

Method for controlling a series resonant DC/DC converter

FIELD OF THE INVENTION

The present invention relates to method for controlling a series resonant DC/DC converter and a series resonant DC/DC converter controlled according to the method.

BACKGROUND OF THE INVENTION

A typical uninterruptable power supply (UPS) system is shown in fig. 1. The UPS system comprises an input converter for converting electric power from an AC or DC power source. A typical UPS has an input power stage that converts the commercial AC mains or a renewable energy AC or DC source, to a DC voltage. The DC voltage is then converted by means of a converter to a controlled AC or DC voltage thus forming a power supply to electrical loads such as computers, refrigerators etc that need uninterrupted power supply. Typically, a regulated DC bus is provided between the input converter and the output converter. The DC bus is ideally suited to be connected to a DC battery. A bidirectional DC/DC converter is needed if the battery voltage differs from the DC voltage on the DC-bus.

A typical AC-UPS can handle a power failure in the AC mains, by using a battery to supply DC power to the DC bus via a DC/DC converter, so the power supplied to the AC load is not interrupted. When the AC mains is operable again, power from the AC mains can be used to recharge the battery and supply energy to the load.

In many UPS systems, one DC/DC converter is used for supplying power from the battery to the DC bus and a separate converter is used to charge the battery. The battery charging converter can either be an AC/DC converter supplied with power from the AC mains, or a separate DC/DC converter supplied with power from the DC bus.

In some applications, the input may also be a DC source, for example a renewable electrical energy source such as solar cells.

There exist many proposed circuits for one-directional and bi-directional DC/DC converters for improved efficiency such as in "*Performance optimization of a High Current Dual Active Bridge with Wide operating Voltage Range*", by Krismer, Round, Kolar" published in Power Electronics Specialists Conference, 2006, "*A new HE ZVZCS Bidirectional DC/DC converter for HEV 42V Power Systems*", by Kim, Han, Park, Moon published in Journal of Power Electronics, Vol. 6, No. 3, July 2006, "*Bidirectional DC/DC Power Conversion using Quasi-Resonant Topology*", by Ray, published in Power Electronics Specialists Conference, 1992, "*A Bidirectional DC-DC converter for renewable energy systems*", by

Jalbrzykowski, Citko, published in Bulletin of the Polish Academy of Technical Sciences Vol. 57, No. 4, 2009. All of these are operated at fixed frequency and controlled by either phase-shifting gate pulses or duty cycle modulation. All of these circuits have the drawback of limited operating ranges for high efficiency operation, such as zero voltage switching (ZVS) of main switches for only a limited load range etc.

The object of the present invention is to provide a method for controlling a series resonant DC/DC converter with improved efficiency. The object is also to provide a method for controlling a series resonant DC/DC converter so that a bidirectional DC/DC converter is achieved. Hence, the series resonant DC/DC converter can be used both for supplying power from the battery to the DC bus during power failures and for supplying power from the DC bus to recharge the battery after a power failure. This reduces the number of components, and hence costs/space can be saved.

SUMMARY OF THE INVENTION

An aspect of the present invention relates to a method for controlling a series resonant DC/DC converter, comprising the steps of:

- defining a switching period TP from time Tstart to time Tend for the series resonant DC/DC converter; where the switching period TP comprises a first half period TA from time Tstart to time Tcenter and a second half period TB from time Tcenter to time Tend, and defining a subsequent switching period TP+1 after the switching period TP;
- controlling a first set of switches of a first switching circuit to be ON from the beginning Tstart of the first half period TA minus a time interval $\Delta TAE1$, where the time interval $\Delta TAE1$ is provided at the end of the first half period TA;
- controlling a second set of switches of the first switching circuit to be ON from the beginning Tcenter of the second half period TB minus a time interval $\Delta TBE1$, where the time interval $\Delta TBE1$ is provided at the end of the second half period TB;
- controlling the first set and the second set of switches of the first switching circuit to be OFF in the time interval $\Delta TAE1$ and the time interval $\Delta TBE1$;
- controlling a first set of switches of a second switching circuit to be ON in the first half period TA minus a time interval $\Delta TAS1$ and minus a time interval $\Delta TAE2$, where the time interval $\Delta TAS1$ is provided at the beginning of the first half period TA and where the time interval $\Delta TAE2$ is provided at the end of the first half period TA;

- controlling a second set of switches of the second switching circuit to be ON in the second half period TB minus time interval $\Delta TBS1$ and minus time interval $\Delta TBE2$, where the time interval $\Delta TBS1$ is provided at the beginning of the second half period TB and where the time interval $\Delta TBE2$ is provided in the end of the second half period TB;

- controlling the first set and the second set of switches of the second switching circuit to be OFF in the time intervals $\Delta TAS1$, $\Delta TAE2$, $\Delta TBS1$ and $\Delta TBE2$;

where the time interval $\Delta TAE1$ forms a first time interval $Tsc1off1$ wherein the first and second sets of switches of the first switching circuit are OFF, and where the time interval ΔTBE forms a second time interval $Tsc1off2$ wherein the first and second sets of switches of the first switching circuit are OFF;

where the time intervals $\Delta TAE2$ and $\Delta TBS1$ form a continuous time interval $Tsc2off1$, where the first and second set of switches of the second switching circuit are OFF; and where the time interval $\Delta TBE2$ and a time interval $\Delta TAS1(TP+1)$ of the subsequent switching period $TP+1$ form a continuous time interval $Tsc2off2$, where the first and second sets of switches of the second switching circuit are OFF;

where the time interval $Tsc1off1$ and the time interval $Tsc2off1$ is overlapping and where the time interval $Tsc1off2$ and the time interval $Tsc2off2$ is overlapping.

In the above aspect, the method further comprises the step of controlling the relation between the voltage between first DC terminals of the series resonant DC/DC converter and the voltage between second DC terminals of the series resonant DC/DC converter by varying the length of the switching period TP.

In one embodiment the method comprises the step of controlling the centre of interval $Tsc1off1$ to be close to or equal to the centre of time interval $Tsc2off1$ and the centre of interval $Tsc1off2$ to be close to or equal to the centre of time interval $Tsc2off2$.

In one embodiment the method comprises the step of controlling the direction of the power flow through the series resonant DC/DC converter by varying the switching period TP.

In one embodiment the method comprises the step of controlling the switches of the first and second switching circuit to provide zero voltage switching at switch turn on and to provide nearly zero current switching at switch turn off by controlling the first and second switching circuit to have a fixed switching frequency close to the series resonant frequency.

In one embodiment the switches of the first and second switching circuit are controlled by switching at an operating point at or near the series resonant frequency for all voltages over the first DC terminals which are inside a specified operating range.

In one embodiment the switches of the first and second switching circuit are controlled by switching at an operating point at or near the series resonant frequency for all load conditions at the second DC terminals.

An aspect of the present invention also relates to a series resonant DC/DC converter comprising:

- first DC terminals;
- second DC terminals;
- an inductor device;
- a first switching circuit connected between the first DC terminals and the inductor device, where the first switching circuit comprises a first set of switches and a second set of switches;
- a second switching circuit and a resonant circuit connected between the second DC terminals and the inductor device, where the second switching circuit comprises a first set of switches and a second set of switches;
- a control circuit for controlling the set of switches of the first and second switching circuits according to one of the methods above.

DETAILED DESCRIPTION

Embodiments of the present invention will be described in detail in the following with reference to the enclosed drawings, where:

Fig. 1 illustrates a typical application for bidirectional DC/DC converters;

Fig. 2 illustrates a first embodiment of the DC/DC converter;

Fig. 3 illustrates a second embodiment of the DC/DC converter;

Fig. 4 illustrates a third embodiment of the DC/DC converter;

Fig. 5 illustrates a fourth embodiment of the DC/DC converter;

Fig. 6 illustrates a fifth embodiment of the DC/DC converter;

Fig. 7 illustrates a fifth embodiment of the DC/DC converter; this embodiment does not have a transformer device;

Fig. 8 shows waveforms of voltages and currents of the second embodiment at full load;

Fig. 9 shows details of fig. 9;

Fig. 10 shows waveforms of voltages and currents of the second embodiment at no load;

Fig. 11 shows details of fig. 10;

Fig. 12 shows the variation of output voltage V_{out} for different switching frequencies and different loads;

Fig. 13 shows the efficiency curve as a function of the output power for the embodiment in fig. 3.

It is now referred to fig. 2 – 7, illustrating embodiments of the series resonant DC/DC converter. It should be noted that by the term “series resonant DC/DC converter series” it is meant different types of series resonant LC DC/DC converters and different types of series resonant LLC DC/DC converters. The series resonant DC/DC converter may also be a bidirectional DC/DC converter.

The DC/DC converter comprises first DC terminals T1P, T1N and second DC terminals T2P, T2N. The first DC terminals comprise a first positive DC terminal T1P and a first negative DC terminal T1N. The second DC terminals comprise a second positive DC terminal T2P and a second negative DC terminal T2N.

The DC/DC converter further comprises an inductor device, either in the form of a single inductor device ID (as in the embodiment of fig. 7) or in the form of a transformer device TD (as in the embodiments of figs. 2 - 6).

The single inductor device ID may comprise a single inductor L_m , or may comprise several inductors, but does not provide a galvanic isolation.

The transformer device TD may comprise a first winding and a second winding. The transformer device provides galvanic isolation between the first DC terminals and the second DC terminals. The transformer also comprises a magnetizing inductance, which forms a parallel resonance circuit together with the resonant capacitor(s).

The transformer ratio of the transformer device is 1:1 in the present embodiments; however, other transformer ratios are also possible and can be designed in order to meet requirements for input output voltage and current ratios.

A first switching circuit SC1 (illustrated by a dashed box) is connected between the first DC terminals T1P, T1N and the inductor device (either the single inductor device ID or the transformer device TD). The first switching circuit SC1 comprises a first set of switches and a second set of switches. The first set and the second set of switches may each comprise one, two or several switches.

The first switching circuit SC1 is arranged to be controlled in three different switching states. The first state allows a current to flow through the inductor device from the first positive DC terminal T1P to the negative DC terminal T1N by commanding the first set of switches to be ON. The second state allows a current to flow through the inductor device from the first negative DC terminal T1N to the first positive DC terminal T1P by commanding the second set of switches to be ON. The third switching state is characterized by commanding both sets of switches to be OFF.

A second switching circuit SC2 (illustrated by a dashed box) and a resonant circuit RC (illustrated by a dashed box) are connected between the second DC terminals T2P, T2N and the inductor device (either the single inductor device ID or the transformer device TD). The second switching circuit SC2 comprises a first set of switches and a second set of switches. The first set and the second set of switches may each comprise one, two or several switches. It can be seen that the second switching circuit SC2 and a resonant circuit RC are connected in series with the inductor device (the single inductor device ID or the transformer device TD) between the second DC-terminals T2P and T2N. The series combination of the resonant circuit RC and the inductor device is connected to the second switching circuit SC2. The second switching circuit, SC2, is arranged to be controlled in three different switching states. The first state allows a resonant current to flow through the series combination of the resonant circuit RC and the inductor device from the second positive DC terminal T2P to the second negative DC terminal T2N by commanding the first set of switches to be ON. The second state allows a resonant current to flow through the series combination of RC and the inductor device from the second negative DC terminal T2N to the second positive DC terminal T2P by commanding the second set of switches to be ON. The third switching state is characterized by commanding both sets of switches to be OFF.

The first switching circuit SC1 may be a push pull circuit or a bridge circuit, such as a full bridge circuit or a half bridge circuit.

The second switching circuit SC2 may also be a bridge circuit, such as a full bridge circuit or a half bridge circuit.

The resonant circuit RC is often referred to as a resonant tank and comprises at least one capacitor or at least one inductor in a suitable configuration together with the inductor device, either the single inductor device ID or the second winding of the transformer device T, where the inductance of the at least one capacitor and/or at least one inductor together with the inductance of the single inductor device ID or the second winding of the transformer device T defines a resonance frequency so that the DC/DC converter exhibits zero voltage turn on switching on all active switches of SC1 and SC2.

The resonant circuit RC may also be a multi-element resonant circuit comprising several capacitors and inductors in a LC network. Hence, the converter can be considered as a series resonant LLC DC/DC converter.

5 In addition, the DC/DC converter comprises a control circuit which can determine the desired direction of power flow and control the direction of current at the first and second DC-terminals and thus make the converter supply energy either to the load connected to the first DC-terminals or the load connected to the second DC-terminals.

10 In the following, several embodiments will be described. In all these embodiments, the switches are MOSFET switches. Alternatively, the switches may be switches with intrinsic diodes or switches connected in parallel with anti-parallel diodes, such as IGBTs with anti-parallel diodes.

First embodiment

15 It is now referred to fig. 2. Here the first switching circuit SC1 is a half bridge circuit comprising a first switch S1sc1 and a second switch S2sc1. The first set of switches of the first switching circuit SC1 here comprises the first switch S1sc1 and the second set of switches of the first switching circuit SC1 comprises the second switch S2sc1.

20 The first switch S1sc1 is connected between the first negative DC terminal T1N and a first terminal of the first winding. The source of the switch is connected to the first negative DC terminal T1N.

The second switch S2sc1 is connected between the first negative DC terminal T1N and a second terminal of the first winding. The source of the switch is connected to
25 the first negative DC terminal T1N.

The first winding of the transformer device T comprises a third terminal connected to the first positive DC terminal T1P. The third terminal of the second winding is provided between the first terminal and the second terminal of the second winding. Hence, the number of turns between the first and third terminals and the number of
30 turns between the second and third terminals is equal to the total number of turns for the second winding. In the present embodiment, the number of turns between the first and third terminals and the number of turns between the second and third terminals is equal to each other.

35 A first capacitor C1 is connected between the first positive DC terminal T1P and the first negative DC terminal T1N.

The second switching circuit SC2 is a half bridge circuit comprising a first switch S1sc2 and a second switch S2sc2. The first set of switches of the second switching circuit SC2 here comprises the first switch S1sc2 and the second set of switches of the second switching circuit SC2 comprises the second switch S2sc2

- 5 The first switch S1sc2 is connected between a first node 10 and the second positive DC terminal T2P. The second switch S2sc2 is connected between the second negative DC terminal T2N and the second node 10. The source of the first switch S1sc2 is connected to the second negative DC terminal T2N and the source of the second switch S2sc2 is connected to the first node 10. The first node 10 is also
10 connected to a first terminal of the second winding of the transformer device T.

- The resonant circuit RC comprises a resonant inductor Lrc, a first resonant capacitor C1rc and a second resonant capacitor C2rc. The resonant inductor Lrc is connected between a second terminal of the second winding of the transformer T and a second node 12. The first resonant capacitor C1rc is connected between the
15 second node 12 and the second positive DC terminal T2P. The second resonant capacitor C2rc is connected between the second node 12 and the second negative DC terminal T2N.

Second embodiment

- 20 It is now referred to fig. 3.

The first switching circuit SC1 is a full bridge circuit comprising a first switch S1sc1, a second switch S2sc1, a third switch S3sc1 and a fourth switch S4sc1.

- The first set of switches of the first switching circuit SC1 here comprises the first switch S1sc1 and the fourth switch S4sc1. The second set of switches of the first
25 switching circuit SC1 comprises the second switch S2sc1 and the third switch S3sc1.

The first switch S1sc1 is connected between the first positive DC terminal T1P and a first node 20. The source of the switch is connected to the first node 20.

- 30 The second switch S2sc1 is connected between the first negative DC terminal T1N and the first node 20. The source of the switch is connected to the first negative DC terminal T1N.

The third switch S3sc1 is connected between the first positive DC terminal T1P and a second node 22. The source of the switch is connected to the second node 22.

The fourth switch S_{4sc1} is connected between the first negative DC terminal T_{1N} and the second node 22. The source of the switch is connected to the first negative DC terminal T_{1N} .

5 The first node 20 is connected to the first terminal of the first winding of the transformer device T. The second node 22 is connected to the second terminal of the first winding of the transformer device T.

A first capacitor C1 is connected between the first positive DC terminal T_{1P} and the first negative DC terminal T_{1N} .

10 The second switching circuit SC2 is here a half bridge circuit comprising a first switch S_{1sc2} and a second switch S_{2sc2} .

The first set of switches of the second switching circuit SC2 here comprises the first switch S_{1sc2} and the second set of switches of the second switching circuit SC2 comprises the second switch S_{2sc2} . The first switch S_{1sc2} is connected between a first node 10 and the second positive DC terminal T_{2P} . The second switch S_{2sc2} is connected between the second negative DC terminal T_{2N} and the second node 10. The source of the first switch S_{1sc2} is connected to the node 10 and the source of the second switch S_{2sc2} is connected to the second negative DC terminal T_{2N} . The first node 10 is also connected to a first terminal of the second winding of the transformer device T.

20 The resonant circuit RC comprises a resonant inductor L_{rc} , a first resonant capacitor C_{1rc} and a second resonant capacitor C_{2rc} . The resonant inductor L_{rc} is connected between a second terminal of the second winding of the transformer T and a second node 12. The first resonant capacitor C_{1rc} is connected between the second node 12 and the second positive DC terminal T_{2P} . The second resonant capacitor C_{2rc} is connected between the second node 12 and the second negative DC terminal T_{2N} .

A second capacitor C2 is connected between the second positive DC terminal T_{2P} and the second negative DC terminal T_{2N} .

30 In fig. 3, the first winding of the transformer device TD is denoted as T_p , the second winding of the transformer device TD is denoted as T_s . The current through the first winding is denoted as I_p , the current through the second winding is denoted as I_s .

As shown in fig. 3, a voltage source with input voltage V_{in} is connected between the first negative DC terminal and the first positive DC terminal T_{1P} , T_{1N} . A load R_{load} is connected between the second negative DC terminal and the second positive DC terminal T_{2P} , T_{2N} .

Third embodiment

It is now referred to fig. 4.

The first switching circuit SC1 is a full bridge circuit comprising a first switch S1sc1, a second switch S2sc1, a third switch S3sc1 and a fourth switch S4sc1.

- 5 The first set of switches of the first switching circuit SC1 here comprises the first switch S1sc1 and the fourth switch S4sc1. The second set of switches of the first switching circuit SC1 comprises the second switch S2sc1 and the third switch S3sc1. The first switch S1sc1 is connected between the first positive DC terminal T1P and a first node 20. The source of the switch is connected to the first node 20.
- 10 The second switch S2sc1 is connected between the first negative DC terminal T1N and the first node 20. The source of the switch is connected to the first negative DC terminal T1N.

The third switch S3sc1 is connected between the first positive DC terminal T1P and a second node 22. The source of the switch is connected to the second node 22.

- 15 The fourth switch S4sc1 is connected between the first negative DC terminal T1N and the second node 22. The source of the switch is connected to the first negative DC terminal T1N.

- 20 The first node 20 is connected to the first terminal of the first winding of the transformer device T. The second node 22 is connected to the second terminal of the first winding of the transformer device T.

A first capacitor C1 is connected between the first positive DC terminal T1P and the first negative DC terminal T1N.

The second switching circuit SC2 is a full bridge circuit comprising a first switch S1sc2, a second switch S2sc2, a third switch S3sc2 and a fourth switch S4sc2.

- 25 The first set of switches of the second switching circuit SC2 here comprises the first switch S1sc2 and the fourth switch S4sc2. The second set of switches of the second switching circuit SC2 comprises the second switch S2sc2 and the third switch S3sc2.

- 30 The first switch S1sc2 is connected between the second positive DC terminal T2P and a first node 10. The source of the first switch S1sc2 is connected to the first node 10.

The second switch S2sc2 is connected between the second negative DC terminal T2N and the first node 10. The source of the switch is connected to the second negative DC terminal T2N.

The third switch S3sc2 is connected between the second positive DC terminal T2P and a second node 12. The source of the switch is connected to the second node 12.

5 The fourth switch S4sc2 is connected between the second negative DC terminal T2N and the second node 12. The source of the switch is connected to the second negative DC terminal T2N.

The second node 12 of the second switching circuit SC2 is also connected to a first terminal of the second winding of the transformer device T.

10 The resonant circuit RC comprises a resonant inductor Lrc and a resonant capacitor Crc connected in series between a second terminal of the second winding of the transformer device T and the first node 10.

A second capacitor C2 is connected between the second positive DC terminal T2P and the second negative DC terminal T2N.

Fourth embodiment

15 It is now referred to fig. 5.

Here, the first switching circuit SC1 is a half bridge circuit comprising a first switch S1sc1 and a second switch S2sc1. The first set of switches of the first switching circuit SC1 here comprises the first switch S1sc1 and the second set of switches of the first switching circuit SC1 comprises the second switch S2sc1. The first switch S1sc1 is connected between the first negative DC terminal T1N and a first terminal of the first winding. The source of the switch is connected to the first negative DC terminal T1N.

20 The second switch S2sc1 is connected between the first negative DC terminal T1N and a second terminal of the first winding. The source of the switch is connected to the first negative DC terminal T1N.

25 The first winding of the transformer device T comprises a third terminal connected to the first positive DC terminal T1P. The third terminal of the second winding is provided between the first terminal and the second terminal of the second winding. Hence, the number of turns between the first and third terminals and the number of turns between the second and third terminals is equal to the total number of turns for the second winding. In the present embodiment, the number of turns between the first and third terminals and the number of turns between the second and third terminals is equal to each other.

30 A first capacitor C1 is connected between the first positive DC terminal T1P and the first negative DC terminal T1N.

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The second switching circuit SC2 is a full bridge circuit comprising a first switch S1sc2, a second switch S2sc2, a third switch S3sc2 and a fourth switch S4sc2.

5 The first set of switches of the second switching circuit SC2 here comprises the first switch S1sc2 and the fourth switch S4sc2. The second set of switches of the second switching circuit SC2 comprises the second switch S2sc2 and the third switch S3sc2.

The first switch S1sc2 is connected between the second positive DC terminal T2P and a first node 10. The source of the first switch S1sc2 is connected to the first node 10.

10 The second switch S2sc2 is connected between the second negative DC terminal T1N and the first node 10. The source of the switch is connected to the second negative DC terminal T2N.

The third switch S3sc2 is connected between the second positive DC terminal T2P and a second node 12. The source of the switch is connected to the second node 12.

15 The fourth switch S4sc2 is connected between the second negative DC terminal T2N and the second node 12. The source of the switch is connected to the second negative DC terminal T2N.

The second node 12 of the second switching circuit SC2 is also connected to a first terminal of the second winding of the transformer device T.

20 The resonant circuit RC comprises a resonant inductor Lrc and a resonant capacitor Crc connected in series between a second terminal of the second winding of the transformer device T and the first node 10.

A second capacitor C2 is connected between the second positive DC terminal T2P and the second negative DC terminal T2N.

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Fifth embodiment

It is now referred to fig. 6.

30 Here, the first switching circuit SC1 is a voltage doubler circuit comprising a first switch S1sc1 and a second switch S2sc1. The first set of switches of the first switching circuit SC1 here comprises the first switch S1sc1 and the second set of switches of the first switching circuit SC1 comprises the second switch S2sc1.

The first switch S1sc1 is connected between the first positive DC terminal T1P and a first terminal of the first winding of the transformer device TD. The source of the

switch is connected to the first terminal of the first winding of the transformer device TD.

5 The second switch S2sc1 is connected between the first negative DC terminal T1N and a second terminal of the first winding of the transformer device TD. The source of the switch is connected to the second terminal of the first winding of the transformer device TD.

10 A first capacitor C1 is connected between the first positive DC terminal T1P and a node 20. A second capacitor C2 is connected between the node 20 and the first negative DC terminal T1N. The node 20 is connected to a third terminal of the first winding of the transformer device TD.

15 The third terminal of the second winding is provided between the first terminal and the second terminal of the second winding. Hence, the number of turns between the first and third terminals and the number of turns between the second and third terminals is equal to the total number of turns for the second winding. In the present embodiment, the number of turns between the first and third terminals and the number of turns between the second and third terminals is equal to each other.

The second switching circuit SC2 is here a half bridge circuit comprising a first switch S1sc2 and a second switch S2sc2.

20 The first set of switches of the second switching circuit SC2 here comprises the first switch S1sc2 and the second set of switches of the second switching circuit SC2 comprises the second switch S2sc2.

The first switch S1sc2 is connected between a first node 10 and the second positive DC terminal T2P. The second switch S2sc2 is connected between the second negative DC terminal T2N and the second node 10.

25 The source of the first switch S1sc2 is connected to the node 10. The source of the second switch S2sc2 is connected to the second negative DC terminal T2N. The first node 10 is also connected to a first terminal of the second winding of the transformer device T.

30 The resonant circuit RC comprises a resonant inductor Lrc, a first resonant capacitor C1rc and a second resonant capacitor C2rc. The resonant inductor Lrc is connected between a second terminal of the second winding of the transformer T and a second node 12. The first resonant capacitor C1rc is connected between the second node 12 and the second positive DC terminal T2P. The second resonant capacitor C2rc is connected between the second node 12 and the second negative DC terminal T2N.

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Sixth embodiment

It is now referred to fig. 7.

The first switching circuit SC1 is a full bridge circuit comprising a first switch S1sc1, a second switch S2sc1, a third switch S3sc1 and a fourth switch S4sc1.

- 5 The first set of switches of the first switching circuit SC1 here comprises the first switch S1sc1 and the fourth switch S4sc1. The second set of switches of the first switching circuit SC1 comprises the second switch S2sc1 and the third switch S3sc1.

- 10 The first switch S1sc1 is connected between the first positive DC terminal T1P and a first node 20. The source of the switch is connected to the first node 20.

The second switch S2sc1 is connected between the first negative DC terminal T1N and the first node 20. The source of the switch is connected to the first negative DC terminal T1N.

- 15 The third switch S3sc1 is connected between the first positive DC terminal T1P and a second node 22. The source of the switch is connected to the second node 22.

The fourth switch S4sc1 is connected between the first negative DC terminal T1N and the second node 22. The source of the switch is connected to the first negative DC terminal T1N.

- 20 As mentioned above, there is no transformer device TD in the present embodiment. Instead, an inductor device ID in the form of a magnetizing inductor Lm is provided.

The first node 20 is connected to the first terminal of the magnetizing inductor Lm. The second node 22 is connected to the second terminal of the magnetizing inductor Lm.

- 25 A first capacitor C1 is connected between the first positive DC terminal T1P and the first negative DC terminal T1N.

The second switching circuit SC2 is here a half bridge circuit comprising a first switch S1sc2 and a second switch S2sc2.

- 30 The first set of switches of the second switching circuit SC2 here comprises the first switch S1sc2 and the second set of switches of the second switching circuit SC2 comprises the second switch S2sc2.

The first switch S1sc2 is connected between a first node 10 and the second positive DC terminal T2P. The second switch S2sc2 is connected between the second negative DC terminal T2N and the second node 10. The source of the first switch

S1sc2 is connected to the node 10 and the source of the second switch S2sc2 is connected to the second negative DC terminal T2N. The first node 10 is also connected to the second terminal of the magnetizing inductor Lm.

- 5 The resonant circuit RC comprises a resonant inductor Lrc, a first resonant capacitor C1rc and a second resonant capacitor C2rc. The resonant inductor Lrc is connected between the first terminal of the magnetizing inductor Lm and a second node 12. The first resonant capacitor C1rc is connected between the second node 12 and the second positive DC terminal T2P. The second resonant capacitor C2rc is connected between the second node 12 and the second negative DC terminal T2N.
- 10 A second capacitor C2 is connected between the second positive DC terminal T2P and the second negative DC terminal T2N.

Control circuit

- A control circuit is provided for controlling the switches of the first and second switching circuits SC1 and SC2 to be ON and OFF. The control circuit may be implemented as a software program executed by a digital signal processor (DSP) or it may be implemented as an analogue circuit.
- 15

- All switches are uni-polar, meaning that the switches can only block conduction in one direction. An example of a uni-polar switch is the MOSFET switch comprising an anti-parallel diode. Another example is the IGBT switch with an anti-parallel diode connected from emitter to drain.
- 20

- The control method according to the invention will now be described in detail below with reference to figs. 8 – 12. Here, the control signals and resulting voltages and/or currents are shown for the embodiment shown in fig. 3. The input voltage Vin was set to 50 VDC, and an output voltage was regulated to 350 VDC. The switching frequency is approximately 110kHz.
- 25

It is now referred to fig. 8.

- In a first step a switching period TP is defined from time Tstart to time Tend for the series resonant DC/DC converter. The switching period TP comprises a first half period TA from time Tstart to time Tcenter and a second half period TB from time Tcenter to time Tend. A next switching period after the switching period TP is denoted as a subsequent switching period TP+1.
- 30

As is described above, the series resonant DC/DC converter has a resonance frequency defined by the properties of the inductor device (ID or TD) and the elements (capacitors and inductors) of the resonance circuit RC.

- 35 The switching period TP, and hence the switching frequency, can be controlled by the control circuit to be higher than, equal to, or lower than the resonance

frequency. Hence, the switching period TP is not dependant of the resonance frequency.

In fig. 8, relevant times T_0 (equal to T_{start}) to T_8 (equal to T_{end}) for the first switching period TP are indicated by dashed lines, and several time intervals are also defined, as will be apparent from the description below. Time T_8 (equal to T_{end}) is the start (i.e. time $T_0(TP+1)$) of the subsequent switching period $TP+1$. Time T_4 is here equal to T_{center} , but the length of the time intervals $T_0 - T_1$, $T_1 - T_2$, $T_2 - T_3$, $T_3 - T_4$, $T_4 - T_5$, $T_5 - T_6$, $T_6 - T_7$, $T_7 - T_8$ are not all equal to each other.

The duty cycle of all set of switches are essentially 50%, meaning that the switches have a control signal demanding the switch to be in a conducting state, ON, during nearly half of the switching period and having the control signal demanding the switch to be in a non-conducting state, OFF, during nearly half of the switching period. The set of switches are controlled independently to have different delays and yet synchronized.

The first set $S1sc1$; $S1sc1$, $S4sc1$ of switches of the first switching circuit $SC1$ is controlled to be ON from the beginning T_{start} of the first half period TA minus a time interval $\Delta TAE1$, where the time interval $\Delta TAE1$ is provided at the end of the first half period TA . The first set $S1sc1$; $S1sc1$, $S4sc1$ of switches of the first switching circuit $SC1$ is controlled to be OFF in the second half period TB . The time interval $\Delta TAE1$ in the present embodiment is starting at time T_3 and is ending at time T_4 .

The second set $S2sc1$; $S2sc1$, $S3sc1$ of switches of the first switching circuit $SC1$ is controlled to be ON from the beginning T_{center} of the second half period TB minus a time interval $\Delta TBE1$, where the time interval $\Delta TBE1$ is provided at the end of the second half period TB . The second set $S2sc1$; $S2sc1$, $S3sc1$ of switches of the first switching circuit $SC1$ is controlled to be OFF in the first half period TA . The time interval $\Delta TBE1$ is in the present embodiment starting at time T_7 and is ending at time T_8 .

The first set $S1sc1$; $S1sc1$, $S4sc1$ and the second set $S2sc1$; $S2sc1$, $S3sc1$ of switches of the first switching circuit $SC1$ is controlled to be OFF in the time interval $\Delta TAE1$ and the time interval $\Delta TBE1$.

The time interval $\Delta TAE1$ forms a first time interval $T_{sc1off1}$ wherein the first and second sets of switches of the first switching circuit $SC1$ are OFF. The time interval $\Delta TBE1$ forms a second time interval $T_{sc1off2}$ wherein the first and second sets of switches of the first switching circuit $SC1$ are OFF.

- The first set S1sc2; S1sc2, S4sc2 of switches of the second switching circuit SC2 is controlled to be ON in the first half period TA minus a time interval ΔT_{AS1} and minus a time interval ΔT_{AE2} , where the time interval ΔT_{AS1} is provided at the beginning of the first half period TA and where the time interval ΔT_{AE2} is provided at the end of the first half period TA. The first set S1sc2; S1sc2, S4sc2 of switches of the second switching circuit SC is controlled to be OFF in the second half period TB. The time interval ΔT_{AS1} in the present embodiment is starting at time T0 and is ending at time T1. The time interval ΔT_{AE2} in the present embodiment is starting at time T2 and is ending at T4.
- The second set S2sc2; S2sc2, S3sc2 of switches of the second switching circuit SC2 is controlled to be ON in the second half period TB minus time interval ΔT_{BS1} and minus time interval ΔT_{BE2} , where the time interval ΔT_{BS1} is provided at the beginning of the second half period TB and where the time interval ΔT_{BE2} is provided in the end of the second half period TB. The second set S2sc2; S2sc2, S3sc2 of switches of the second switching circuit SC2 is controlled to be OFF in the first half period TA. The time interval ΔT_{BS1} in the present embodiment is starting at time T4 and is ending at time T5. The time interval ΔT_{BE2} in the present embodiment is starting at T6 and is ending at T8.
- The first set S1sc2; S1sc2, S4sc2 and the second set S2sc2; S2sc2, S3sc2 of switches of the second switching circuit SC2 are controlled to be OFF in the time intervals ΔT_{AS1} , ΔT_{AE2} , ΔT_{BS1} and ΔT_{BE2} .
- The time intervals ΔT_{AE2} and ΔT_{BS1} form a continuous time interval Tsc2off1 from time T2 to time T5 where the first and second sets of switches of the second switching circuit SC2 are OFF. The time intervals ΔT_{BE2} and $\Delta T_{AS1}(TP+1)$ (that is, the time interval ΔT_{AS1} of a subsequent switching period TP+1) form a continuous time interval Tsc2off2 from time T6 to time T1(TP+1) (that is, the time instance T1 of a subsequent switching period TP+1) where the first and second sets of switches of the second switching circuit SC2 are OFF.
- Table 1 below shows the states for the first and second set of switches for the first switching circuit SC1 for the switching period TP. The start time and end time of each interval are also given.

	TA		TB	
	TA minus ΔT_{AE1} (T0 – T3)	ΔT_{AE1} (T3 – T4)	TB minus ΔT_{BE1} (T4 – T7)	ΔT_{BE1} (T7 – T8)
		Tsc1off1		Tsc1off2
First set of SC1	ON	OFF	OFF	OFF

Second set of SC1	OFF	OFF	ON	OFF
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Table 1: ON/OFF states for first and second set of switches of the first switching circuit SC1.

Table 2 below shows the states for the first and second set of switches for the second switching circuit SC2 for the switching period TP. The start time and end time of each interval are also given.

	TA (T0-T4)			TB (T4-T8)		
	$\Delta TAS1$ (T0-T1) TA minus ($\Delta TAS1$ and	$\Delta TAE2$ (T1 - T2)	$\Delta TAE2$ (T2 - T4)	$\Delta TBS1$ (T4 - T5)	TB minus TBS1 and $\Delta TBE2$	(T5 - T6) $\Delta TBE2$ (T6 - T8)
	Tsc2off2			Tsc2off1		Tsc2off2
First set of SC2	OFF	ON	OFF	OFF	OFF	OFF
Second set of SC2	OFF	OFF	OFF	OFF	ON	OFF

Table 2: ON/OFF states for first and second set of switches of the second switching circuit SC2.

- 10 The time interval Tsc1off1 and the time interval Tsc2off1 are at least partially overlapping, i.e. the time interval Tsc1off1 starts before the time interval Tsc2off1 ends or the time interval Tsc2off1 starts before the time interval Tsc1off1 ends. Moreover, the time interval Tsc1off2 and the time interval Tsc2off2 are at least partially overlapping, i.e. the time interval Tsc1off2 starts before the time interval Tsc2off2 ends or the time interval Tsc2off2 starts before the time interval Tsc1off2 ends. In this way the switches of the first switching circuit SC1 and switches of the second switching circuit SC2 are synchronized.

15 In the present embodiment, the length of time interval Tsc2off1 is equal to the length of time interval Tsc2off2, and the length of time interval Tsc1off1 is equal to the length of time interval Tsc1off2.

20 In the embodiment above, the time intervals Tsc2off1 and Tsc2off2 are longer than the time intervals Tsc1off1 and Tsc1off2. However, they could have the same duration, or the time interval Tsc1off could be longer than the period Tsc2off. This

depends on the required time for achieving Zero Voltage Switching (ZVS) in the switching circuits and may also depend on the voltage between the first positive and negative DC terminals and the voltage between the second positive and negative DC terminals.

- 5 In the embodiment above, the centre of time interval $T_{sc1off1}$ is controlled to be close to or equal to the centre of time interval $T_{sc2off1}$ and the centre of time interval $T_{sc1off2}$ is controlled to be close to or equal to the centre of time interval $T_{sc2off2}$.

10 Zero Voltage Switching is maintained for all switches at turn ON at high to full load as is illustrated in 8.

In fig. 9, voltage V_{10} at node 10 and voltage V_{20} at node 20 are both high before time instance T_2 , thus switches S_{1sc1} , S_{4sc1} (first set of SC1) and S_{1sc2} (first set of SC1) are all conducting and the switches S_{2sc1} , S_{3sc1} (second set of SC1) and S_{2sc2} (second set of SC2) are all non-conducting.

- 15 The first set S_{1sc2} of switches in the second switching circuit SC2 is turned off at time instance T_2 . At the time instance when current I_s becomes positive it is capable of bringing the voltage at node 10 from high to low by discharging the output capacitances in both the first and second set of switches of the second switching circuit. The second set of switches S_{2sc2} of the second switching circuit
20 is commanded to be ON at T_5 , and are thus turned on with a voltage close to zero without any significant switching losses, so called Zero Voltage Switching (ZVS).

25 Since I_p is positive, turning off first set of switches S_{1sc1} and S_{4sc1} at T_3 results in a rapid change of voltage at node 20 from high to low and voltage at node 22 from low to high, caused by the discharging/charging of the output capacitances in the first and second sets of switches S_{1sc1} , S_{3sc1} and S_{2sc1} , S_{4sc1} of the first switching circuit. The second set of switches S_{2sc1} and S_{3sc1} of the first switching circuit SC1 are commanded to be ON at T_4 , and are thus turned on with a voltage close to zero without any significant switching losses, so called ZVS.

- 30 Note that in the present embodiment, the time interval T_2 to T_5 , between turning off S_{1sc2} and turning on S_{2sc2} is longer than the time interval T_3 to T_4 for turning off S_{1sc1} , S_{4sc1} and turning on S_{2sc1} , S_{3sc1} since it will take longer time for the voltage V_{out} of 350 V of the second switching circuit SC2 to commute than for
35 the voltage V_{in} of 50 V of the first switching circuit SC1.

ZVS is also maintained for all switches at turn on even at low to no load which is illustrated in figure 10. We are now referring to figure 11.

Voltage V10 at node 10 and the voltage V20 at node 20 are both high before time instance T2, thus switches S1sc1, S4sc1, and S1sc2 are all conducting.

5 The switch S1sc2 is turned off at time instance T2. The current I_s is positive and is therefore capable of bringing V10 from high to low by discharging the output capacitances in the switches S1sc2 and S2sc2.

10 The current I_s is decaying due to the changed voltage over resonant inductor, L_{RC} , during the time period T2 to T3. However the magnetizing current I_{LM} in winding L_S is still increasing and is therefore reflected to primary winding, L_P , and causes the current I_P to increase. Since I_P is increasing and positive, turning off switches S1sc1 and S4sc1 results in a rapid change of voltage V20 at node 20 from high to low and voltage V22 at node 22 from low to high, caused by the
15 discharging/charging of the output capacitances in the switches S1sc1, S3sc1 and S2sc1, S4sc1.

The output voltage V_{out} may be controlled by changing the switching frequency. This is illustrated in fig. 12, where it is shown that the output voltage V_{out} may be varied for different loads and different switching frequencies. The ZVS operation of
20 all switches is controlled by proper delays, i.e. the time intervals $T_{sc1off1}$, $T_{sc1off2}$, $T_{sc2off1}$ and $T_{sc2off2}$, between switching instances as described in the text and in figure 8 and table 2 and table 3.

25 The relation between the voltage between first DC terminals T1P, T1N of the series resonant DC/DC converter and the voltage between second DC terminals T2P, T2N of the series resonant DC/DC converter can be controlled by varying the length of the switching period T_P .

30 The direction of the power flow through the series resonant DC/DC converter can be controlled by varying length of the switching period T_P . Hence, the series resonant DC/DC converter can be controlled to be a bidirectional series resonant DC/DC converter.

35 The switches of the first and second switching circuit SC1, SC2 are controlled to provide zero voltage switching ZVS at switch turn on and to provide nearly zero current switching ZCS at switch turn off by controlling the first and second switching circuit to have a fixed switching frequency close to the series resonant frequency.

The switches of the first and second switching circuit SC1, SC2 can be controlled by switching at an operating point at or near the series resonant frequency for all voltages over the first DC terminals which are inside a specified operating range.

The switches of the first and second switching circuit SC1, SC2 can be controlled by switching at an operating point at or near the series resonant frequency for all load conditions at the second DC terminals.

UPS system with series resonant DC/DC converter

5 In the introduction above, the typical uses of a series resonant DC/DC converter was described. In a typical UPS system there will be one common control system for all the components of the UPS system, including the series resonant DC/DC converter. The common control circuit can for example comprise a status flag signal as an indicator for the direction of the power flow through the bidirectional DC/DC
10 converter.

Moreover, the control circuit comprises sensors for sensing the current and/or the voltage at the first DC terminals T1P, T1N and the second DC terminals T2P, T2N.

In a first mode of operation the status flag signal indicates that the power should flow from the first DC terminals T1P, T1N to the second DC terminals T2P, T2N.

15 Here, the control circuit is controlling the current and/or voltage of the second DC terminals T2P, T2N based on a predetermined reference signal for the first mode of operation.

In a second mode of operation the status flag signal indicates that the power should flow from the second DC terminals T2P, T2N to the first DC terminals T1P, T1N.

20 Here, the control circuit is controlling the current and/or voltage of the first DC terminals T1P, T1N based on a predetermined reference signal for the second mode of operation.

As mentioned above, the series resonant DC/DC converter may be used as a DC/DC converter for an UPS system, as shown in fig. 1, where its first DC terminals T1P, T1N are connected to the battery and its second DC terminals T2P, T2N connected to a DC bus (not shown).
25

The status flag signal may be switched to the first mode of operation when a failure in the AC mains is detected. In such a situation power should be transferred from the battery connected to the first DC terminals to the DC bus connected to the second DC terminals. Here, the control circuit is controlling the voltage and/or
30 current at the second DC terminals T2P, T2N at a predetermined level suitable as input to the DC/AC converter as long as the battery power supply allows it.

The status flag signal may be switched to the second mode of operation when the AC mains is working again, then supplying power from the DC bus to the battery for recharging the battery. Here, the control circuit is controlling the voltage and/or
35 current at the first DC terminals T1P, T1N at a predetermined level suitable as input to the battery.

The status flag signal may have a third mode of operation for indicating that no power should be transferred through the bidirectional DC/DC converter. In this mode of operation, all switches should be switched off. In this mode of operation there is no failure in the AC mains, and the battery is fully charged.

- 5 Another application for the series resonant DC/DC converter is for re-use of energy stored in battery storages.

Results

- 10 The efficiency of the series resonant DC/DC converter according to fig. 3 of has been tested. Fig. 12 shows the results of the testing. In the testing, two efficiency curves are illustrated, the first curve shows the efficiency as a function of output power for a circuit having an input voltage V_{in} of 50V and the second curve shows the efficiency as a function of output power for a circuit having an input voltage V_{in} of 48V. The output voltage V_{out} was controlled to be 355V.

- 15 As seen, the efficiency is above 96% in the power output range from ca 400W to 2200W. The maximum power efficiency is above 97.5%. This is a considerable improvement over the prior art DC/DC converters mentioned in the introduction, which showed efficiencies of ca 92%.

CLAIMS

1. Method for controlling a series resonant DC/DC converter, comprising the steps of:

- defining a switching period TP from time Tstart to time Tend for the series resonant DC/DC converter; where the switching period TP comprises a first half period TA from time Tstart to time Tcenter and a second half period TB from time Tcenter to time Tend, and defining a subsequent switching period TP+1 after the switching period TP;
- controlling a first set of switches of a first switching circuit to be ON from the beginning Tstart of the first half period TA minus a time interval $\Delta TAE1$, where the time interval $\Delta TAE1$ is provided at the end of the first half period TA;
- controlling a second set of switches of the first switching circuit to be ON from the beginning Tcenter of the second half period TB minus a time interval $\Delta TBE1$, where the time interval $\Delta TBE1$ is provided at the end of the second half period TB;
- controlling the first set and the second set of switches of the first switching circuit to be OFF in the time interval $\Delta TAE1$ and the time interval $\Delta TBE1$;
- controlling a first set of switches of a second switching circuit to be ON in the first half period TA minus a time interval $\Delta TAS1$ and minus a time interval $\Delta TAE2$, where the time interval $\Delta TAS1$ is provided at the beginning of the first half period TA and where the time interval $\Delta TAE2$ is provided at the end of the first half period TA;
- controlling a second set of switches of the second switching circuit to be ON in the second half period TB minus time interval $\Delta TBS1$ and minus time interval $\Delta TBE2$, where the time interval $\Delta TBS1$ is provided at the beginning of the second half period TB and where the time interval $\Delta TBE2$ is provided in the end of the second half period TB;
- controlling the first set and the second set of switches of the second switching circuit to be OFF in the time intervals $\Delta TAS1$, $\Delta TAE2$, $\Delta TBS1$ and $\Delta TBE2$;

where the time interval $\Delta TAE1$ forms a first time interval Tscloff1 wherein the first and second sets of switches of the first switching circuit are OFF, and where the time interval $\Delta TBE1$ forms a second time interval Tscloff2 wherein the first and second sets of switches of the first switching circuit are OFF;

where the time intervals $\Delta TAE2$ and $\Delta TBS1$ form a continuous time interval $T_{sc2off1}$, where the first and second set of switches of the second switching circuit are OFF; and where the time interval $\Delta TBE2$ and a time interval $\Delta TAS1(TP+1)$ of the subsequent switching period $TP+1$ form a continuous time interval $T_{sc2off2}$, where the first and second sets of switches of the second switching circuit are OFF;

where the time interval $T_{sc1off1}$ and the time interval $T_{sc2off1}$ is overlapping and where the time interval $T_{sc1off2}$ and the time interval $T_{sc2off2}$ is overlapping

where the method comprises the step of controlling the relation between the voltage between first DC terminals of the series resonant DC/DC converter and the voltage between second DC terminals of the series resonant DC/DC converter by varying the length of the switching period TP .

2. Method according to claim 1, where the method comprises the step of controlling the centre of interval $T_{sc1off1}$ to be close to or equal to the centre of time interval $T_{sc2off1}$ and the centre of interval $T_{sc1off2}$ to be close to or equal to the centre of time interval $T_{sc2off2}$.

3. Method according to any one of claims 1 - 2, where the method comprises the step of controlling the direction of the power flow through the series resonant DC/DC converter by varying the switching period TP .

4. Method according to any one of claims 1 - 3, where the method comprises the step of controlling the switches of the first and second switching circuit to provide zero voltage switching (ZVS) at switch turn on and to provide nearly zero current switching (ZCS) at switch turn off by controlling the first and second frequency switching circuit to have a fixed switching frequency close to the series resonant frequency.

5. Method according to claim 4, where the switches of the first and second switching circuit are controlled by switching at an operating point at or near the series resonant frequency for all voltages over the first DC terminals which are inside a specified operating range.

6. Method according to claim 4, where the switches of the first and second switching circuit are controlled by switching at an operating point at or near the series resonant frequency for all load conditions at the second DC terminals.

7. Series resonant DC/DC converter comprising:

- first DC terminals;
- second DC terminals;
- an inductor device;
- a first switching circuit connected between the first DC terminals and the inductor device, where the first switching circuit comprises a first set of switches and a second set of switches;
- a second switching circuit and a resonant circuit connected between the second DC terminals and the inductor device, where the second switching circuit comprises a first set of switches and a second set of switches;
- a control circuit for controlling the set of switches of the first and second switching circuits according to the method of any one of claims 1 - 6.