Dual active bridge dc-dc converter with extended operation range

Zhang, Zhe; Manez, Kevin Tomas

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Title: DUAL ACTIVE BRIDGE DC-DC CONVERTER WITH EXTENDED OPERATION RANGE

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.
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.

5 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.

10 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

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

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 \( \phi \) at different \( \phi_p \).

Fig. 5 (A and B) show average current as a function of \( \phi \) at different \( \phi_p \).

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 \( /LAC \) (Ch3) with (a) \( \phi_p=0 \), (b) \( 0<\phi_p<\phi \) 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 \( V_{1.1} \) (Ch1), voltage \( V_{1.2} \) (Ch2), current \( /1 \) (Ch3) and current \( /2 \) (Ch4) with (a) \( \phi_p=0 \), (b) \( 0<\phi_p<\phi \), and (c) \( \phi_p<\phi \) for the implementation of fig. 1. The currents \( /1 \) and \( /2 \) 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 S1, 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 S1
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 S1 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 (V2) 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:

\[ P = \frac{2nV_1V_2}{f_s L_{AC}} \phi(1 - 2\phi) \]

where the phase shift \( \phi \) 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 \((L_{\text{AC}}, V_{\text{AC}})\). 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 \(\phi_{\rho}\) is inserted. In one embodiment the second phase-shift angle is less than the first phase-shift angle. This may be represented by \(0 < \phi_{\rho} < \phi\).

Based on the waveforms in the example of fig. 3, \(I_1, I_2\) and \(I_3\) can be calculated accordingly in.

\[
I_1 = \frac{(4\varphi - 2\varphi_{\rho} - 1)2nV_1 + V_2}{4f_{\text{S}}L_{\text{AC}}}
\]

\[
I_2 = \frac{(1 - 2\varphi_{\rho})2nV_1 + (4\varphi - 1)V_2}{4f_{\text{S}}L_{\text{AC}}}
\]

\[
I_3 = \frac{(1 - 2\varphi_{\rho})2nV_1 + (4\varphi - 4\varphi_{\rho} - 1)V_2}{4f_{\text{S}}L_{\text{AC}}}
\]

By using the mean-value theorem, the power equation for dual active bridge DC-DC converter with \(\phi\) and \(\phi_{\rho}\) as the control parameters is expressed can be expressed as:

\[
P = \frac{2nV_1V_2}{f_{\text{S}}L_{\text{AC}}} \varphi (1 - 2\varphi + 2\varphi_{\rho} - \frac{\varphi_{\rho}}{2\varphi} - \frac{\varphi_{\rho}}{\varphi}) \quad (0 < \phi_{\rho} < \phi)
\]
In comparison with the single phase-shift modulation it has an additional term

\[ 2\varphi_p - \frac{\varphi_p^2}{2\varphi} - \frac{\varphi_p^2}{\varphi} \]

Similarly, the power equation for \( \phi < \phi_p < 0.25 \) is can be expressed as:

\[ P = \gamma \frac{V_2}{\lambda c}(\varphi - \varphi_p)(\frac{1}{2} - \varphi_p) \quad (0 < \varphi_p \leq 0.25) \]

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

\[ P = \frac{2nV_iV_2}{f_sL_{ac}} \varphi(1 - 2\varphi + 2\varphi_p - \frac{\varphi_p^2}{2\varphi} - \frac{\varphi_p^2}{\varphi}) \]

wherein \( V_i \) is the input voltage, \( V_2 \) is the output voltage, \( f_s \) is the switching frequency, \( L_{ac} \) is the sum of external inductance, \( \varphi \) is the first phase-shift angle, and \( \varphi_p \) is the second phase-shift angle.

Examples of the power as a function of \( \phi \) and \( \varphi_p \) are shown and compared against single phase-shift modulation \( (\phi = \varphi_p) \) 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 \( (\varphi_p) \) an unequal power distribution, and/or an unequal current distribution between the parallel low voltage active bridge circuits can be achieved. When \( 0 < \varphi_p < \phi \), the average input currents \( I_{i - \text{avg}} \) and \( I_{o - \text{avg}} \) in the parallel low voltage active bridge circuits can be calculated as follows:
It follows that the current distribution between the two paralleled bridges depends on the phase-shift angles \( \phi \) and \( \phi_p \) and \( m \). Fig. 5 shows the ratios of the average currents \( I_{in1_{avg}} \) and \( I_{in2_{avg}} \) against \( n^2 V_1 / f_s L_{ac} \) as a function of \( \phi \). The dashed line and solid line represent \( I_{i1_{avg}} \) and \( I_{i2_{avg}} \) respectively. Fig. 5A shows the average current as a function of \( \phi \) at different \( \phi_p \), 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.

\[
I_{i1_{rms}} = I_{i2_{rms}}
\]

**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 $S_1, S_2, S_3,$ and $S_4$ in an H-bridge configuration. In this configuration a node between $S_1$ and $S_2$ 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 $S_3$ and $S_4$ may be connected to another side of the primary winding of the first transformer. The inputs of $S_1$ and $S_3$ may be connected to a first low voltage terminal of the low voltage port, and the inputs of $S_2$ and $S_4$ 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 $S_{1,2}, S_{2,2}, S_{3,2},$ and $S_{4,4}$ in an H-bridge configuration. A node between $S_{1,2}$ and $S_{2,2}$ 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 $S_{3,2}$ and $S_{4,2}$ to connected to the other side of the primary winding of the second transformer. The inputs of $S_{1,2}$ and $S_{3,2}$ may be connected to a first low voltage terminal of the low voltage port, and the inputs of $S_{2,2}$ and $S_{4,2}$ 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 $\phi$ as a percentage of the switching period $T_s$. The second phase-shift angle may be represented by $\phi_p$. The first phase shift angle and the second phase-shift angle may have the relationship $(0 < \phi_p \leq \phi)$. 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 operating 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 \( V_i \) (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 \( V_i \) (2) has a capacitor \( C_i \) (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 (\( \phi \), shift between S1/S4 and S5/S8, then between S2/S3 and S6/S7 etc.). In addition to the first phase-shift angle \( \phi \) there is a second phase-shift angle \( \phi_p \) between the low voltage active bridge circuits (\( \phi_p' \), 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 (\( i_{LAC} \)) and voltage (\( v_{LAC} \)) 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 (\( \phi_p \) and \( \phi_p' \)) are shown.

Fig. 7-8 show experimental voltage and current waveform comparisons for voltage \( (v_i + v_i) \) (Ch1), voltage \( v_2 \) (Ch2) and current \( i_{LAC} \) (Ch3) with (a) \( \phi_p = 0 \), (b) \( 0 < \phi_p < \phi \) and (c) \( \phi < \phi_p \) for one embodiment of the presently disclosed dual active bridge DC-DC converter. In fig. 7 (a) \( \phi_p = 0.034 \) and \( \phi_p = 0 \), (b) \( \phi_p = 0.08 \) and \( \phi_p = 0.06 \), and (c) \( \phi_p = 0.04 \) and \( \phi_p = 0.05 \). When \( \phi_p \neq 0 \), the voltage across the series connected high-voltage windings, i.e. \( n \cdot (v_i + v_i) \) becomes a three-level waveform consisting of \( \pm 2n v_i \) and 0, which changes the current waveforms accordingly. Fig. 8 illustrates the effect of \( \phi_p \) on the low
voltage side. Fig. 8 shows experimental voltage and current waveform comparisons for voltage $V_M$ (Ch1), voltage $v_i$ (Ch2), current $i_1$ (Ch3) and current $i_2$ (Ch4) with (a) $\phi_p=0$, (b) $0<\phi_p<\phi$, and (c) $\phi_p>\phi$ for the implementation of fig. 1. The currents $i_1$ and $i_2$ are the same regardless the phase-shift angles. Moreover, as can be seen, $L_w$ 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 $\phi_p$ 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 $i_{n1}$ and $i_{n2}$ 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 preferably 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

\[ P = \frac{2nV_i V_2}{f_s L_{ac}} \left( 1 - 2\phi + 2\phi_p - \frac{\phi_p^2}{2\phi} - \frac{\phi_p^2}{\phi} \right), \]

wherein \( V_i \) is the input voltage, \( V_2 \) is the output voltage, \( f_s \) is the switching frequency, \( L_{ac} \) is the sum of external inductance, \( \phi \) is the first phase-shift angle, and \( \phi_p \) 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_2 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 preferably 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 preferably 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 1-11.
FIG. 8A

FIG. 8B

FIG. 8C
INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/0535 18

A. CLASSIFICATION OF SUBJECT MATTER

INTERNATIONAL INVENTION

H02M3/335

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 - International, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Date of the actual completion of the international search
11 April 2019

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

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