converter comprises three trap capacitors and each trap inductors, the trap inductors connected together and in series with each one trap capacitors, whereby each one trap capacitor is connected to a respective phase inductor and the low frequency diode-based converter.
- [0019] According to another preferred implementation the converter comprises three phase capacitors connected to together and to a respective phase of the PFC input. Such embodiments are in particular advantageous for reducing fifth and seventh harmonics, in particular by providing such trap filter thereby improving THD, total harmonic distortion, significantly. THD is a measurement of the harmonic distortion present in a signal and normally defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency.
- [0020] According to a further preferred implementation the converter comprises the high frequency PFC diode and the high frequency PFC switch

connected in parallel to the PFC output of the converter, further comprising a second high frequency PFC diode and a second high frequency PFC switch connected in parallel, whereby each the PFC diodes the PFC switches are connected in parallel to the PFC output of the converter. Such embodiment allows for lower voltage rating switches and multi-level switching thereby reducing input and output ripple and/inductance values.

[0021] According to another preferred implementation the converter comprises the plurality of high frequency PFC switches each connected in parallel to one of the diodes of the converter, further comprising a second high frequency PFC switch connected in parallel to the PFC inductor.

[0022] According to a further preferred implementation the converter comprises the plurality of high frequency PFC switches each connected in parallel to one of the diodes of the converter, further comprising a high frequency Ćuk switch connected in parallel to the high frequency Ćuk diode, a second frequency Ćuk switch and a second high frequency Ćuk diode connected in parallel to the second high frequency Ćuk switch, whereby each the high frequency Ćuk diodes the high frequency Ćuk switches are connected in parallel to the series connection of the first Ćuk inductor and the Ćuk capacitor. As before, such embodiment allows as well for lower voltage rating switches and multi-level switching thereby reducing input and output ripple and/inductance values.

[0023] Further embodiments and advantages of the method are directly and unambiguously derived by the person skilled in the art from the system as described before.

Brief description of drawings

[0024] These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

[0025] In the drawings:

- [0026] Fig. 1 shows in a schematically drawing a three-phase alternating current, AC, to direct current, DC, power converter according to a preferred embodiment of the invention,
- [0027] Fig. 2 shows in a schematically drawing a three-phase alternating current, AC, to direct current, DC, power converter according to another preferred embodiment of the invention,
- [0028] Fig. 3 shows in a schematically drawing a partial view of the power converter according to Fig. 1 in another preferred embodiment of the invention,
- [0029] Fig. 4 shows in a schematically drawing a partial view of the power converter according to Fig. 1 in even another preferred embodiment of the invention, and
- [0030] Fig. 5 shows in a schematically drawing a partial view of the power converter according to Fig. 2 in another preferred embodiment of the invention.

Description of embodiments

- [0031] Fig. 1 shows in a schematically drawing a three-phase alternating current, AC, to direct current, DC, power converter for charging an electrical vehicle 1 according to a preferred embodiment.
- [0032] The converter comprises a boost power factor correction, PFC, circuit 2, a Ćuk converter 3 and a transformer 4. The PFC circuit 2 is on one side connected to an AC source 5, such as an AC grid. On the other side the PFC circuit 2 is connected to the transformer 4, which is then connected to the Ćuk converter 3, to which the electrical vehicle 1 is connected as DC load 6.
- [0033] The three phase PFC circuit 2 comprises a low frequency diode-based converter 7, a high frequency PFC diode 8, a high frequency PFC switch

9, a PFC inductor 10 and a PFC capacitor 11. The high frequency PFC diode 8 and the high frequency PFC switch 9, which is provided as a voltage controlled FET switch, are arranged in parallel and thereby connected in parallel to an output of the diode-based converter 7 such that the anodes as well as the cathodes of the diodes of the diode-based converter 7 and of the high frequency PFC diode 8 are respectively connected together. The PFC inductor 10 has an inductance of 10 mH and the PFC capacitor 11 has a capacitance of 1000 μ F are connected in series such that the PFC inductor 10 is connected to the cathodes and the PFC capacitor 11 is connected to the anodes.

[0034] Fig. 2 shows a further preferred embodiment, wherein, opposite to Fig. 1, the high frequency PFC diode 8 and the high frequency PFC switch 9 are not connected in parallel to the output of the diode-based converter 7. Instead, each one high frequency PFC switch 9 is connected in parallel to each diode of the diode-based converter 7.

[0035] The Ćuk converter 3 comprises a first Ćuk inductor 12 and a Ćuk capacitor 13, which are connected in series. The first Ćuk inductor 12 has an inductance of 10 mH and the Ćuk capacitor 13 has a capacitance of 1000 μ F. The Ćuk converter 12 further comprises a high frequency Ćuk diode 14, which is connected in parallel to the series connection of the first Ćuk inductor 12 and the Ćuk capacitor 13. The anode of the high frequency Ćuk diode 14 is connected, via the transformer 4, to the anode of the high frequency PFC diode 8.

[0036] The Ćuk converter 3 further comprises a second Ćuk inductor 15 having an inductance of 1000 μ H, which is connected to the cathode of the high frequency Ćuk diode 14. Such way the second Ćuk inductor 15 and the anode of the high frequency Ćuk diode 14 form a Ćuk output 16, to which the electrical vehicle 1 is connected as DC load 6. Further, the anode of the high frequency Ćuk diode 13 is connected to the negative potential of the Ćuk output 16. The further embodiment of Fig. 2 shows a high frequency Ćuk switch 17, which is connected in parallel to the high frequency Ćuk diode 14.

[0037] The transformer 4 is connected with its primary side in parallel to the PFC capacitor 11 and with its secondary side in parallel to the Ćuk capacitor

13, thereby connecting the PFC circuit 2 and the Ćuk converter 3. Such way the Ćuk capacitor 13 and the PFC capacitor 11 are connected, via the transformer 4, to the negative potential of the Ćuk output 16. The PFC inductor 10 is connected, via the transformer 4 and the first Ćuk inductor 11 and the second Ćuk inductor 15 to the positive potential of the Ćuk output 16.

[0038] Fig. 3 shows an enlarged respectively partial view of the PFC circuit 2 according to a further preferred embodiment. Phase inductors 18 having each an inductance of 1000 μ H are provided in each current path between the AC source 5 and the diode-based converter 7. Further, a trap filter is provided comprising two sets of each three trap capacitors 19 having each a capacitance of 1000 μ F and three respective trap inductors 20 having each an inductance of 1000 μ H. Each three trap inductors 20 are connected star-like together and in series with each one trap capacitors 19 to one phase between the phase inductors 18 and the converter 7. Furthermore, three phase capacitors 21 are provided each having a capacitance of 1000 μ F. The phase capacitors 21 are connected star-like together and each to one phase between the phase inductors 18 and the AC source 7.

[0039] Fig. 4 shows a further embodiment of the PFC circuit 2, whereby a second high frequency PFC diode 22 and a second high frequency PFC switch 23 are provided. The high frequency PFC diode 8 and the second high frequency PFC diode 22 are connected in series and such wise in parallel to the output of the converter 7. The high frequency PFC switch 9 and the second high frequency PFC switch 23 are also connected in series and such wise in parallel to the output of the converter 7. Besides that said switches 9, 23 and diodes 8, 22 are star-like interconnected. A further high frequency PFC diode 24 is provided for receding losses

[0040] In Fig. 5 another embodiment is depicted, wherein each one high frequency PFC switch 9 is connected in parallel to one of the diodes of the converter 7. Further, the second high frequency PFC switch 23 is connected in parallel to the PFC inductor 10. The Ćuk converter 3 comprises a second high frequency Ćuk switch 24 and a second high frequency Ćuk diode 25. The high frequency Ćuk switch 17 and the high

frequency Ćuk switch 24 are connected in series and such wise parallel to the series connection of the second high frequency Ćuk switch 24 and the second high frequency Ćuk diode 25, which are connected in parallel to the series connection of the Ćuk first inductor 12 and the Ćuk capacitor 13.

[0041] While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive; the invention is not limited to the disclosed embodiments. Other variations to be disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims. In the claims, the word “comprising” does not exclude other elements or steps, and the indefinite article “a” or “an” does not exclude a plurality. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage. Any reference signs in the claims should not be construed as limiting scope.

Reference signs list

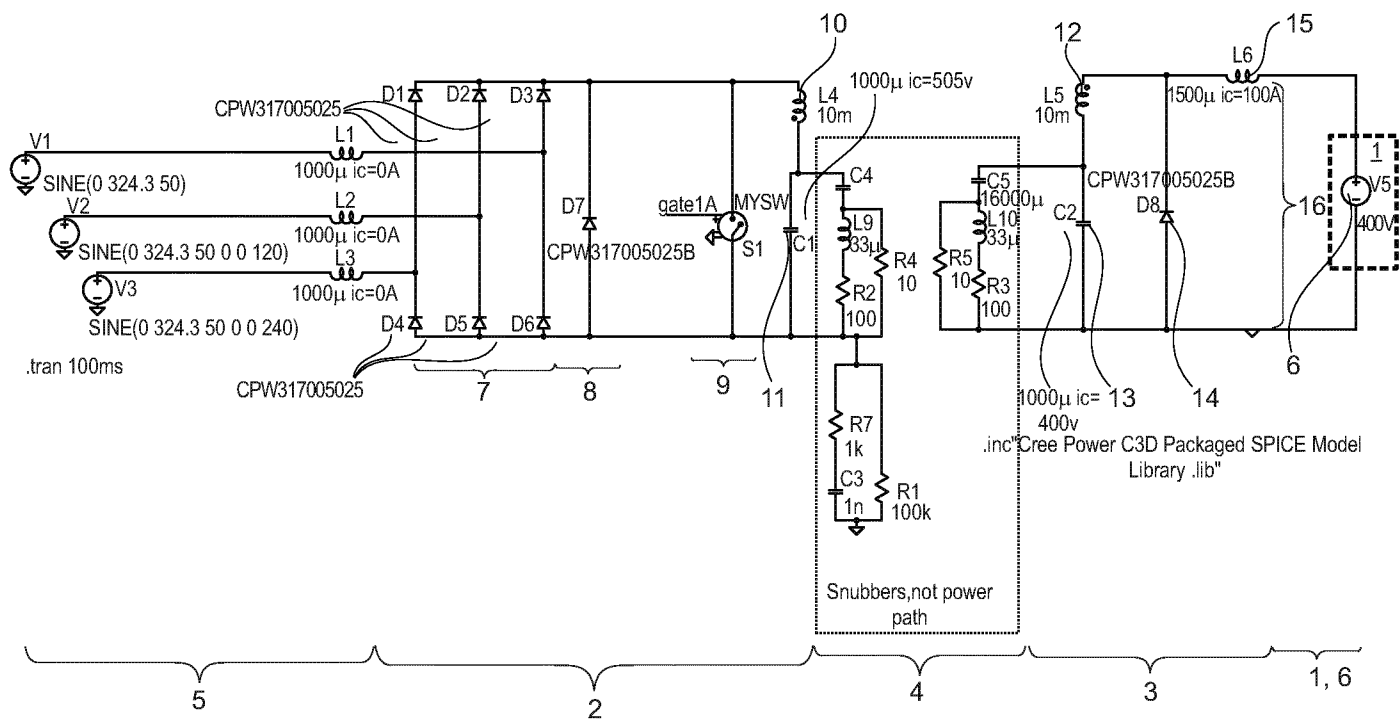
- [0042]
- 1 electrical vehicle
 - 2 PFC circuit
 - 3 Ćuk converter
 - 4 transformer
 - 5 AC source
 - 6 DC load
 - 7 diode-based converter
 - 8 high frequency PFC diode
 - 9 PFC switch
 - 10 PFC inductor
 - 11 PFC capacitor
 - 12 first Ćuk inductor
 - 13 Ćuk capacitor
 - 14 high frequency Ćuk diode
 - 15 second Ćuk inductor
 - 16 Ćuk output
 - 17 high frequency Ćuk switch
 - 18 phase inductor
 - 19 trap conductor
 - 20 trap inductor
 - 21 phase capacitor
 - 22 second high frequency PFC diode
 - 23 second high frequency PFC switch
 - 24 second high frequency Ćuk switch
 - 25 second high frequency Ćuk diode

Claims

1. Three-phase alternating current, AC, to direct current, DC, power converter, comprising
 - a boost power factor correction, PFC, circuit (2) comprising a low frequency diode-based converter (7) configured for connecting a PFC input of the converter (7) to an AC source (5), and a PFC inductor (10) and a PFC capacitor (11) connected in series together and in parallel to a PFC output of the converter (7), further comprising either a high frequency PFC diode (8) and a high frequency PFC switch (9) connected in parallel to the PFC output of the converter (7) or comprising a plurality of high frequency PFC switches (9) each connected in parallel to one of the diodes of the converter (7),
 - a Ćuk converter (3) comprising a first Ćuk inductor (12) and a Ćuk capacitor (13) connected in series, a second Ćuk inductor (15) and a high frequency Ćuk diode (14) connected in parallel to the series connection and forming, via a series connection with the second Ćuk inductor (15), a Ćuk output (16) to which a DC load (6) can be connected, and
 - a transformer (4) having a primary side connected in parallel to the PFC capacitor (11) and a secondary side connected in parallel to the Ćuk capacitor (13).
2. Converter according to the previous claims, whereby the PFC capacitor (11), via the transformer (4), and the Ćuk capacitor (13) are connected to the negative potential of the Ćuk output (16) and the PFC inductor (10) is connected, via the transformer (4), the first Ćuk inductor (12) and the second Ćuk inductor (15), to the positive potential of the Ćuk output (16).
3. Converter according to any of the previous claims, whereby the anode of the high frequency Ćuk diode (14) is connected to the negative potential of the Ćuk output (16).
4. Converter according to any of the previous claims, whereby the second Ćuk inductor (15) is connected to the positive potential of the Ćuk output (16) and in series with the first Ćuk inductor (12).

5. Converter according to any of the previous claims, comprising a high frequency Ćuk switch (17) connected in parallel to the high frequency Ćuk diode (14).
6. Converter according to any of the previous claims, comprising three phase inductors (18) each arranged in a respective current path between the PFC input and the low frequency diode-based converter (7).
7. Converter according to the previous claims, comprising each three trap capacitors (19) and trap inductors (20), the trap capacitors (19) are connected together and in series with each one trap capacitors (20), whereby each one trap capacitor (19) is connected to a respective phase inductor (18) and the low frequency diode-based converter (7).
8. Converter according to any of the two previous claims, comprising three phase capacitors (21) connected to together and to a respective phase of the PFC input.
9. Converter according to any of the previous claims, comprising the high frequency PFC diode (8) and the high frequency PFC switch (9) connected in parallel to the PFC output of the converter (7), further comprising a second high frequency PFC diode (22) and a second high frequency PFC switch (23) connected in parallel, whereby each the PFC diodes (8, 22) the PFC switches (9, 23) are connected in parallel to the PFC output of the converter (7).
10. Converter according to any of the previous claims 1 to 8, comprising the plurality of high frequency PFC switches (9) each connected in parallel to one of the diodes of the converter (7), further comprising a second high frequency PFC switch (23) connected in parallel to the PFC inductor (10).
11. Converter according to any of the previous claims 1 to 8 or 10, comprising the plurality of high frequency PFC switches (9) each connected in parallel to one of the diodes of the converter (7), further comprising a high frequency Ćuk switch (17) connected in parallel to the high frequency Ćuk diode (14), a second high frequency Ćuk switch (24) and a second high frequency Ćuk diode (25) connected

in parallel to the second frequency Ćuk switch (17), whereby each the high frequency Ćuk diodes (14, 25) and the high frequency Ćuk switches (17, 24) are connected in parallel to the series connection of the first Ćuk inductor (12) and the Ćuk capacitor (13).



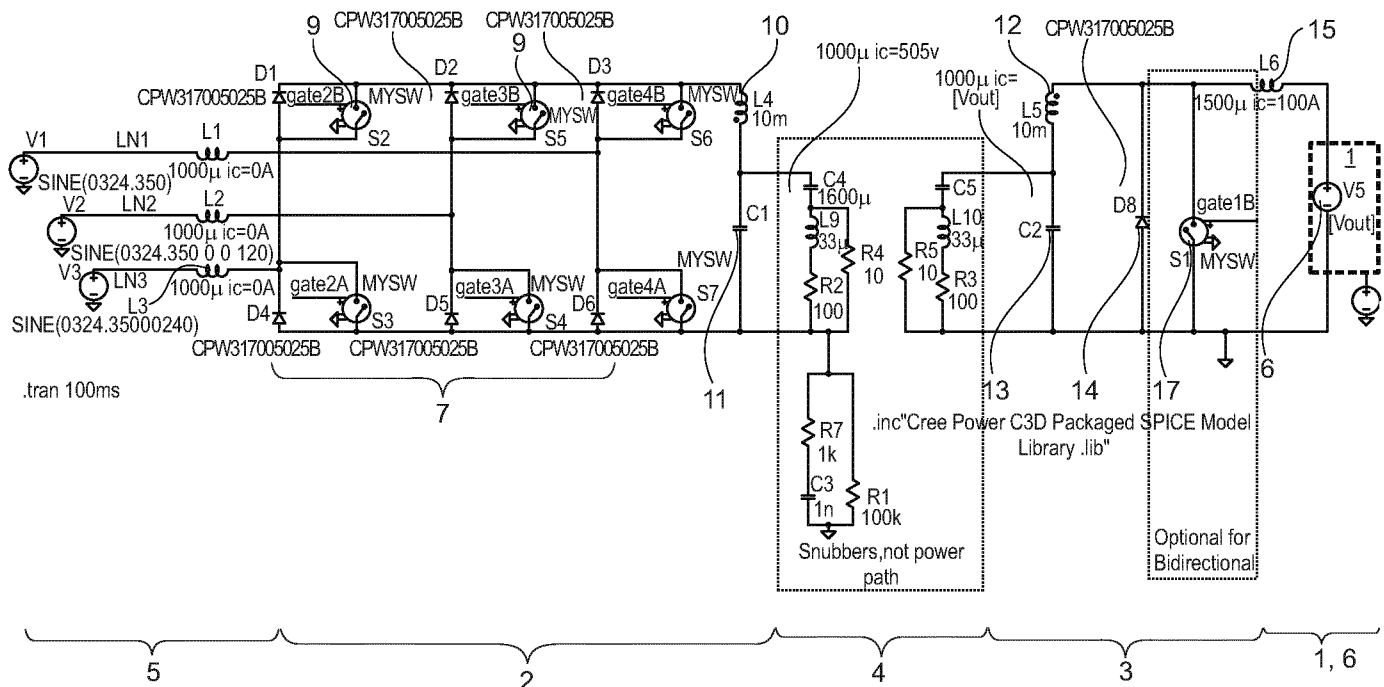


Fig. 2

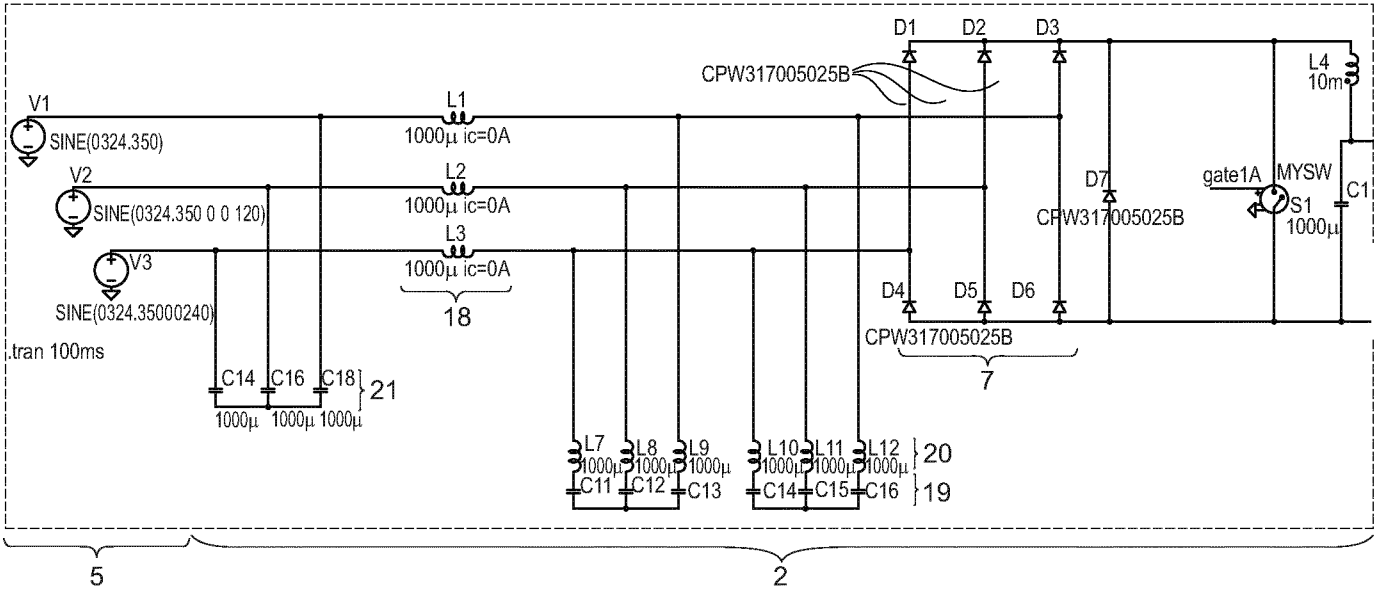


Fig. 3

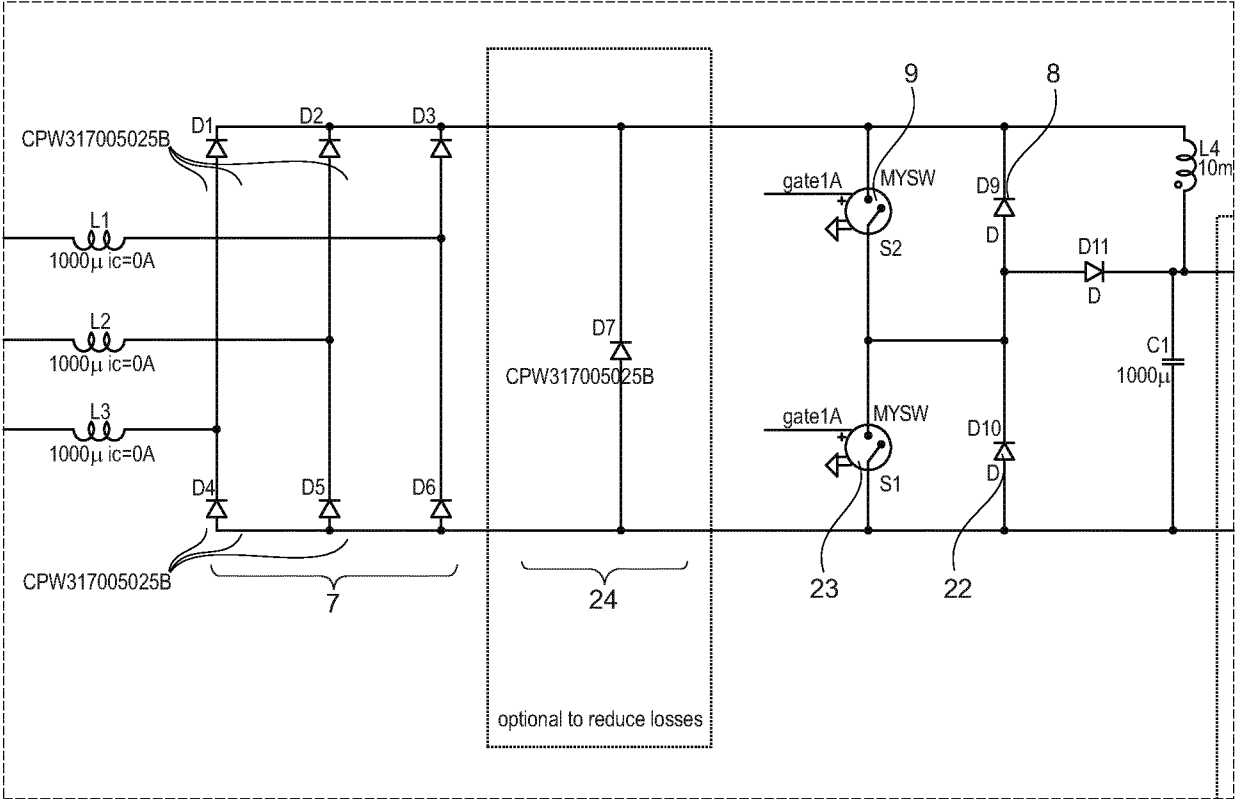


Fig. 4

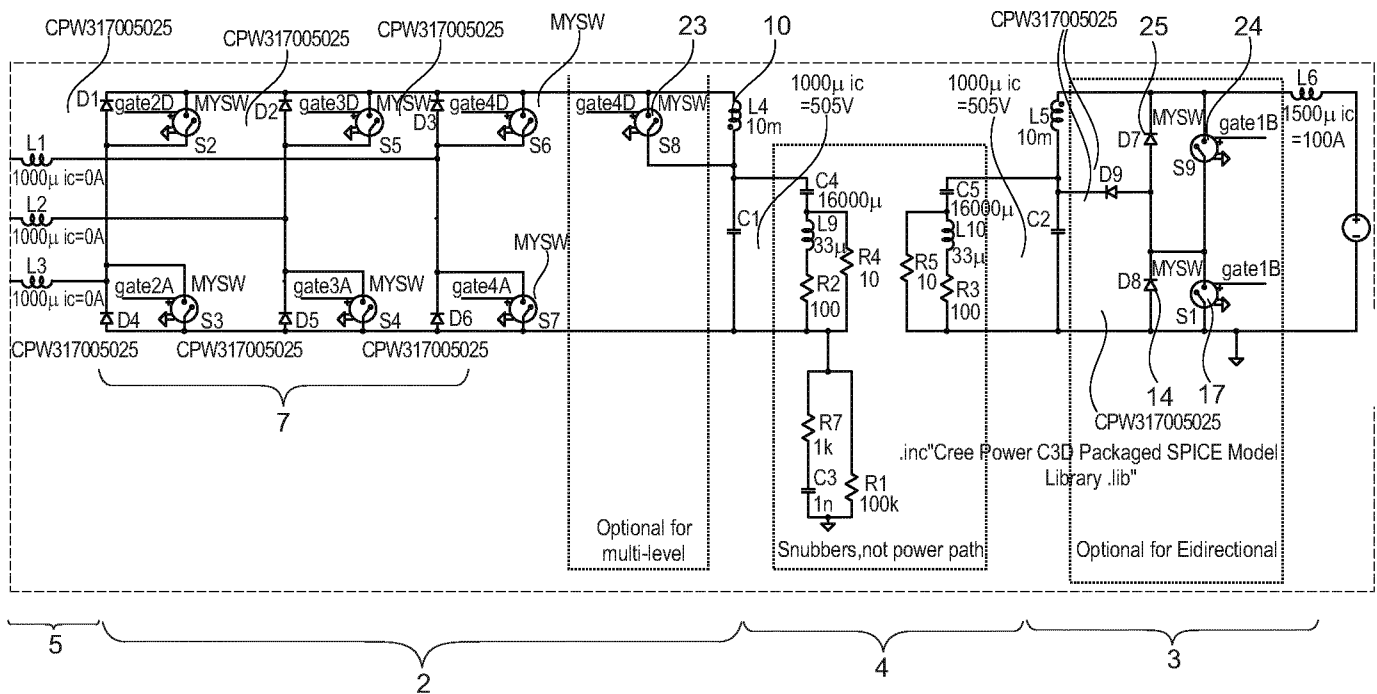


Fig. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2020/057180

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02M1/42 H02M3/00 H02M1/12
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
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.
Y	BHIM SINGH ET AL: "Comprehensive Study of Single-Phase AC-DC Power Factor Corrected Converters With High-Frequency Isolation", IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, IEEE SERVICE CENTER, NEW YORK, NY, US, vol. 7, no. 4, 1 November 2011 (2011-11-01), pages 540-556, XP011362440, ISSN: 1551-3203, DOI: 10.1109/TII.2011.2166798 figure 11 ----- -/-	1-11



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

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

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

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"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

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Date of the actual completion of the international search

3 June 2020

Date of mailing of the international search report

12/06/2020

Name and mailing address of the ISA/

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Fax: (+31-70) 340-3016

Authorized officer

van Wesenbeeck, R

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2020/057180

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JOSE A POMILIO ET AL: "High-Precision Current Source Using Low-Loss, Single-Switch, Three-Phase AC/DC Converter", IEEE TRANSACTIONS ON POWER ELECTRONICS, INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, USA, vol. 11, no. 4, 1 July 1996 (1996-07-01), XP011042987, ISSN: 0885-8993 figures 1, 3 -----	1-11
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