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Dual active bridge dc-dc converter with extended operation range

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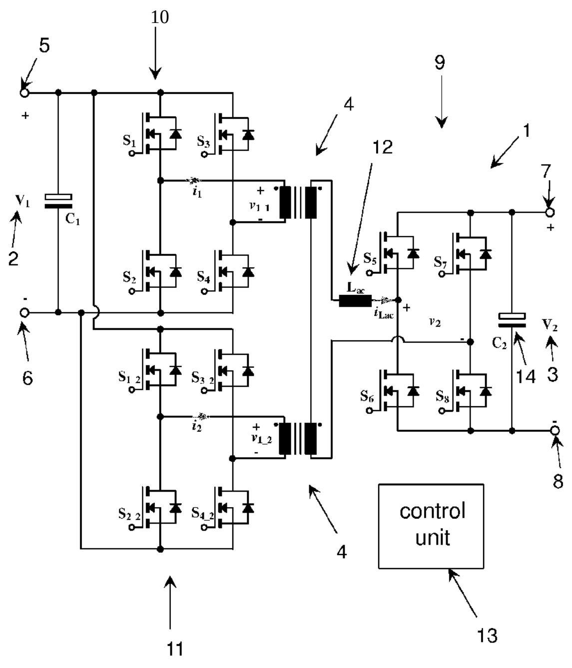

FIG. 1

(57) Abstract: The present disclosure relates to a dual active bridge DC-DC converter comprising a low voltage port; a high voltage port; a set of *n* transformers, each transformer comprising a primary and a secondary winding magnetically coupled to each other; a single active high voltage bridge circuit connected between the high voltage port and the set of *n* transformers, wherein the *n* transformers are arranged to operate in series; *n* low voltage active bridge circuits connected in parallel between the set of *n* transformers and the low voltage port, wherein the *n* transformers are arranged to operate in parallel; a control unit configured to control: a first phase-shift angle between one of the *n* low voltage active bridge circuits and the single active high voltage bridge circuit; and a second phase-shift angle between the *n* low voltage active bridge circuits, thereby extending an operation range of the dual active bridge DC-DC converter; wherein *n* is a positive integer number larger than or equal to 2.

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Dual active bridge DC-DC converter with extended operation range

The present disclosure relates to a dual active bridge DC-DC converter with an extended operation range and to a method for controlling a dual active bridge DC-DC converter to achieve an extended operation range.

Background of invention

Bidirectional DC-DC converters provide the capability of effectively and flexibly regulating reversible DC power flows, making them suitable for use in applications such as renewable energy systems, electrical vehicles and DC microgrids. One bidirectional DC-DC topology which has gained popularity is the dual active bridge (DAB) converter.

The efficiency of DAB converters suffer from large root mean square (RMS) current caused by voltage mismatch between the low voltage side (LVs) and high voltage side (HVs) and phase-shift control introducing reactive power. When voltage amplitudes of the two sides of the transformer of the dual active bridge converter do not match, the difference causes RMS current. A greater mismatch increases the RMS current.

Various techniques for high current applications have been proposed. One method is to use parallel semiconductor devices or converter modular units. However, paralleling switches complicates circuit layout and increases parasitic inductance. Moreover, thicker copper or a parallel structure must be applied to transformer windings resulting in high manufacturing cost and high interwinding capacitance especially for print circuit board (PCB) windings. Paralleling converter modular units also need an additional control scheme to eliminate circulating current between units.

Summary of invention

In the present disclosure a new dual active bridge (DAB) converter is proposed. The problem of large root mean square (RMS) current because of voltage mismatch between the low voltage side (LVs) and high voltage side (HVs) typically become even more severe for high voltage gain high power applications. The proposed DAB converter may therefore be particularly useful for high-power high-voltage-gain applications. The disclosure relates to a partially paralleled DAB configuration, in which AC current balancing between parallel full-bridges is ensured by series connected transformer windings on the high voltage side of the DAB. The present disclosure therefore relates to a partially paralleled dual active bridge converter, wherein a low-voltage (LV) side parallel and high-voltage (HV) side series topology is configured to achieve high voltage gain while reducing current stress over switching devices and transformer windings on the low voltage high current side of the DAB converter. The configuration is based on an idea of connecting the circuit parts which need to carry high current in parallel and connecting the circuit parts which need to block high voltage in series. Moreover, by regulating the phase shift between the paralleled low voltage active bridge circuits on the low voltage side, the DAB converter may extend the operating range of the DAB converter in terms of output power, which is described in further detail below.

A first embodiment of the present invention therefore relates to a dual active bridge DC-DC converter comprising:

- a low voltage port;
- a high voltage port;
- a set of *n* transformers, each transformer comprising a primary and a secondary winding magnetically coupled to each other;
- a single active high voltage bridge circuit connected between the high voltage port and the set of *n* transformers, wherein the *n* transformers are arranged to operate in series;
- *n* low voltage active bridge circuits connected in parallel between the set of n transformers and the low voltage port, wherein the *n* transformers are arranged to operate in parallel;
- a control unit configured to control:
    - o a first phase-shift angle between one of the *n* low voltage active bridge circuits and the single active high voltage bridge circuit; and
    - o a second phase-shift angle between the *n* low voltage active bridge circuits to regulate a generated power and/or output voltage and/or current of the dual active bridge DC-DC converter, thereby extending an operation range of the dual active bridge DC-DC converter;

wherein n is a positive integer number larger than or equal to 2.

Fig. 1 shows an example of such an embodiment. In this embodiment the single active high voltage bridge is a high voltage H-bridge comprising four controllable switches, and the parallel low voltage active bridge circuits are low voltage H-bridges, each low voltage H bridge comprising four controllable switches.

The control unit may control the second shift angle between the parallel low voltage active bridge circuits to modify the power equations of the circuit and thereby extend the operation range of the circuit in terms of power. This means that the control unit may also be operable to adjust the second phase shift angle, and/or use a number of different configurations with different second phase shift angles in order to get a number of different power output curves. By exploiting the different second phase angle configurations, the operation range may be further extended. The presently disclosed dual active bridge DC-DC converter can thus be said to introduce an additional degree of freedom to control output power or voltage.

The first phase shift angle ϕ may be represented as a percentage of the switching period of the dual active bridge DC-DC converter. The second phase-shift angle φ_p may then be a value between 0 and ϕ ($0<\phi_p<\phi$).

The present disclosure further relates to a method for controlling a dual active bridge DC-DC converter having *n* transformers; a single active high voltage bridge circuit, such as a high voltage H-bridge, connected to a high voltage port, and *n* low voltage active bridge circuits, such as low voltage H-bridge circuits, connected in parallel to a low voltage port, the method comprising the steps of:

- applying a first pulse width modulated drive signal to the single active high voltage bridge circuit;
- applying a second pulse width modulated drive signal to a first low voltage active bridge circuit of the *n* active low voltage active bridge circuits, the second pulse width modulated drive signal having a first phase-shift angle in relation to the first pulse width modulated drive signal;
- applying a third pulse width modulated drive signal to a second low voltage active bridge circuit of the *n* low voltage active bridge circuits, the third pulse width modulated drive signal having a second phase-shift angle in relation to the first pulse width modulated drive signal, wherein the second phase-shift angle is less than the first phase-shift angle;

The method may be carried out using any embodiment of the presently disclosed dual active bridge DC-DC converter.

These and other aspects of the invention are set forth in the following detailed description if the invention.

Description of drawings

Fig. 1 shows an example of the presently disclosed dual active bridge DC-DC converter having a single active high voltage bridge circuit and two low voltage active bridge circuits connected in parallel connected to the same low voltage port.

Fig. 2 **and** 3 show different phase shift modulations for the dual active bridge DC-DC converter.

Fig. 4 shows transferred power as a function of ϕ at different ϕ_{ρ}.

Fig. 5 (A and B) show average current as a function of ϕ at different ϕ_{ρ}.

Fig. 6 shows an example of the presently disclosed dual active bridge DC-DC converter having a single active high voltage bridge circuit and more than two low voltage active bridge circuits connected in parallel connected to the same low voltage port

Fig. 7 shows experimental voltage and current waveform comparisons for voltage ($v_{1\_1}+v_{1\_2}$) (Ch1), voltage v_2 (Ch2) and current i_{LAC} (Ch3) with (a) $\phi_P=0$, (b) $0<\varphi_p<\phi$ and (c) $\phi<\phi_p$ for one embodiment of the presently disclosed dual active bridge DC-DC converter.

Fig. 8 shows experimental voltage and current waveform comparisons for voltage v_{i_1} (Ch1), voltage v_{1_2} (Ch2), current i_1 (Ch3) and current i_2 (Ch4) with (a) $\phi_P=0$, (b) $0<\phi_p<\phi$, and (c) φ_p><pfor the implementation of fig. 1.The currents i_1 and i_2 are the same regardless the phase-shift angles.

Detailed description of the invention

The present disclosure relates to a dual active bridge DC-DC converter comprising a low voltage port; a high voltage port; one high voltage bridge circuit; a plurality of parallel low voltage active bridge circuits, wherein a plurality of transformers, arranged to operate in series, connect the high voltage bridge circuit with the plurality of parallel low voltage active bridge circuits. Preferably, the dual active bridge DC-DC converter comprises a control unit for controlling phase-shift angles between the high voltage bridge circuit and the plurality of parallel low voltage active bridge circuits, and phase-shift angles between the parallel low voltage active bridge circuits. By regulating the phase shift between the paralleled low voltage active bridge circuits on the low voltage side, the DAB converter may extend the operating range of the DAB converter in terms of output power. Each transformer may comprise a primary and a secondary winding magnetically coupled to each other by means of for example a transformer core of high magnetic permeability. Preferably, the plurality of transformers are arranged to operate in series, as shown in for example fig. 1, wherein each of the parallel low voltage active bridge circuits are connected to one transformer, and wherein the transformers are connected in series on the high voltage side. Preferably, the control unit is configured to control a first phase-shift angle between one of the *n* low voltage active bridge circuits, for example a selected reference low voltage active bridge circuit, and the single active high voltage bridge circuit. Fig. 2 shows an example of a first phase-shift angle between a first low voltage active bridge circuit (S1 , S2, S3, S4) and the high voltage bridge circuit (S5, S6, S7, S8) based on the topology of fig. 1. In addition to the first phase-shift angle, there is preferably at least one second phase-shift angle internally between the low voltage active bridge circuits. Fig. 2 shows an example of such a second phase-shift angle between two low voltage active bridge circuits, (S1 , S2, S3, S4), (S1_2, S2_2, S3_2, S4_2) respectively. If the first phase-shift angle is not the same as the second phase-shift angle, the operation range of the dual active bridge DC-DC converter can be extended. Preferably, when using the presently disclosed dual active bridge DC-DC converter, the total current between the low voltage port and the n transformers is split between the *n* low voltage active bridge circuits.

The single active high voltage bridge circuit may be a high voltage H-bridge comprising four controllable switches, for example S5, S6, S7, S8. The low voltage active bridge circuits may be low voltage H-bridges, each low voltage H bridge comprising four controllable switches, for example S 1, S2, S3, S4 and S1_2, S2_2, S3_2, S4_ 2 and so forth. Examples of H-bridges are shown in fig. 1. Generally, H-bridge refers to a structure derived from a typical graphical representation of an integrated circuit that enables a voltage to be applied across a load in opposite directions. An H-bridge is typically built with four switches as shown in for example fig. 1. When the switches S 1 and S4 are closed, and S2 and S3 are open, a positive voltage is applied between the node between S1-2 and the node between S3-4. By opening the S 1 and S4 switches and closing the S2 and S3 switches, this voltage is reversed.

The dual active bridge DC-DC converter, in particular the H-bridges of the converter, may operate for example with a switching frequency between 1 kHz and 1 MHz, preferably between 10 kHz and 500 kHz, more preferably between 50 kHz and 200 kHz. The switching frequency in this regard may refer to the switching of the S1-S8, S1_2-S4_2 as illustrated in fig. 3.

The dual active bridge DC-DC converter may be configured to operate on low voltage (Vi) on the low voltage port that is lower than 100V, preferably lower than 50V, more preferable lower than 40V, even more preferably lower than 25V, most preferably lower than 10V. A high voltage (V_2) on the high voltage port may be for example higher than 100V, preferably higher than 150V, more preferable higher than 200V, even more preferably higher than 300V.

Operation and phase-shift angle management

As stated, the partial parallel configuration may split the high-current loops into two smaller loops with half the total input current, thereby reducing conduction and switching losses.

The basic converter operating waveforms under single phase-shift modulation (first phase-shift angle only) are presented in fig. 2. The converter’s steady-state power equation can be derived from:

$$P = \frac{2\mathrm{n}V_1V_2}{f_S L_{AC}}\varphi(1-2\varphi)$$

where the phase shift ϕ is represented as a percentage of the switching period T_s, f_s is the switching frequency and L_{ac} is the sum of the external inductance and the transformer leakage inductance seen from the high-voltage side.

The four controllable switches of each high voltage H-bridge and/or the low voltage H-bridge may form two pairs of switches, wherein the control unit is configured to open and close the two pairs of switches in mutually exclusive configurations, as described. The first phase-shift angle may represent a first shift in time, preferably a predetermined shift in time, between switching of pairs of switches of the high voltage H-bridge and pairs of switches of a first low voltage H-bridge. The first phase-shift angle can be said to determine the shape of the current and voltage on the high voltage side (LAC, VLAC). An example is shown in fig. 2.

In addition to the first phase-shift angle, the present disclosure proposes a second phase-shift angle between the low voltage active bridge circuits. The second phase-shift angle may represent a second shift in time, preferably a predetermined second shift in time, between switching of corresponding pairs of switches a first low voltage H-bridge and a second low voltage H-bridge. An example of such a second phase-shift angle is shown in fig. 3, wherein the phase-shift angle between the first low voltage H-bridge and the second low voltage H-bridge is different than the phase-shift angle between the first low voltage H-bridge and the high voltage H-bridge.

Regulating the phase shift between the two paralleled active bridges gives an additional degree of freedom to control output power or voltage. Fig. 3 shows an example of a switching pattern and the typical AC inductor current and voltage waveforms when the second phase shift ϕ_p is inserted. In one embodiment the second phase-shift angle is less than the first phase-shift angle. This may be represented by 0« p_p« p.

Based on the waveforms in the example of fig. 3, /1, I_2 and I_3 can be calculated accordingly in.

$$I_1 = \frac{(4\varphi - 2\varphi_p - 1)2\mathrm{n}V_1 + V_2)}{4f_S L_{ac}}$$

$$I_2 = \frac{(1 - 2\varphi_p)2\mathrm{n}V_1 + (4\varphi - 1)V_2)}{4f_S L_{ac}}$$

$$I_3 = \frac{(1 - 2\varphi_p)2\mathrm{n}V_1 + (4\varphi - 4\varphi_p - 1)V_2)}{4f_S L_{ac}}$$

By using the mean-value theorem, the power equation for dual active bridge DC-DC converter with ϕ and ϕ_p as the control parameters is expressed can be expressed as:

$$P = \frac{2\mathrm{n}V_1V_2}{f_S L_{ac}}\varphi(1 - 2\varphi + 2\varphi_p - \frac{\varphi_p}{2\varphi} - \frac{\varphi_p^2}{\varphi} \qquad (0<\varphi_p \leq \varphi)$$

In comparison with the single phase-shift modulation it has an additional term

$$2\varphi_p - \frac{\varphi_p}{2\varphi} - \frac{\varphi_p^2}{\varphi}$$

Similarly, the power equation for $\phi < \phi_\rho < 0.25$ is can be expressed as:

$$\boldsymbol{p} = \tfrac{3}{4}\ \frac{V_2}{\iota c}(\varphi - ?\ )(\frac{1}{2} - \varphi_p) \qquad (0 < \varphi_\rho \leq 0.25)$$

Therefore, in one embodiment of the presently disclosed dual active bridge DC-DC converter, the generated power of the converter is expressed as:

$$P = \frac{2nV_1V_2}{f_S L_{ac}}\varphi(1 - 2\varphi + 2\varphi_p - \frac{\varphi_p}{2\varphi} - \frac{\varphi_p^2}{\varphi}$$

wherein Vi is the input voltage, V_2 is the output voltage, f_s is the switching frequency, L_{AC} is the sum of external inductance, ϕ is the first phase-shift angle, and ϕ_p is the second phase-shift angle.

Examples of the power as a function of ϕ and ϕ_p are shown and compared against single phase-shift modulation *($\phi = \phi_p$)* in fig. 4. In one embodiment of the presently disclosed dual active bridge DC-DC converter, the control unit is configured to control the second phase-shift angle dynamically to regulate a generated power of the dual active bridge DC-DC converter to optimize the transferred power. Moreover, the control of the second phase-shift may be based on a relation between an input voltage on the low voltage port and an output voltage on the output voltage port. The control unit may be configured to control the second phase-shift angle to regulate an output voltage and/or power and/or current, such as a steady-state power, of the dual active bridge DC-DC converter.

By regulating the second phase-shift angle (ϕ_p) an unequal power distribution, and/or an unequal current distribution between the parallel low voltage active bridge circuits can be achieved. When $0<\phi_p<\phi$, the average input currents $I_{in_{1-avg}}$ and I_{in2_avg} in the parallel low voltage active bridge circuits can be calculated as follows:

$$I_{in1\_avg} = \frac{n^2 V_1}{f_S L_{ac}} [2m\varphi(1-2\varphi) + \varphi_p(2\varphi_p - 1)]$$

$$I_{in2\_avg} = \frac{n^2 V_1}{f_S L_{ac}} [2m(\varphi - \varphi_p)(1 - 2\varphi + 2\varphi_p) + \varphi_p(1 - 2\varphi_p)]$$

where

$$m = \frac{V_2}{2nV_1}$$

It follows that the current distribution between the two paralleled bridges depends on the phase-shift angles ϕ and $ϕ_ρ$ and *m*. Fig. 5 shows the ratios of the average currents $li_{n\text{-}\backslash\text{-}avg}$ and $I_{in2\text{-}avg}$ against $n^2\text{-}V\text{^}f_S/L_{ac}$ as a function of ϕ. The dashed line and solid line represent $I_{n\text{i - a}vg}$ and I_{in2_avg} respectively. Fig. 5A shows the average current as a function of ϕ at different $ϕ_{ρ.}$ when $m = 1$ and 5B shows the same when $m \neq 1$.

Despite the possible unequal distribution of current, the series winding connection of the transformers may constrain the RMS currents to be equal in all the semiconductor switches on the low voltage side.

$$Isi\sim S4\_rms = \text{^}SI\_2\sim S4\_2\_rms$$

Topology details

Fig. 1 shows an example of the presently disclosed dual active bridge DC-DC converter having a single active high voltage bridge circuit and two low voltage active bridge circuits connected in parallel connected to the same low voltage port.

Preferably the plurality of low voltage active bridge circuits is connected to the same low voltage port. The active high voltage bridge circuit may comprise four controllable semiconductor switches (S5, S6, S7, and S8) in an H-bridge configuration, wherein a first output of the plurality transformers is connected to a node between S5 and S6, and wherein a second output of the plurality of transformers is connected to a node between S7 and S8. An inductor may be placed between the first output of the plurality transformers and the node between S5 and S6. The outputs of S5 and S7 of the high voltage H-bridge are preferably connected to a first high voltage terminal of the high voltage port. Similarly, the outputs of S6 and S8 may be connected to a second high voltage terminal of the high voltage port.

On the low voltage side, the first low voltage H-bridge may comprise four controllable semiconductor switches S1, S2, S3, and S4 in an H-bridge configuration. In this configuration a node between S1 and S2 may be connected to one side of the primary winding (i.e. the low voltage side of the transformer) of a first transformer. A node between S3 and S4 may be connected to another side of the primary winding of the first transformer. The inputs of S1 and S3 may be connected to a first low voltage terminal of the low voltage port, and the inputs of S2 and S4 connected to a second low voltage terminal of the low voltage port. This configuration results in that the first transformer is connected to the low voltage port through the first low voltage active bridge circuits.

In one embodiment of the presently disclosed dual active bridge DC-DC converter, the second low voltage active bridge circuit is a second low voltage H-bridge which comprises four controllable semiconductor switches S1_2, S2_2, S3_2, and S4_4 in an H-bridge configuration. A node between S1_2 and S2_2 may be connected to one side of the primary winding (i.e. the low voltage side of the transformer) of a second transformer, and a node between S3_2 and S4_2 to connected to the other side of the primary winding of the second transformer. The inputs of S1_2 and S3_2 may be connected to a first low voltage terminal of the low voltage port, and the inputs of S2_2 and S4_2 connected to a second low voltage terminal of the low voltage port. This configuration results in that the second transformer is connected to the low voltage port through the second low voltage active bridge circuits.

The first and second low voltage active bridge circuits may thereby be seen as parallel, whereas the secondary windings of the transformers are serially connected, wherein the ends of the chain formed by the secondary windings are connected to the connection nodes of the high voltage active bridge circuits.

The presently disclosed concept of a partially paralleled dual active bridge converter can be extended to a higher number of parallel transformers and low voltage active bridge circuits. In one embodiment the dual active bridge DC-DC converter therefore comprises:

- a set of *n* transformers, each transformer comprising a primary and a secondary winding magnetically coupled to each other;

- a single active high voltage bridge circuit connected between the high voltage port and the set of *n* transformers, wherein the *n* transformers are arranged to operate in series;
- *n* low voltage active bridge circuits connected in parallel between the set of n transformers and the low voltage port, wherein the *n* transformers are arranged to operate in parallel;

wherein n is a positive integer number larger than or equal to 3, or larger than 4, or larger than 5. The controllable number of shift angles between the first low voltage active bridge circuits and the second/third/fourth (etc.) low voltage active bridge circuits may therefore be n-1. The extended number of parallel low voltage active bridge circuits is shown in fig. 6.

Method for controlling a dual active bridge DC-DC converter

The present disclosure further relates to a method for controlling a dual active bridge DC-DC converter. The dual active bridge DC-DC converter may be any embodiment of the presently disclosed dual active bridge DC-DC converter. Preferably the DAB DC converter has *n* transformers; a single active high voltage bridge circuit, such as a high voltage H-bridge, connected to a high voltage port, and *n* low voltage active bridge circuits, such as low voltage H-bridge circuits, connected in parallel to a low voltage port.

In a first embodiment the method for controlling a dual active bridge DC-DC converter comprises the steps of:

- applying a first pulse width modulated drive signal to the single active high voltage bridge circuit;
- applying a second pulse width modulated drive signal to a first low voltage active bridge circuit of the *n* low voltage active bridge circuits, the second pulse width modulated drive signal having a first phase-shift angle in relation to the first pulse width modulated drive signal;
- applying a third pulse width modulated drive signal to a second low voltage active bridge circuit of the *n* low voltage active bridge circuits, the third pulse width modulated drive signal having a second phase-shift angle in relation to the first pulse width modulated drive signal, wherein the second phase-shift angle is less than the first phase-shift angle.

The first phase shift angle may be represented by ϕ as a percentage of the switching period T_s. The second phase-shift angle may be represented by φ_{p}. The first phase shift angle and the second phase-shift angle may have the relationship $(0<\phi_{\rho}\leq \phi)$. As can be seen from for example fig. 3, the inventors have realized that a partially parallel implementation combined with individual control of the parallel low voltage active bridge circuits can be used to shape and balance power and/or current differently, which may be particularly useful and high voltage and/or high power applications. The opearting range of the dual active bridge DC-DC converter may be extended by applying different second phase angles. The second phase angle may be controlled dynamically.

In one embodiment the second phase-shift angle is chosen for distributing power over the *n* low voltage active bridge circuits, optionally for distributing the power unequally over the *n* low voltage active bridge circuits. One way of selecting the second phase shift angle is based on an input and output voltage relation of the dual active bridge DC-DC converter. This may also involve the step of adapting the combined effect of the first phase-shift angle and the second phase-shift angle to regulate a load power of the dual active bridge DC-DC converter.

As described above, the single active high voltage bridge circuit may comprise a high voltage H-bridge and each low voltage active bridge circuit may comprise a low voltage H-bridge circuit. The four controllable switches of each high voltage H-bridge and/or the low voltage H-bridge may form two pairs of switches. The first and second pulse width modulated drive signals may therefore, accordingly, be switching signals for the pairs of switches of H-bridge circuits.

Detailed description of drawings

The invention will in the following be described in greater detail with reference to the accompanying drawings. The drawings are exemplary and are intended to illustrate some of the features of the presently disclosed dual active bridge DC-DC converter and method for controlling a dual active bridge DC-DC converter, and are not to be construed as limiting to the presently disclosed invention.

Fig. 1 shows an example of the presently disclosed dual active bridge DC-DC converter (1) having a single active high voltage bridge circuit (9) and two low voltage active bridge circuits (10, 11) connected in parallel connected to the same low voltage port Vi (2) having a positive terminal (+) (5) and a negative terminal (-) (6). The single active high voltage bridge circuit (9) is connected to a high voltage port V_2 (3) having a positive terminal (+) (7) and a negative terminal (-) (8). In this example there are two parallel low voltage active bridge circuits (10, 11) and two transformers (4). A control unit (13) controls the phase angles between the low voltage and high voltage side and between the two low voltage active bridge circuits (10, 11). The low voltage port Vi (2) has a capacitor Ci (2) and the high voltage port V_2 (3) has a capacitor C_2 (3). In the example of fig. 1, the high voltage bridge circuits (9, 10, 11) are implemented as H-bridges, each H-bridge having four controllable switches, (S1 , S2, S3, S4), (S1_2, S2_2, S3_2, S4_2) respectively.

Fig. 3 shows an example of a configuration, wherein a first phase-shift angle has been introduced between one of the low voltage active bridge circuits and the high voltage active bridge circuit (ϕ, shift between S1/S4 and S5/S8, then between S2/S3 and S6/S7 etc.). In addition to the first phase-shift angle ϕ there is a second phase-shift angle ϕ_ρ between the low voltage active bridge circuits (ϕ_ρ, shift between S1/S4 and S1_2/S4_2, then between S2/S3 and S2_2/S2_4 etc.). The additional phase-shift has, as can be seen in the figure, an impact on the current (/LAC) and voltage (VLAC) of the dual active bridge DC-DC converter.

Fig. 6 shows an example of the presently disclosed dual active bridge DC-DC converter having a single active high voltage bridge circuit (9) and more than two low voltage active bridge circuits (10, 11A, 11B) connected in parallel connected to the same low voltage port. The *n* transformers are connected in series. The extension of the concept into further parallel low voltage active bridge circuits allows for combinations of addition internal phase-shift angles between the low voltage active bridge circuits. In the example of fig. 6 two such phase-shift angles ($\phi_\rho\iota$ and $\phi_{\rho\eta}$-ι) are shown.

Fig. 7-8 show experimental voltage and current waveform comparisons for voltage (vi_i+vi_$_2$) (Ch1), voltage v_2 (Ch2) and current /LAC (Ch3) with (a) $\phi_P=0$, (b) $0<\varphi_p<\phi$ and (c) $\phi<\phi_\rho$ for one embodiment of the presently disclosed dual active bridge DC-DC converter. In fig. 7 (a) <p=0.034 and $\phi_P=0$, (b) <p=0.08 and $\varphi_p=0.06$, and (c) <p=0.04 and $\varphi_p=0.05$. When $\phi_\rho\neq0$, the voltage across the series connected high-voltage windings, i.e. n-(vi_i+vi$_{_2}$) becomes a three-level waveform consisting of ±2nVi and 0, which changes the current waveforms accordingly. Fig. 8 illustrates the effect of ϕ_ρ on the low

voltage side. Fig. 8 shows experimental voltage and current waveform comparisons for voltage v-M (Ch1), voltage v-i_2 (Ch2), current i_1 (Ch3) and current i_2 (Ch4) with (a) φ_p=0, (b) $0<\phi_\rho<\phi$, and (c) $\varphi_p>\varphi$ for the implementation of fig. I .The currents i_1 and i_2 are the same regardless the phase-shift angles. Moreover, as can be seen, L_{ac} causes the AC current to lag behind the AC voltage, which introduces reactive power and leads to extra conduction losses. The larger the phase shift, the higher the loss. However, in this scenario, regulating ϕ_ρ is able to delay the AC voltage v-M , so that the effective phase-shift angle between v-M and i_1 is reduced, as highlighted in Fig. 8 (b) and (c) with the dashed lines, and the reactive power decreases. This also explains why the input currents i_{in1} and i_{in2} have different average values.

Further details of the invention

1. A dual active bridge DC-DC converter comprising:
   - a low voltage port;
   - a high voltage port;
   - a set of *n* transformers, each transformer comprising a primary and a secondary winding magnetically coupled to each other;
   - a single active high voltage bridge circuit connected between the high voltage port and the set of *n* transformers, wherein the *n* transformers are arranged to operate in series;
   - *n* active low voltage active bridge circuits connected in parallel between the set of n transformers and the low voltage port, wherein the *n* transformers are arranged to operate in parallel;
   - a control unit configured to control:
     - a first phase-shift angle between one of the *n* active low voltage active bridge circuits and the single active high voltage bridge circuit; and
     - a second phase-shift angle between the *n* active low voltage active bridge circuits, thereby extending an operation range of the dual active bridge DC-DC converter;

   wherein n is a positive integer number larger than or equal to 2.

2. The dual active bridge DC-DC converter according to any of the preceding items, wherein the single active high voltage bridge circuit is a high voltage H-bridge comprising four controllable switches, and wherein the *n* active low

voltage active bridge circuits are low voltage H-bridges, each low voltage H bridge comprising four controllable switches.

3. The dual active bridge DC-DC converter according to item 2, wherein the four controllable switches of each high voltage H-bridge and/or the low voltage H-bridge form two pairs of switches, and wherein the control unit is configured to open and close the two pairs of switches in mutually exclusive configurations.

4. The dual active bridge DC-DC converter according to item 3, wherein the first phase-shift angle represents a first predetermined shift in time between switching of pairs of switches of the high voltage H-bridge and pairs of switches of a first low voltage H-bridge.

5. The dual active bridge DC-DC converter according to any of the preceding items, wherein the second phase-shift angle represents a second predetermined shift in time between switching of corresponding pairs of switches a first low voltage H-bridge and a second low voltage H-bridge.

6. The dual active bridge DC-DC converter according to any of items 2-5, wherein the H-bridges are switched with a switching frequency between 1 kHz and 1 MHz, preferably between 10 kHz and 500 kHz, more preferably between 50 kHz and 200 kHz.

7. The dual active bridge DC-DC converter according to any of the preceding items, wherein the second phase-shift angle is less than the first phase-shift angle.

8. The dual active bridge DC-DC converter according to any of the preceding items, wherein the control unit is configured to control the second phase-shift based on a relation between an input voltage on the low voltage port and an output voltage on the output voltage port.

9. The dual active bridge DC-DC converter according to any of the preceding items, said converter being adapted to operate on a low voltage on the low voltage port, said low voltage lower than 100V, preferably lower than 50V, more

preferable lower than 40V, even more preferably lower than 25V, most preferably lower than 10V.

10. The dual active bridge DC-DC converter according to any of the preceding items, said converter being adapted to operate on a high voltage on the high voltage port, said high voltage higher than 100V, preferably higher than 150V, more preferable higher than 200V, even more preferably higher than 300V.

11. The dual active bridge DC-DC converter according to any of the preceding items, wherein the control unit is configured to control the second phase-shift angle dynamically to regulate a generated power of the dual active bridge DC-DC converter.

12. The dual active bridge DC-DC converter according to item 11, wherein the generated power of the converter is expressed as

$$P = \frac{2nV_1V_2}{f_s L_{ac}} \varphi \left(1 - 2\varphi + 2\varphi_p - \frac{\varphi_p}{2\varphi} - \frac{\varphi_p{}^2}{\varphi} \right)$$

, wherein Vi is the input voltage, V_2 is the output voltage, f_s is the switching frequency, LAC is the sum of external inductance, ϕ is the first phase-shift angle, and ϕ_p is the second phase-shift angle.

13. The dual active bridge DC-DC converter according to any of the preceding items, wherein the control unit is configured to control the second phase-shift angle to regulate an output voltage and/or power, such as a steady-state power, of the dual active bridge DC-DC converter.

14. The dual active bridge DC-DC converter according to any of the preceding items, wherein the *n* active low voltage active bridge circuits are connected to the same low voltage port.

15. The dual active bridge DC-DC converter according to any of the preceding items, wherein the active high voltage bridge circuit comprises four controllable semiconductor switches S5, S6, S7, and S8 in an H-bridge configuration, wherein a first output of the *n* transformers is connected to a node between S5

and S6, and wherein a second output of the *n* transformers is connected to a node between S7 and S8.

16. The dual active bridge DC-DC converter according to item 15, wherein outputs of S5 and S7 are connected to a first high voltage terminal of the high voltage port, and wherein outputs of S6 and S8 are connected to a second high voltage terminal of the high voltage port.

17. The dual active bridge DC-DC converter according to any of the preceding items, wherein a first low voltage H-bridge comprises four controllable semiconductor switches S1, S2, S3, and S4 in an H-bridge configuration, wherein a node between S1 and S2 is connected to one side of the primary winding of a first transformer, and a node between S3 and S4 is connected to another side of the primary winding of the first transformer.

18. The dual active bridge DC-DC converter according to item 17, wherein inputs of S1 and S3 are connected to a first low voltage terminal of the low voltage port, and wherein inputs of S2 and S4 are connected to a second low voltage terminal of the low voltage port.

19. The dual active bridge DC-DC converter according to any of the preceding items, wherein a second low voltage H-bridge comprises four controllable semiconductor switches S1_2, S2_2, S3_2, and S4_4 in an H-bridge configuration, wherein a node between S1_2 and S2_2 is connected to one side of the primary winding of a second transformer, and a node between S3_2 and S4_2 is connected to another side of the primary winding of the second transformer.

20. The dual active bridge DC-DC converter according to item 19, wherein inputs of S1_2 and S3_2 are connected to the first low voltage terminal of the low voltage port, and wherein inputs of S2_2 and S4_2 are connected to the second low voltage terminal of the low voltage port.

21. The dual active bridge DC-DC converter according to any of the preceding items, wherein a total current between the low voltage port and the n transformers is split between the *n* active low voltage active bridge circuits.

22. A method for controlling a dual active bridge DC-DC converter having *n* transformers; a single active high voltage bridge circuit, such as a high voltage H-bridge, connected to a high voltage port, and *n* active low voltage active bridge circuits, such as low voltage H-bridge circuits, connected in parallel to a low voltage port, the method comprising the steps of:
   - applying a first pulse width modulated drive signal to the single active high voltage bridge circuit;
   - applying a second pulse width modulated drive signal to a first active low voltage active bridge circuit of the *n* active low voltage active bridge circuits, the second pulse width modulated drive signal having a first phase-shift angle in relation to the first pulse width modulated drive signal;
   - applying a third pulse width modulated drive signal to a second active low voltage active bridge circuit of the *n* active low voltage active bridge circuits, the third pulse width modulated drive signal having a second phase-shift angle in relation to the first pulse width modulated drive signal, wherein the second phase-shift angle is less than the first phase-shift angle.

23. The method for controlling a dual active bridge DC-DC converter according to item 22, wherein the second phase-shift angle is chosen for distributing power over the *n* active low voltage active bridge circuits, optionally distributing the power unequally over the *n* active low voltage active bridge circuits.

24. The method for controlling a dual active bridge DC-DC converter according to any of items 22-23, wherein the second phase-shift angle is chosen based on an input and output voltage relation of the dual active bridge DC-DC converter.

25. The method for controlling a dual active bridge DC-DC converter according to any of items 22-24, further comprising the step of adjusting the first phase-shift angle and the second phase-shift angle to regulate a load power of the dual active bridge DC-DC converter.

26. The method for controlling a dual active bridge DC-DC converter according to any of items 22-25, wherein the first and second pulse width modulated drive signals are switching signals for pairs of switches of H-bridge circuits.

27. The method for controlling a dual active bridge DC-DC converter according to any of items 22-26, wherein the dual active bridge DC-DC converter is the converter of any of items 1-21 .

28. The method for controlling a dual active bridge DC-DC converter according to any of items 22-27, further comprising the step of providing the dual active bridge DC-DC converter of any of items 1-21 .

Claims

1. A dual active bridge DC-DC converter comprising:
   - a low voltage port;
   - a high voltage port;
   - a set of *n* transformers, each transformer comprising a primary and a secondary winding magnetically coupled to each other;
   - a single active high voltage bridge circuit connected between the high voltage port and the set of *n* transformers, wherein the *n* transformers are arranged to operate in series;
   - *n* low voltage active bridge circuits connected in parallel between the set of n transformers and the low voltage port, wherein the *n* transformers are arranged to operate in parallel;
   - a control unit configured to control:
     - a first phase-shift angle between one of the *n* low voltage active bridge circuits and the single active high voltage bridge circuit; and
     - a second phase-shift angle between the *n* low voltage active bridge circuits to regulate a generated power and/or output voltage and/or current of the dual active bridge DC-DC converter, thereby extending an operation range of the dual active bridge DC-DC converter;

   wherein n is a positive integer number larger than or equal to 2.

2. The dual active bridge DC-DC converter according to any of the preceding claims, wherein the single active high voltage bridge circuit is a high voltage H-bridge comprising four controllable switches, and wherein the *n* low voltage active bridge circuits are low voltage H-bridges, each low voltage H bridge comprising four controllable switches.

3. The dual active bridge DC-DC converter according to claim 2, wherein the four controllable switches of each high voltage H-bridge and/or the low voltage H-bridge form two pairs of switches, and wherein the control unit is configured to open and close the two pairs of switches in mutually exclusive configurations.

4. The dual active bridge DC-DC converter according to claim 3, wherein the first phase-shift angle represents a first predetermined shift in time between switching of pairs of switches of the high voltage H-bridge and pairs of switches of a first low voltage H-bridge and the second phase-shift angle represents a second predetermined shift in time between switching of corresponding pairs of switches a first low voltage H-bridge and a second low voltage H-bridge.

5. The dual active bridge DC-DC converter according to any of claims 2-4, wherein the H-bridges are switched with a switching frequency between 1 kHz and 1 MHz, preferably between 10 kHz and 500 kHz, more preferably between 50 kHz and 200 kHz.

6. The dual active bridge DC-DC converter according to any of the preceding claims, wherein the second phase-shift angle is less than the first phase-shift angle.

7. The dual active bridge DC-DC converter according to any of the preceding claims, said converter being adapted to operate on a low voltage on the low voltage port, said low voltage lower than 100V, preferably lower than 50V, more preferable lower than 40V, even more preferably lower than 25V, most preferably lower than 10V.

8. The dual active bridge DC-DC converter according to any of the preceding claims, said converter being adapted to operate on a high voltage on the high voltage port, said high voltage higher than 100V, preferably higher than 150V, more preferable higher than 200V, even more preferably higher than 300V.

9. The dual active bridge DC-DC converter according to any of the preceding claims, wherein the *n* low voltage active bridge circuits are connected to the same low voltage port.

10. The dual active bridge DC-DC converter according to any of the preceding claims, wherein the active high voltage bridge circuit comprises four controllable semiconductor switches S5, S6, S7, and S8 in an H-bridge configuration, wherein a first output of the *n* transformers is connected to a node between S5 and S6, and wherein a second output of the *n* transformers is connected to a

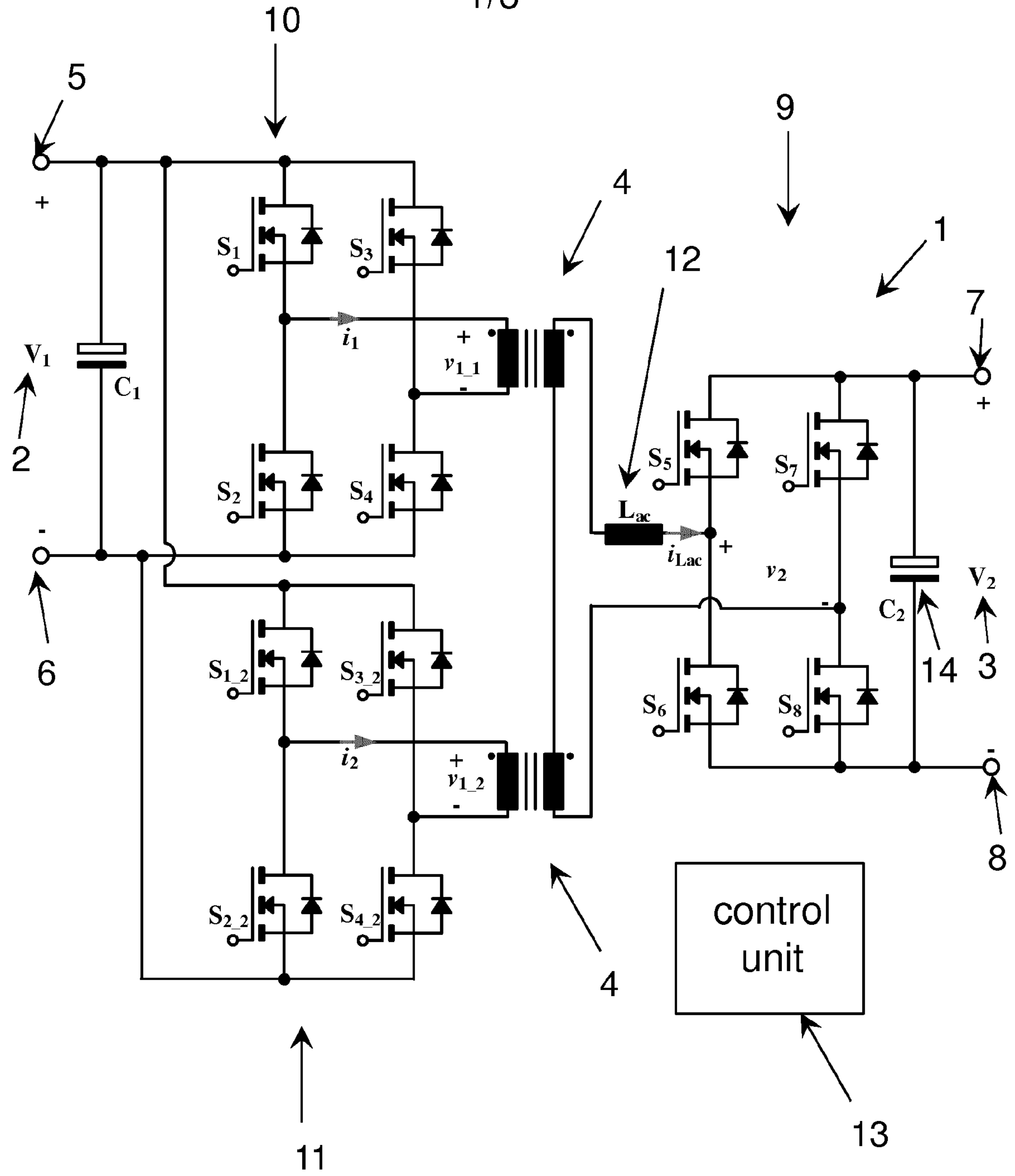
node between S7 and S8, and wherein a first low voltage H-bridge comprises four controllable semiconductor switches S1, S2, S3, and S4 in an H-bridge configuration, wherein a node between S1 and S2 is connected to one side of the primary winding of a first transformer, and a node between S3 and S4 is connected to another side of the primary winding of the first transformer, and wherein a second low voltage H-bridge comprises four controllable semiconductor switches S1_2, S2_2, S3_2, and S4_4 in an H-bridge configuration, wherein a node between S1_2 and S2_2 is connected to one side of the primary winding of a second transformer, and a node between S3_2 and S4_2 is connected to another side of the primary winding of the second transformer.

11. The dual active bridge DC-DC converter according to any of the preceding claims, wherein a total current between the low voltage port and the n transformers is split between the *n* low voltage active bridge circuits.

12. A method for controlling a dual active bridge DC-DC converter having *n* transformers; a single active high voltage bridge circuit, such as a high voltage H-bridge, connected to a high voltage port, and *n* low voltage active bridge circuits, such as low voltage H-bridge circuits, connected in parallel to a low voltage port, the method comprising the steps of:

- applying a first pulse width modulated drive signal to the single active high voltage bridge circuit;
- applying a second pulse width modulated drive signal to a first low voltage active bridge circuit of the *n* low voltage active bridge circuits, the second pulse width modulated drive signal having a first phase-shift angle in relation to the first pulse width modulated drive signal;
- applying a third pulse width modulated drive signal to a second low voltage active bridge circuit of the *n* low voltage active bridge circuits, the third pulse width modulated drive signal having a second phase-shift angle in relation to the first pulse width modulated drive signal, wherein the second phase-shift angle is less than the first phase-shift angle.

13. The method for controlling a dual active bridge DC-DC converter according to claim 12, wherein the dual active bridge DC-DC converter is the converter of any of claims 1-1 1.


10
5
9
4
12
1
7
+
S_1
S_3
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V_1
C_1
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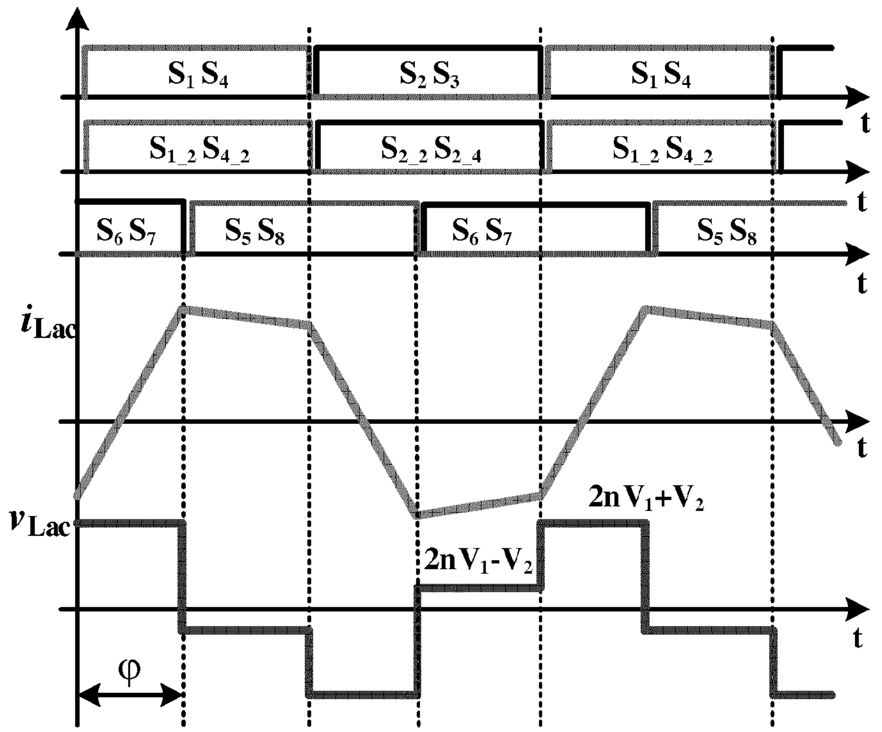
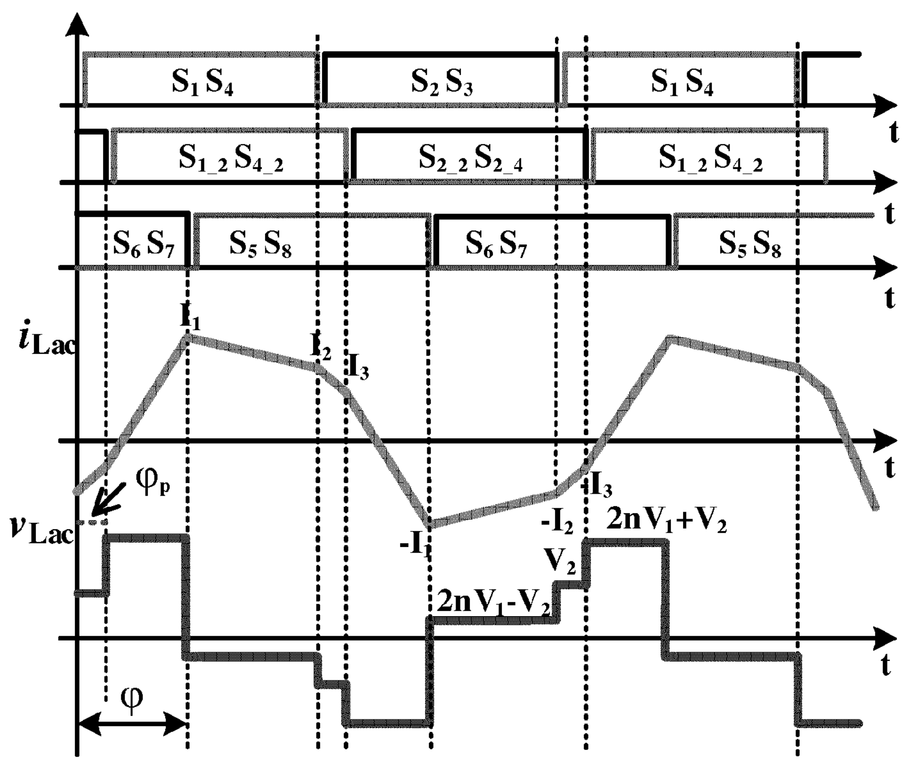
S_4
S_5
S_7
L_{ac}
i_{Lac}
v_2
-
6
S_{1_2}
S_{3_2}
C_2
V_2
14
3
S_6
S_8
i_2
v_{1_2}
8
S_{2_2}
S_{4_2}
4
control unit
13
11

FIG. 1



S1 S4
S2 S3
S1 S4
t
S1_2 S4_2
S2_2 S2_4
S1_2 S4_2
t
S6 S7
S5 S8
S6 S7
S5 S8
t
iLac
t
vLac
2nV1+V2
2nV1-V2
t
φ

FIG. 2



S1 S4
S2 S3
S1 S4
t
S1_2 S4_2
S2_2 S2_4
S1_2 S4_2
t
S6 S7
S5 S8
S6 S7
S5 S8
t
I1
iLac
I2
I3
t
φp
I3
vLac
-I2
2nV1+V2
-I1
V2
2nV1-V2
t
φ

FIG. 3

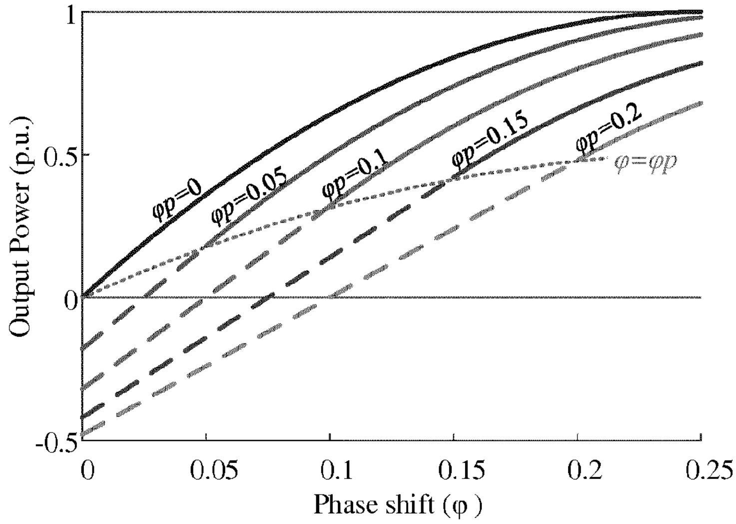


FIG. 4

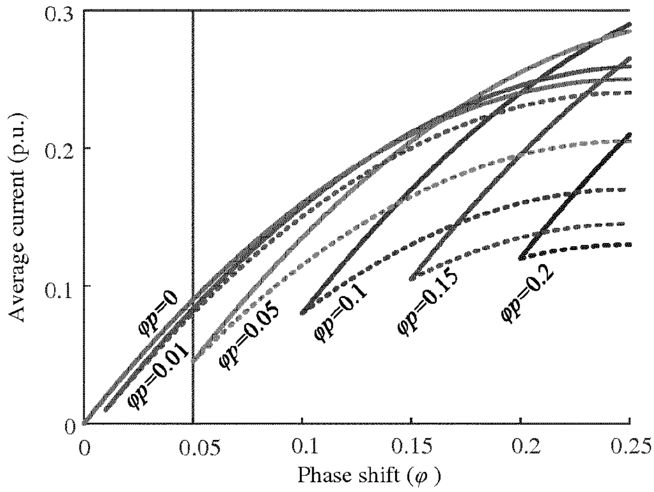


FIG. 5A

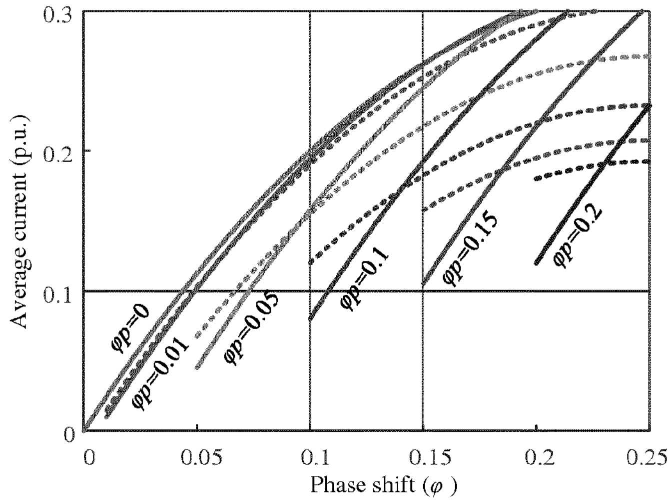
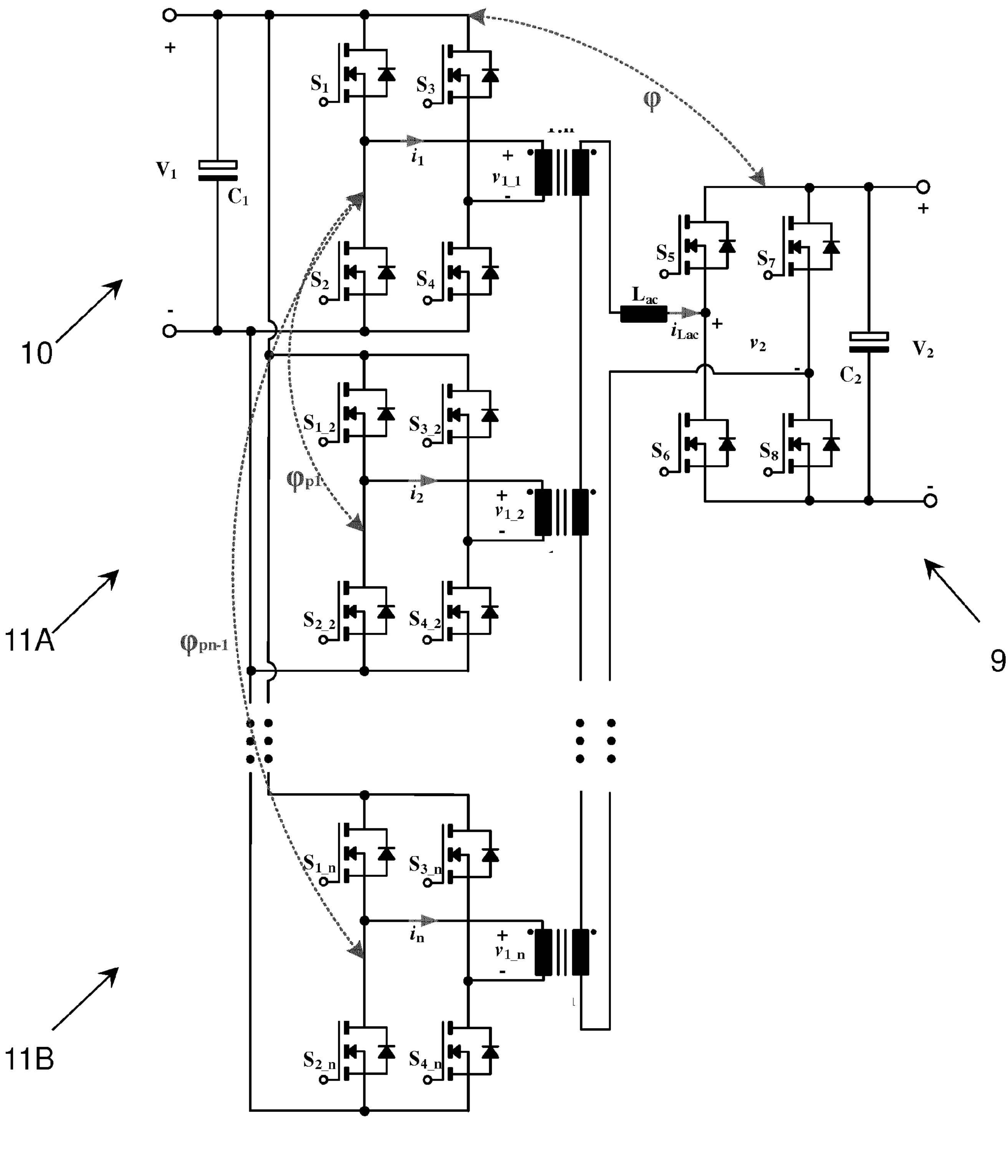


FIG. 5B



+
V1
C1
S1
S3
S2
S4
i1
v1_1
φ
Lac
iLac
v2
S5
S7
S6
S8
C2
V2
+
-
10
11A
11B
9
S1_2
S3_2
S2_2
S4_2
φp1
i2
v1_2
φpn-1
S1_n
S3_n
S2_n
S4_n
in
v1_n

FIG. 6

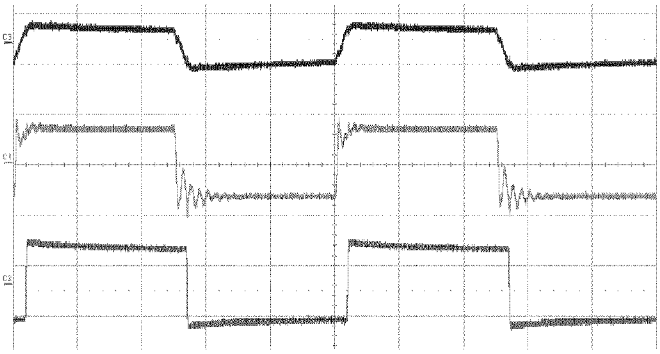


FIG. 7A

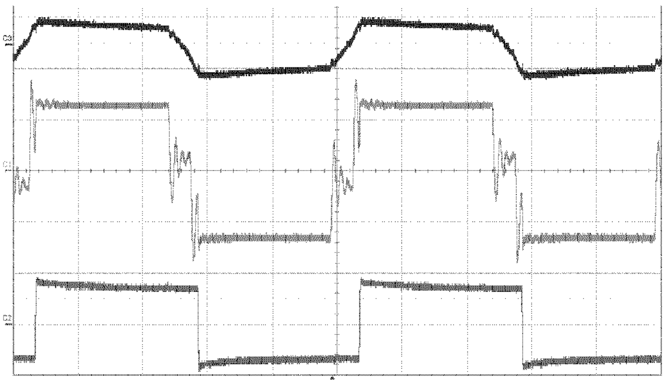


FIG. 7B

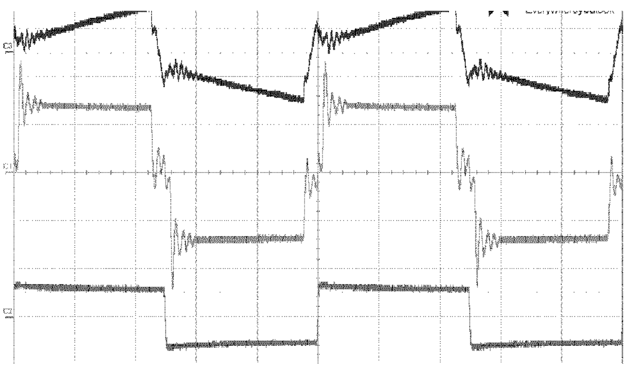


FIG. 7C

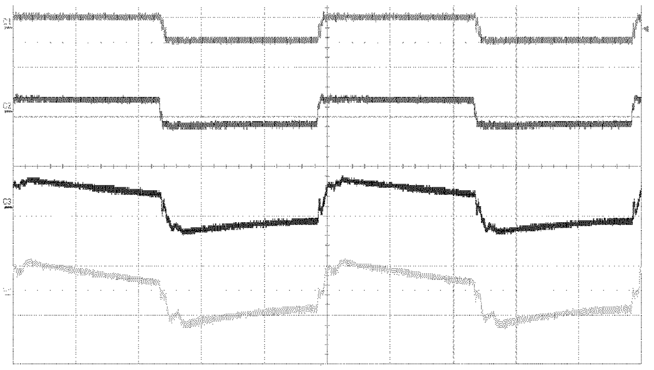


FIG. 8A

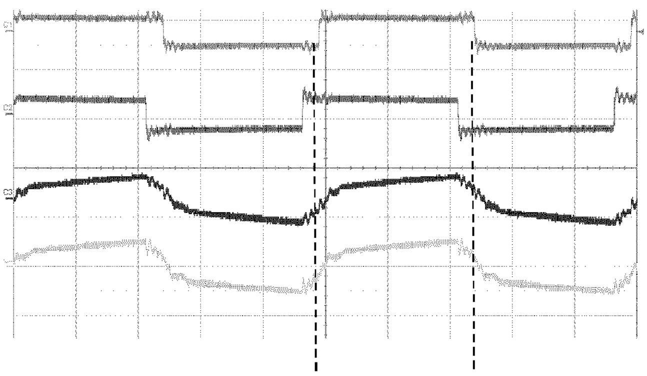


FIG. 8B

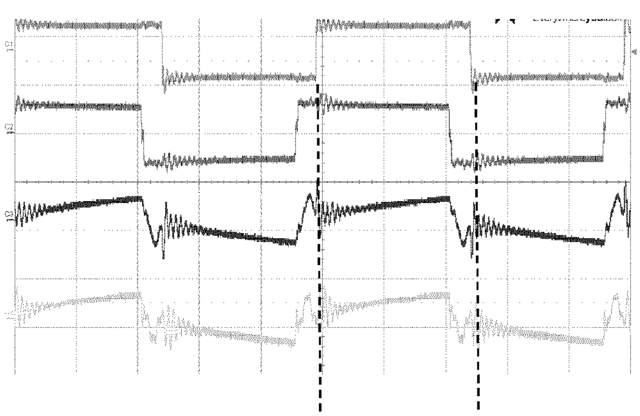


FIG. 8C

INTERNATIONAL SEARCH REPORT

International application No
PCT/ EP20 19/0535 18

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02M3/335
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.
A	US 2016/020702 A1 (TRESCASES OLIVIER [CA] ET AL) 21 January 2016 (2016-01-21) paragraph [0057]; figures 2,3 -----	1-13
A	DE 10 2005 036806 A1 (LORCH SCHWEISSTECH GMBH [DE]) 8 February 2007 (2007-02-08) figure 1 -----	1-13
A	WO 2014/135449 A1 (UNIV DANMARKS TEKNISKE [DK]) 12 September 2014 (2014-09-12) page 14, lines 21-32; figure 1B -----	1-13

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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

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

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

"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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 April 2019	18/04/2019

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	van Wesenbeeck, R

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2019/053518

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