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(54) **INTERLEAVED LLC CONVERTER**

(57) An inductive component is described herein. In accordance with one example, the inductive component includes a magnetic core assembly comprising at a first portion and a second portion, which is magnetically separated from the first portion of the magnetic core assembly via two or more air gaps. The inductive component further includes an inductor with a variable inductance including a first coil that is arranged on the first portion of the magnetic core assembly, a second coil arranged on the second portion of the magnetic core assembly and

configured to generate a bias magnetic field in the second portion of the magnetic core assembly. The first coil is configured to generate a magnetic flux in a magnetic path that includes the first portion of the magnetic core assembly, the two or more air gaps and a part of the second portion of the magnetic core assembly. Furthermore, multiphase LLC switching converter, which includes the above-mentioned inductive component is described herein.

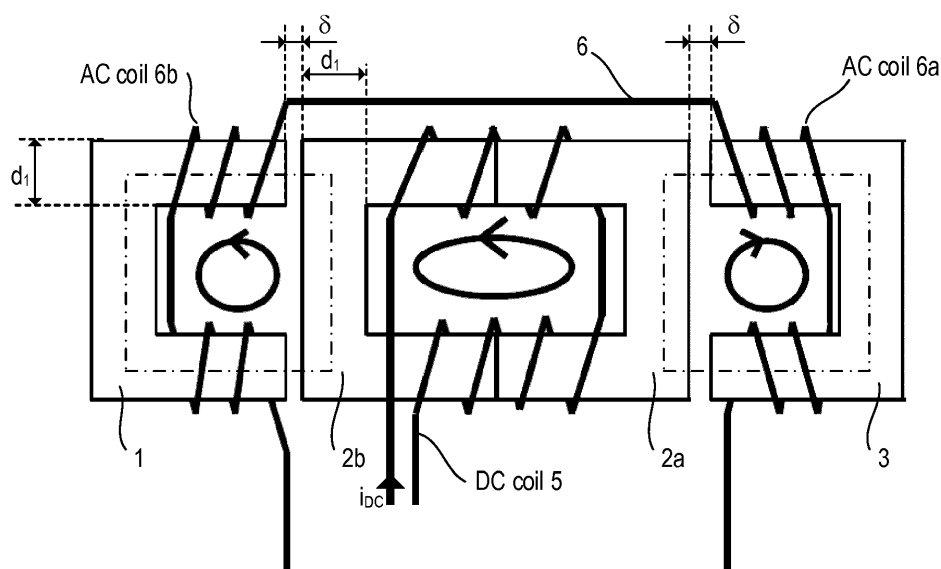


FIG. 3

Description

TECHNICAL FIELD

[0001] The present disclosure relates to the field of switching converters, in particular to an Interleaved LLC converter (ILLC converter).

BACKGROUND

[0002] LLC resonant converters are commonly used in modern power supply designs due to their ability to operate with high efficiency at moderate complexity with regard to control circuitry. Furthermore, multiple LLC resonant converters may be combined in parallel to spread power losses and to decrease the size of output filters and thus the ripple of the output voltage. Such combinations of two or more LLC converter units are referred to as Interleaved LLC converter or ILLC converter.

[0003] Additional control circuitry is usually employed in ILLC converters, for example to balance the load (i.e. the output current) among the individual LLC converter units. A misbalance/asymmetry of the output currents provided by the individual LLC converter units is, inter alia, caused by tolerances of circuit components used in the tank circuits (LC circuits) of the individual LLC converter units. Standard tolerances of, e.g. 5%, may lead to significantly differing resonance frequencies of the mentioned tank circuits and thus to the LLC converter units operating at different operating points.

[0004] One approach to balance the load among two or more LLC converter units includes using *current-controlled variable inductors* (CCVIs) in the tank circuits of the individual LLC converter units which allows to tune the resonance frequency of the tank circuits by adjusting the inductance of the CCVI. Usually a CCIV is composed of a coil, which is wound around a magnetic core with an air gap. The coil has an inductance, which can be varied by generating a magnetic bias field in the magnetic core using a further coil, which is also wound around the magnetic core. The magnitude of the magnetic bias field depends on a control current passing through the further coil.

[0005] CCIVs may be implemented in various different ways, and one problem to be solved by the embodiments described herein can be regarded as how to improve an interleaved LLC converter by improving the CCIV with regards to, for example, efficiency (low losses), electromagnetic compatibility (low disturbing stray fields) and size.

SUMMARY

[0006] The above-identified problem can be solved by the inductive component according to claim 1 and the method according to claim 15. Various embodiments and further developments are covered by the dependent claims.

[0007] An inductive component is described herein. In accordance with one example, the inductive component includes a magnetic core assembly comprising at a first portion and a second portion, which is magnetically separated from the first portion of the magnetic core assembly via two or more air gaps. The inductive component further includes an inductor with a variable inductance including a first coil that is arranged on the first portion of the magnetic core assembly, a second coil arranged on the second portion of the magnetic core assembly and configured to generate a bias magnetic field in the second portion of the magnetic core assembly. The first coil is configured to generate a magnetic flux in a magnetic path that includes the first portion of the magnetic core assembly, the two or more air gaps and a part of the second portion of the magnetic core assembly. Furthermore, multiphase LLC switching converter, which includes the above-mentioned inductive component is described herein. Furthermore, a multiphase LLC switching converter is described herein which includes at least two LLC switching converter units, each including a tank circuit and each tank circuit including an inductor as mentioned above.

[0008] Moreover, a method for controlling the inductance of an inductor is described herein. In accordance with one example, the method includes supplying an AC current to a first coil, which is arranged on a first portion of a magnetic core assembly. The method further includes generating a bias magnetic field in a second portion of the magnetic core assembly by supplying a DC current to a second coil that is arranged on the second portion of the magnetic core assembly. The second portion of the magnetic core assembly is magnetically separated from the first portion of the magnetic core assembly via two or more air gaps. Further, the method includes controlling the inductance of the first coil by adjusting the DC current supplied to the second coil. Thereby, the AC current, when passing through the first coil, generates a magnetic flux in a magnetic path that includes the first portion of the magnetic core assembly, the two or more air gaps and a part of the second portion of the magnetic core assembly.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The invention can be better understood with reference to the following drawings and descriptions. The components in the figures are not necessarily to scale; instead emphasis is placed upon illustrating the principles of the invention. Moreover, in the figures, like reference numerals designate corresponding parts. In the drawings:

Figure 1 illustrates one example of a multi-phase LLC converter including two LLC converter units whose outputs are coupled in parallel.

Figure 2 is a diagram illustrating the characteristic

curve of the resonance of the tank circuit used in an LLC converter unit.

Figures 3 to 6 illustrate different embodiments of a current-controlled variable inductor (CCVI) for use in the multi-phase LLC converter of Fig. 1.

Figures 7 and 8 includes magnetic circuit diagrams illustrating the equivalent magnetic paths of the examples shown in Figs. 3 and 4 and, respectively, Figs. 5 and 6.

DETAILED DESCRIPTION

[0010] Fig. 1 illustrates one example of an Interleaved LLC (ILLC) converter, also referred to as multi-phase LLC converter. In the present example, the ILLC converter is composed of two LLC converter units 10 and 20 whose outputs are coupled in parallel. However, dependent on the application more than two LLC converter units may be coupled in parallel. A balancing of the output currents of the individual LLC converter units is achieved by using a current-controlled variable inductor (CCVI) in the tank circuits of the LLC converter units. Before discussing the implementation of the CCVIs in more detail, the general construction of an ILLC converter is explained with reference to Fig. 1.

[0011] According to Fig. 1 the first LLC converter unit 10 includes a tank circuit that is composed of a capacitor C_{IN1} , an inductor L_{V1} and a further inductor L_{P1} . The inductance of the inductor L_{V1} can be varied by applying a control current, and the inductor L_{P1} , either as a whole or parts thereof, forms the primary winding of a transformer. The respective secondary winding is represented by inductor L_{S1} , which has a middle-tap in the present example. Diodes D_{11} and D_{12} form a rectifier, which rectifies the current induced in the secondary winding L_{S1} , wherein the diodes D_{11} and D_{12} are connected between the outer taps of the secondary winding L_{S1} and an output node of the first LLC converter unit 10. A current sense resistor R_{S1} may be connected between the middle tap of the secondary winding L_{S1} and a reference node (e.g. ground node GND) of the first LLC converter unit 10. The voltage drop across the current sense resistor R_{S1} may be tapped to obtain a voltage signal representative of the output current of the first LLC converter unit 10.

[0012] It is understood that other circuitry may be used to obtain information representing the output current. Alternatively, current measurement may also take place on the primary side of the transformer. The alternating input voltage V_{IN1} applied across the tank circuit, which is a series resonance circuit formed by the series circuit of capacitor C_{IN1} , inductor L_{V1} , and inductor L_{P1} , is usually provided by a transistor H-bridge circuit or, alternatively, by a transistor half-bridge circuit (not shown in Fig. 1) dependent on the actual implementation. It is understood that the transistor bridge circuits may be implemented using MOS transistors that provide a current sensing

function in order to obtain current information. In this case, the current sense resistor R_{S1} can be omitted.

[0013] In the example of Fig. 1, the second LLC converter unit 20 is substantially identical with the first LLC converter unit 10. According to Fig. 1, the second LLC converter unit 20 includes a tank circuit, which is a series resonance circuit formed by the series circuit of capacitor C_{IN2} , inductor L_{V2} , and inductor L_{P2} , wherein the latter represents the primary winding of a further transformer. The respective secondary winding is represented by inductor L_{S2} , which has a middle-tap, and diodes D_{21} and D_{22} form a rectifier, which rectifies the current induced in the secondary winding L_{S2} . Diodes D_{11} and D_{12} are connected between the outer taps of the secondary winding L_{S2} and an output node of the second LLC converter unit 20. A current sense resistor R_{S2} may be connected between the middle tap of the secondary winding L_{S2} and a reference node (e.g. ground node GND) of the second LLC converter unit 20. As mentioned, the outputs of both LLC converter units 10 and 20 are connected in parallel, wherein an output capacitor C_{OUT} may be provided to reduce the ripple of the common output voltage V_{OUT} . The input voltage V_{IN2} applied across the tank circuit may also be provided by a transistor bridge circuit. Usually, the alternating input voltages V_{IN1} and V_{IN2} are phase shifted with respect to each other.

[0014] According to the example of Fig. 1, the ILLC converter includes a regulator circuit 30 that is configured to provide control currents for the inductors L_{V1} and L_{V2} (which are CCVIs) so as to tune the respective inductances such that the two LLC converter unit 10 and 20 are at least approximately equally loaded. Accordingly, a mismatch between the inductances of inductor L_{V1} and L_{V2} can be compensated for. It is noted, that in case of an ILLC converter with two converter units it would be sufficient if only one of the two LLC converter units includes a CCVI whereas the corresponding inductance in the other LLC converter unit may be fixed. Generally, in case of an ILLC converter with N LLC converter units at least $N-1$ LLC converter units must be equipped with a CCVI in order to be able to balance the loads. However, the depicted example, in which each LLC converter has a CCVI, provides somewhat more flexibility.

[0015] The resonance frequency f_{R1} of the first converter unit's tank circuit composed of capacitor C_{IN1} and inductors L_{V1} and L_{P1} can be approximated by the following equation

$$f_{R1} = \frac{1}{2\pi \cdot \sqrt{C_{IN1}(L_{V1} + L_{P1})}},$$

and, accordingly, the resonance frequency f_{R1} increases with a decreasing inductance L_{V1} . Similarly, the resonance frequency f_{R2} of the second converter unit's tank circuit is

$$f_{R2} = \frac{1}{2\pi \cdot \sqrt{C_{IN2}(L_{V2} + L_{P2})}}.$$

[0016] To balance the two LLC converter units 10 and 20, the variable inductance (L_{V1} or L_{V2}) of that LLC converter unit, which provides the lower output current, is decreased in order to increase the resonance frequency (f_{R1} or f_{R2}) and thus also the output current of the respective LLC converter unit and to reduce the mismatch between the output currents. In fact, the first converter unit's tank circuit as shown in Fig. 1 has two resonance frequencies, one being associated with capacitance C_{IN1} and inductance L_{V1} , and a further one being associated with capacitance C_{IN1} and inductance $L_{V1}+L_{P1}$. The same applies for the second converter unit's tank circuit.

[0017] The mechanism described above is further illustrated by the diagram of Fig. 2, which shows the characteristic curve of the resonance of the tank circuit used in the LLC converter unit that provides the lower output current. As mentioned, the regulator circuit 30 controls the CCVI of the respective LLC converter unit to lower values thus shifting the resonance frequencies and hence shifting the respective characteristic curve (solid line) to higher frequencies (dashed line). As consequence the operating point is shifted, for a given operating frequency f_{OP} from point A to point B, i.e. towards higher output voltages and hence increasing the output current. As already mentioned, the specific way the current information is obtained is not relevant for the further discussion, and there are various different ways to obtain the current information which are as such known and are thus not explained herein in more detail.

[0018] The further discussion focusses on the implementation of the CCVIs that may be used as inductor L_{V1} and/or L_{V2} in the embodiment of Fig. 1. Generally, a CCVI is implemented by a coil (referred to as "AC coil") wound around a magnetic core. A control current is fed into a further coil (referred to as "DC coil") that is also wound around the magnetic core. The control current passing through the DC coil is a direct current (DC), whereas the input current supplied to an LLC converter unit (e.g. using a transistor bridge) and thus to AC coil is an alternating current (AC) that alternates in accordance with the operating frequency f_{OP} . The control current passing through the DC coil causes a magnetic bias field in the magnetic core, and the relative permeability of the magnetic core decreases as the bias field increases and the magnetic core gradually saturates. When the magnetic core becomes fully saturated due to a sufficiently high bias field, the relative permeability of the magnetic core reaches its minimum (relative permeability of one). The inductance of the AC coil depends on (and is approximately proportional to) the relative permeability of the magnetic core. Accordingly, an increasing control current passing through the DC coil causes the inductance of the AC coil to decrease and vice versa. The inductance

of the AC coil reaches its maximum at a control current of zero and its minimum when the control current is so high that the magnetic core is fully saturated. The general principle of a CCVI is as such known and thus not explained herein in more detail.

[0019] When using a CCVI in a switching converter it is desirable that the CCVI is designed to be efficient in terms of low power losses and low electromagnetic emissions (mainly caused by stray fields). Further, the CCVI should be able to be operated as high frequencies which, in turn, allows the magnetic core to be small. Some known CCVI concepts exhibit the problem that the AC currents passing through the AC coil can induce comparably high voltages in the DC coil, in particular when the DC-coil has a high number of windings in order to keep the control currents low. The induced voltages may be so high that a breakthrough may occur between neighboring windings of the DC coil.

[0020] Fig. 3 illustrates one embodiment of a CCVI that may be used to improve performance of an ILLC converter. According to Fig. 3 a so-called COC core assembly is used as magnetic core for the AC coil 6 that forms the CCVI and the DC coil 5 that is used to control the inductance of the AC coil 6 as explained above. The COC core assembly is composed of several core elements, in the present example an O-shaped core 2 (that may be formed by two opposing C-shaped cores 2a and 2b) and two C-shaped cores 1 and 4 that are arranged at opposing sides of the O-shaped core 2 so that air gaps δ remain between the vertical segments of the O-shaped core 2 and the adjacent (but magnetically separated therefrom by the air gaps) front sides of the horizontal segments of the C-shaped cores 1 and 3. In other words, the O-shaped core 2 is arranged between the two opposing C-shaped cores 1 and 3. It is understood that the terms "vertical" and "horizontal" merely refer to the depicted drawings as the actual CCVI may be mounted in an arbitrary position. The term O-shaped core basically denotes a ring core, i.e. a magnetic core that provides a closed, gap-free magnetic path for the magnetic field generated by a coil wound around one or more segments of the ring core. An O-shaped core may be composed of two or more parts, e.g. by two adjoining C-cores (cf. example of Fig. 3 or 5) or by a C-core and an adjoining I-core (cf. example of Fig. 5).

[0021] According to Fig. 3, the AC coil 6 is split into two partial coils 6a and 6b which are wound around C-shaped core 1 and, respectively, C-shaped core 3, and which are electrically connected in series, wherein partial coil 6a has a winding direction (winding sense) opposite to the winding direction of partial coil 6b. The partial coils 6a and 6b may be wound on both horizontal segments of the C-shaped cores 1 and 3, respectively, with an equal number of turns around the upper horizontal segments and the lower horizontal segments. Additionally or alternatively, the vertical segments of the C-shaped cores 3 and 1 may be used to arrange the turns of the coils 6a and 6b, respectively. In Fig. 3, the arrows indicate the

orientation of the resulting magnetic field obtained for positive inductor currents. The dash-dotted lines illustrate schematically the magnetic (main) paths for the magnetic flux generated by the partial coils 6a and 6b during operation. This magnetic paths, which includes the C-shaped cores 1 and 3, the air gaps and parts (vertical segments) of the O-shaped core 2, is further explained later with reference to Fig. 7.

[0022] The DC coil 5 is wound around the O-shaped core 2 which forms a closed magnetic path for the resulting bias magnetic field. The DC coil 5 has a comparably high number of turns so that even small currents will cause a magnetic field that is high enough to change the inductance of the AC coil 6. The magnetic path of coil 6a is formed by the C-shaped core 3, the two air gaps with width δ and the right vertical segment of the O-shaped core 2. Likewise, the magnetic path of coil 6b is formed by the C-shaped core 1, the two air gaps with width δ and the left vertical segment of the O-shaped core 2. When a magnetic bias field is generated in the O-shaped core by applying a DC control current i_{DC} to the DC coil 5, then the vertical segments of the O-shaped core 2 will increasingly cause magnetic losses with an increasing bias magnetic field. The magnetic resistance of the vertical segments of the O-shaped core 2 increases with an increasing bias magnetic field and, as a consequence, the magnetic resistance of the magnetic paths associated with coils 6a and 6b increases and the inductance of the AC coil 6 (composed of coils 6a and 6b) decreases accordingly.

[0023] As mentioned, the magnetic paths of AC coils 6a and 6b are formed basically by the C-shaped cores 1 and 3 and the adjacent vertical segments of the O-shaped core 2. However, a part of the (alternating) magnetic field generated by the AC coils 6a and 6b will also pass the horizontal segments of the O-shaped core 2. Due to the symmetric arrangement of the AC coils 6a and 6b and due to the fact that they have opposite winding directions, the AC fields in the horizontal segments of the O-shaped core 2 caused by AC coil 6a and AC coil 6b at least approximately compensate. Thus only little (and ideally no) AC currents are induced in the DC coil 5. Furthermore, the series connection of the AC-coils in combination with their opposite winding directions result in an improved linearity of the CCVI.

[0024] The example of Fig. 4 is almost identical to the example of Fig. 3. The only difference is that the widths d_2 of the left and right vertical segments of the O-shaped core 2 are smaller than the corresponding width d_1 in the example of Fig. 3 (and thus the respective cross-section area is smaller). Particularly, the cross-section areas of the vertical segments of the O-shaped core 2 are between 0.5 to 0.9 times the cross-section area of the C-shaped cores 1 and 3. The smaller cross-section ensures that the magnetic bias field caused by the DC current i_{DC} passing through the DC coil 5 is substantially kept inside the horizontal segments of the O-shaped core 2 even when the vertical segments reach magnetic saturation.

Consequently, the magnetic flux is better focused to the vertical segments of the O-shaped core and hence the required maximum control current i_{DC} can be reduced.

[0025] Fig. 5 illustrates another embodiment of a CCVI that may be used to improve performance of an ILLC converter. According to Fig. 5 a so-called ICICI core assembly is used as magnetic core for the AC coil 6 that forms the CCVI and the DC coil 5 that is used to control the inductance of the AC coil 6. The magnetic arrangement of Fig. 5 is similar to the example of Fig. 3. However, the positions of AC coil and DC coil are interchanged. According to Fig. 5, the AC coil 6 is arranged between the outer coils 5a and 5b, which are connected in series and form the DC coil 5, whereas, in contrast, the outer coils are the AC coils in the previous example of Fig. 3. The outer C-shaped cores 9 and 11 are each completed by a respective vertical I-shaped core 9b, 11b and are thus effectively O-shaped cores, that are arranged side-by-side with two horizontal I-shaped cores 7 and 8 in between, wherein air gaps δ remain between the right and left front sides of the I-shaped cores 7 and 8 and the adjacent C-shaped cores 9 and 11. The AC coil 6 is formed by partial coils 6a, and 6b, which are wound around the I-shaped cores 8 and 7, respectively. The dash-dotted line illustrates schematically the magnetic (main) path for the magnetic flux generated by the AC coil 6 during operation. This magnetic path, which includes the I-shaped cores 7 and 8, the air gaps and parts (segments 9a, 11a) of the outer ring cores 9, 9a, 11, 11a, is further explained later with reference to Fig. 8.

[0026] The O-shaped cores 9, 9a and 11, 11a each form a closed magnetic path for the partial coils 5b and 5a, respectively, which together form the DC coil 5. Similar as in the previous example of Fig. 3, the vertical segments 11a and 9a of the C-shaped cores 11 and 9 are part of the magnetic path of the partial DC coils 5a and 5b as well as part of the magnetic part of the AC coil 6, which is formed by the vertical segments 9a and 11a, the air gaps δ as well as the vertical I-shaped cores 7 and 8. When a control current i_{DC} is supplied to the DC coil 5, then the vertical segments 11a and 9a of the C-shaped cores 11 and 9 are magnetized by the resulting magnetic bias field which causes a respective increase of the magnetic resistance of the magnetic path associated with the AC coil 6 and a corresponding decrease of the inductance. Similar as in the example of Fig. 4, the width d_3 of the vertical segments 11a and 9a may be lower than the width d_1 of the other segments (and the respective cross-section area as well). For example, the cross-section area of the vertical segments 11a and 9a may be a factor 0.5 to 0.9 of the cross-section area of the other segments of the C-shaped cores 9 and 11.

[0027] Most of the magnetic field generated by the AC coil 6 (magnetic AC flux) is guided through the vertical segments 9a, 11a of the C-shaped cores 9 and 11. However, a minor portion of the AC-flux will also run through the DC coils 5a and 5b arranged on the horizontal segments of the C-shaped cores 9 and 11 thereby inducing

an AC-voltage in the DC coils 5a and 5b. Unlike in the previous example of Fig. 3, the AC flux is not (approximately) compensated at the position of the DC coils and thus the mentioned AC voltage is induced. However, at sufficiently high operating frequencies, the mentioned AC voltage is effectively shorted by the winding capacitance of the multi-turn DC-coils 5a, 5b. In order to prevent problems at lower frequencies additional short circuit windings with a single turn can be placed on the C-shaped cores 9, 11, e.g. over the DC coils 5a and 5b or on the outer I-cores 9b and 11b. For example, the short circuit windings may be made of copper foil or the like. The example of Fig. 6 is substantially identical to the example of Fig. 5 but additionally includes the mentioned short circuit windings which are denoted with numerals 12a and 12b.

[0028] The CCVI embodiments described herein allow lower loss and low electromagnetic emissions. Furthermore, the CCVI embodiments described herein allow operation of the ILLC switching converter at a comparable high frequency and therefore the size of the CCVI can be reduced. One feature that is (at least in part) responsible for the comparably low losses is the division of the total air gap in the magnetic path of the AC flux into four smaller air gaps δ . As a consequence the parasitic stray fields are lower and also the parasitic eddy currents resulting from the stray fields. Furthermore, losses are further reduced due to the symmetric arrangement of the coils. Accordingly, only a small portion of the core segments that form the magnetic path for the AC flux is pre-magnetized (which entails enhanced core losses) by the magnetic bias field. These are the vertical segments 9a and 11a of C-shaped cores 9 and 11 in the example of Fig. 5, and the vertical segments of O-shaped core 2 in the example of Fig. 3. The reduction of the cross-sectional area of the mentioned vertical segments (cf. Fig. 4) further helps to concentrate saturation to the relevant parts of the core assembly.

[0029] Another aspect addresses electromagnetic emissions (EMI). Particularly when the relevant core segments are strongly magnetized (up to saturation) by the magnetic bias field. Different from known CCVI implementations, which basically produce a magnetic AC flux similar to a rod magnet when magnetized up to saturation by the bias field, the ICICI-CCVI of Fig. 5 basically produces a magnetic quadrupole field when the vertical core segments are magnetized up to saturation by the bias field. The (approximate) quadrupole field is generated because the AC coil 6 is composed of two partial coils with I-shaped cores (see Fig. 5 horizontal cored 7, 8) arranged anti-parallel closely adjacent to each other. Such an arrangement is also more efficient in terms of losses.

[0030] Figures 7 and 8 includes magnetic circuit diagrams illustrating the equivalent magnetic paths of the examples shown in Figs. 3 and 4 and, respectively, Figs. 5 and 6. Both diagrams illustrate the magnetic resistances (often referred to as reluctances) of the components

(air gaps and cores) that form the magnetic paths for a magnetic flux as well as the sources of magnetomotive force (corresponding to the DC coils generating the magnetic biasing field). It can be seen that the four magnetic resistances R_δ are symmetrically arranged with respect to the cores the form the magnetic core assembly.

[0031] The magnetic circuit of Fig. 7 represents the embodiment of Fig. 3 and 4. In these examples the AC coil is formed by series circuit of a two partial coils 6a, 6b (not shown in Fig. 7), which are arranged side by side with the DC coil 5 in between. In this case, the magnetic core assembly includes one ring core 2 (composed of C-shaped core elements 2a and 2b), around which the DC coil 5 is wound, and two further cores 1 and 3, around which the two partial coils 6a, 6b of the first coil are wound. The two further cores 1 and 3 are arranged on opposing sides of the ring core 2 so that two air gaps δ are formed between the ring core 2 and each one of the two further cores 1 and 3.

[0032] In Fig. 7 the air gaps are represented by magnetic resistances R_δ , and the (O-shaped) ring core 2 is represented by the magnetic resistances R_{2a} and R_{2b} . It is noted that R_{2a} and R_{2b} in fact represent only the vertical segments of the ring core 2 (cf. Fig. 4), which is a simplification because the magnetic resistance of the horizontal segments of the ring core 2 is comparably small. The DC coil 5 is represented by the source MMF₅ of magnetomotive force generating the DC flux (representing the magnetic bias field). The magnetic resistances R_{2a} and R_{2b} are variable and depend on the magnetic flux generated by the source MMFs of magnetomotive force (DC coil 5) as explained above. The further cores 1 and 3 are represented by magnetic resistances R_1 and R_3 which are, however, negligibly small as compared to the magnetic resistance R_δ of an air gap. The magnetic resistance of the magnetic path of the AC coils 6a and 6b, which determines the inductance of the CCVI, basically depends on the air gaps (magnetic resistances R_δ) and the magnetic resistances R_{2a} and R_{2b} that depend on the DC flux generated by the DC coil 5.

[0033] The magnetic circuit of Fig. 8 represents the embodiment of Fig. 5 and 6. In these examples the DC coil 5 is a series circuit of a two partial coils 5a and 5b, which are arranged side by side with the AC coil 6 in between. In this case, the magnetic core assembly includes two ring cores (see Fig. 5, cores 9 and 9b and cores 11 and 11b), around which the two partial coils 5a and 5b of the DC coil 5 are wound. The magnetic core assembly further includes a further core comprising two core segments (see Fig. 5, I-shaped cores 7 and 8), around which the AC coil 6 is wound. The further core segments 7 and 8 are arranged between the two ring cores leaving an air gap δ between each one of the two core segments 7, 8 and each one of the two ring cores.

[0034] As in the previous example of Fig. 7, the magnetic resistances of the outer ring cores are essentially determined by the magnetic resistances R_9 and R_{11} of the vertical segments 9a and 11a (see Fig. 5), whose

magnetic resistances depends on the magnetomotive force generated by the sources MMF_{5a} and MMF_{5b} (representing partial coils 5a and 5b) and on the resulting DC flux. The magnetic resistance of the magnetic path of the AC coil, which determines the inductance of the CCVI, basically depends on the air gaps (magnetic resistances R_{δ}) and the magnetic resistances R_9 and R_{11} . The magnetic resistances R_8 and R_7 are negligible as compared to the magnetic resistances of the air gaps.

[0035] Although the invention has been illustrated and described with respect to one or more implementations, alterations and/or modifications may be made to the illustrated examples without departing from the spirit and scope of the appended claims. In particular regard to the various functions performed by the above described components or structures (units, assemblies, devices, circuits, systems, etc.), the terms (including a reference to a "means") used to describe such components are intended to correspond - unless otherwise indicated - to any component or structure, which performs the specified function of the described component (e.g., that is functionally equivalent), even though not structurally equivalent to the disclosed structure, which performs the function in the herein illustrated exemplary implementations of the invention.

Claims

1. An inductive component comprising:

a magnetic core assembly comprising a first portion (1, 3; 7, 8) and a second portion (2a, 2b; 9a, 11a), which is magnetically separated from the first portion (1, 3; 7, 8) of the magnetic core assembly via two or more air gaps (δ);
 an inductor with a variable inductance including a first coil (6; 6a, 6b) that is arranged on the first portion (1, 3; 7, 8) of the magnetic core assembly;
 a second coil (5, 5a, 5b) arranged on the second portion (2a, 2b; 9, 11) of the magnetic core assembly and configured to generate a bias magnetic field in the second portion (2a, 2b; 9, 11) of the magnetic core assembly,
 wherein the first coil (6; 6a, 6b) is configured to generate a magnetic flux in a magnetic path that includes the first portion (1, 3; 7, 8) of the magnetic core assembly, the two or more air gaps (δ) and a part of the second portion (2a, 2b; 9, 11) of the magnetic core assembly.

2. The inductive component of claim 1,

wherein the first coil comprises a first partial coil (6a) and a second partial coil (6b) connected in series to the first partial coil (6a), and
 wherein the first partial coil (6a) is arranged on

a first core segment (1, 7) and the second partial coil (6b) is arranged on a second core segment (3, 8) of the first portion of the magnetic core assembly.

3. The inductive component of claim 1 or 2, wherein the second portion (2a, 2b) of the magnetic core assembly forms a closed magnetic path for the magnetic flux generated, during operation, by the second coil (5).

4. The inductive component of claim 3, wherein the first portion of the magnetic core assembly includes a first core (1) and a second core (3) arranged on opposing sides of the second portion (2a, 2b) of the magnetic core assembly.

5. The inductive component of claim 4, wherein the first core (1) and a second core (3) of the first portion (1, 3) of the magnetic core assembly are arranged symmetrically with respect to the second portion (2a, 2b) of the magnetic core assembly.

6. The inductive component of any of claims 3 to 5,

wherein the second portion (2a, 2b) of the magnetic core assembly forms an magnetic ring core; and

wherein the first portion (1, 3) of the magnetic core assembly is composed of two C-shaped magnetic cores, each separated from the magnetic ring core by the two air gaps.

7. The inductive component of claim 1 or 2, wherein the second portion of the magnetic core assembly includes a first ring core (11, 11b) and a second ring core (9, 9b) that are arranged on opposing sides of the first portion (7, 8) of the magnetic core assembly.

8. The inductive component of claim 7, wherein the first ring core (11, 11b) and a second core (9, 9b) of the second portion of the magnetic core assembly are arranged symmetrically with respect to the first portion (7, 8) of the magnetic core assembly.

9. The inductive component of claim 7 or 8,

wherein the second coil (5) comprises a first partial coil (5a) and a second partial coil (5b) connected in series to the first partial coil (5a), and wherein the first partial coil (5a) of the second coil (5) is arranged on the first ring core (11, 11b) and the second partial coil (5b) of the second coil (5) is arranged on the second ring core (9, 9b).

10. The inductive component of any of claims 7 to 9,
wherein the first portion of the magnetic core assembly includes a first I-shaped core (8) and a second I-shaped core (7) arranged substantially parallel to the first I-shaped core (8). 5
11. The inductive component of any of claims 7 to 10,
wherein the part of the second portion of the magnetic core assembly, which is included in the magnetic path of the flux generated by the first coil (6), is formed by one segment (11a) of the first ring core (11, 11b) and one segment (9a) of the second ring core (9, 9a). 10
12. The inductive component of any of claims 7 to 11, 15
wherein a first short circuit winding is arranged on the first ring core (11, 11b) and a second short circuit winding is arranged on the second ring core (9, 9a).
13. The inductive component of any of claims 1 to 12, 20
wherein the part of the second portion of the magnetic core assembly, which is included in the magnetic path of the flux generated by the first coil (6), as a lower magnetic cross-section area than the remainder of the second portion of the magnetic core assembly, which is not included in the magnetic path of the flux generated by the first coil (6). 25
14. A multiphase LLC switching converter comprising: 30
at least two LLC switching converter units, each including a tank circuit and each tank circuit including an inductor,
wherein the inductor of the tank circuit of at least one of the LLC switching converters is an inductive component in accordance with any of claims 1 to 13. 35
15. A method comprising: 40
supplying an AC current to a first coil (6; 6a, 6b), wherein the first coil (6; 6a, 6b) is arranged on a first portion (1, 3; 7, 8) of a magnetic core assembly, and
generating a bias magnetic field in a second portion (2a, 2b; 9, 11) of the magnetic core assembly by supplying a DC current to a second coil (5, 5a, 5b) that is arranged on the second portion (2a, 2b; 9, 11) of the magnetic core assembly; 45
the second portion (2a, 2b; 9a, 11a) of the magnetic core assembly being magnetically separated from the first portion (1, 3; 7, 8) of the magnetic core assembly via two or more air gaps (δ); and
controlling the inductance of the first coil (6; 6a, 6b) by adjusting the DC current supplied to the second coil (5, 5a, 5b); 50
wherein the AC current, when passing through 55

the first coil (6; 6a, 6b), generates a magnetic flux in a magnetic path that includes the first portion (1, 3; 7, 8) of the magnetic core assembly, the two or more air gaps (δ) and a part of the second portion (2a, 2b; 9, 11) of the magnetic core assembly.

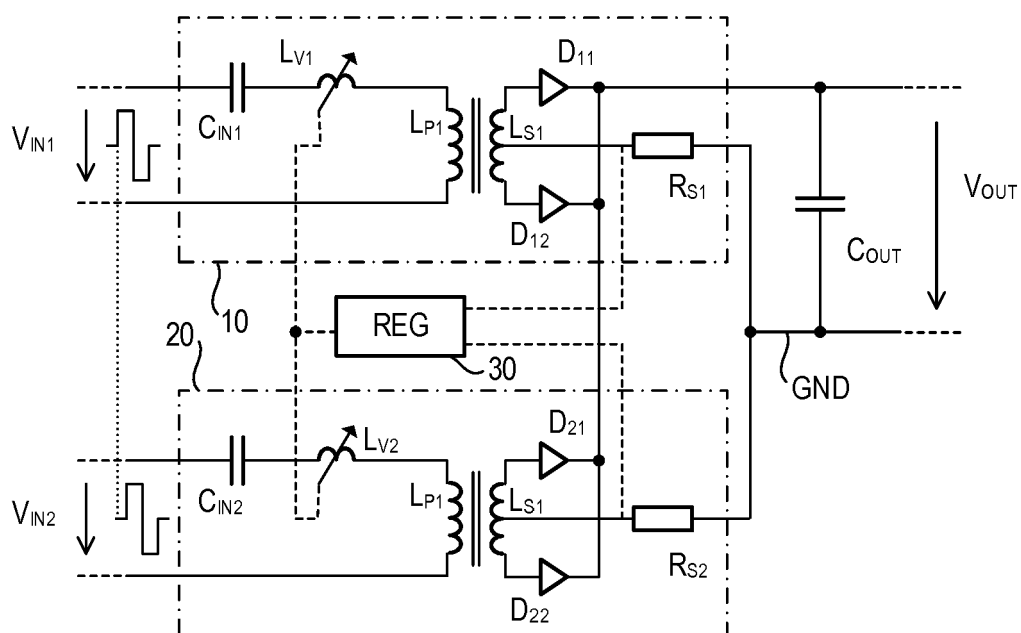


FIG. 1

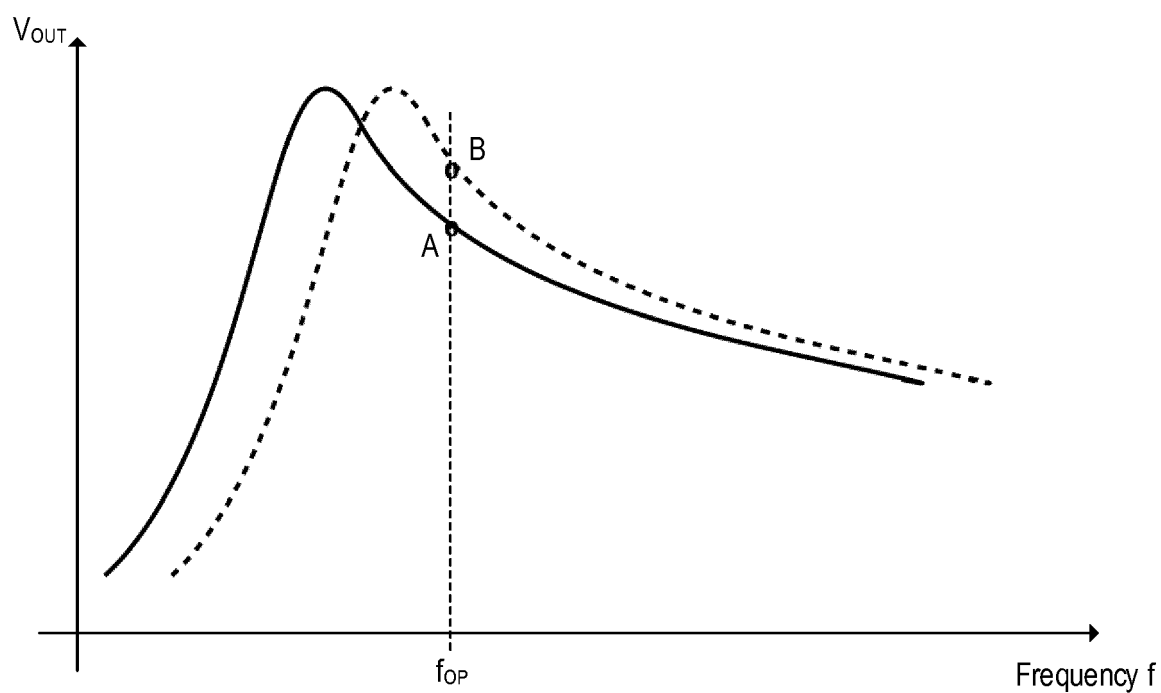


FIG. 2

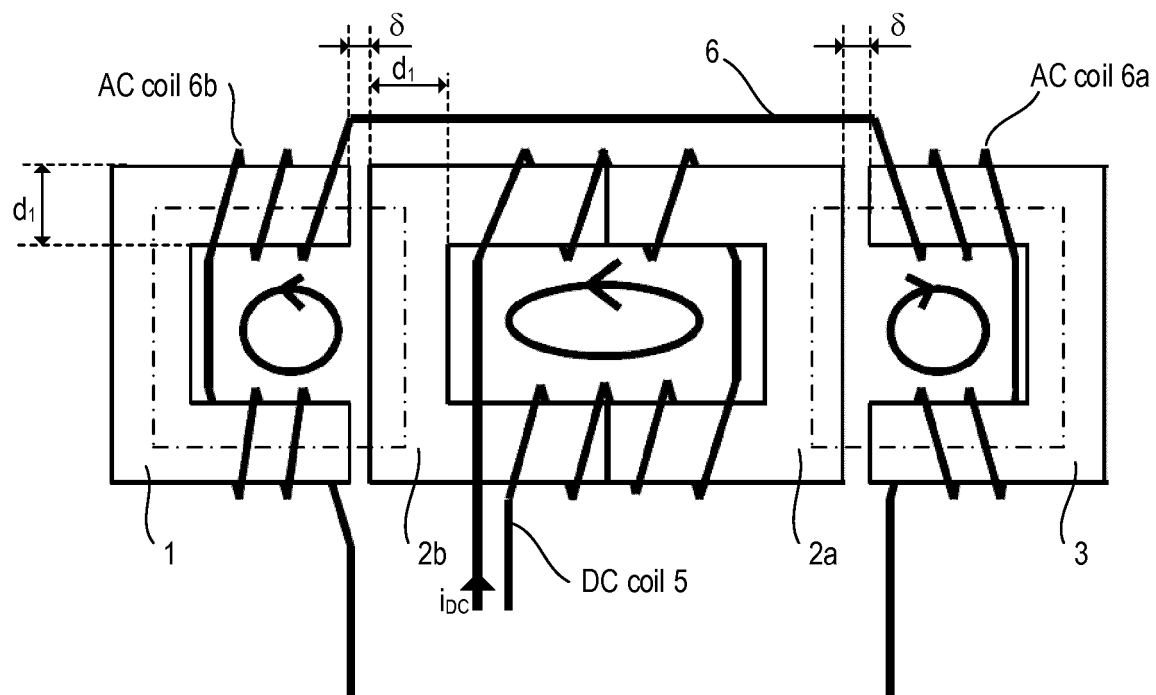


FIG. 3

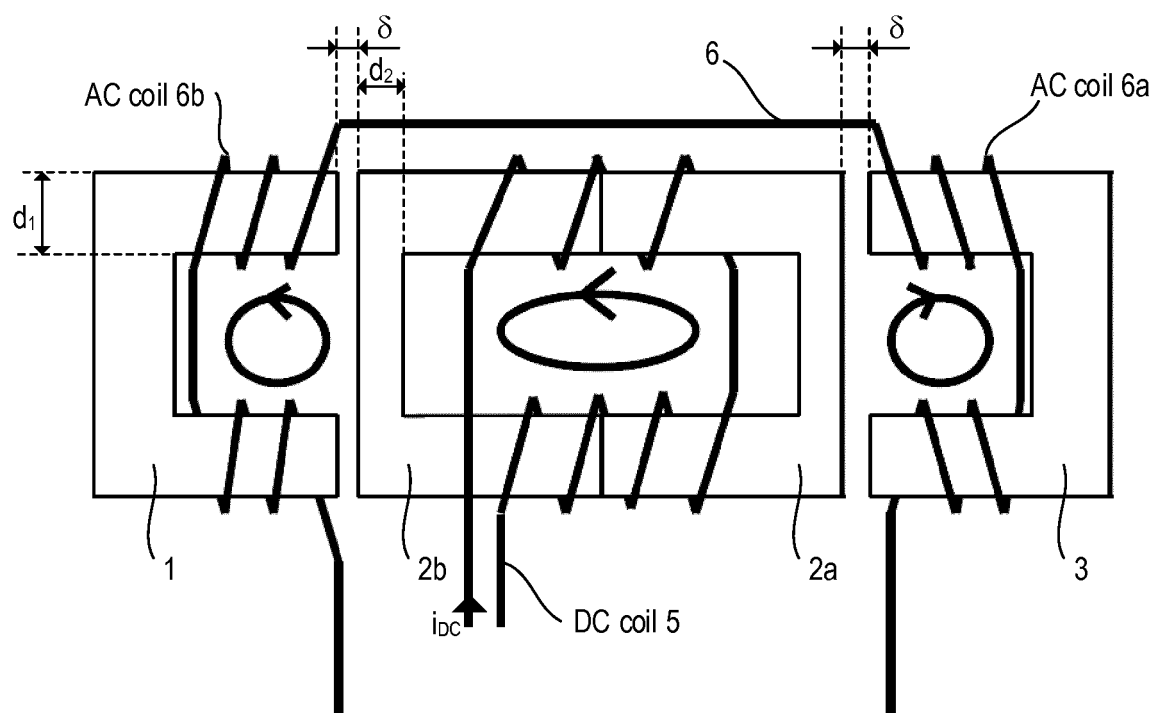


FIG. 4

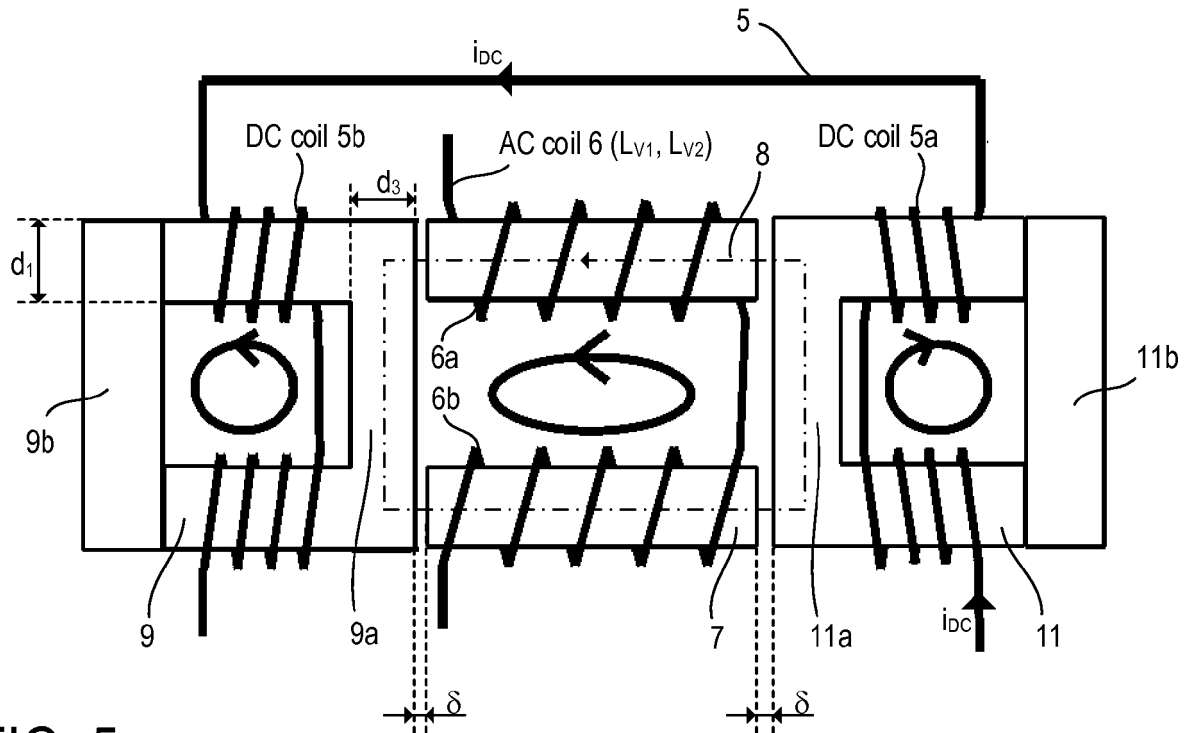


FIG. 5

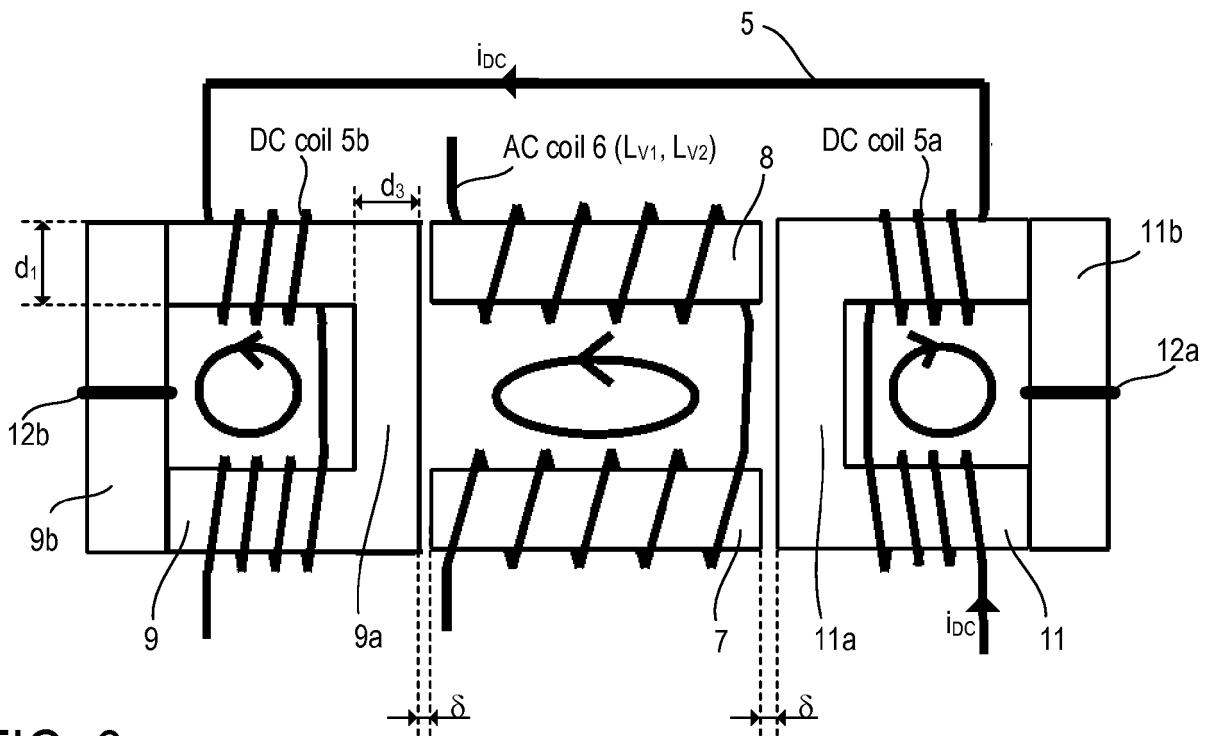


FIG. 6

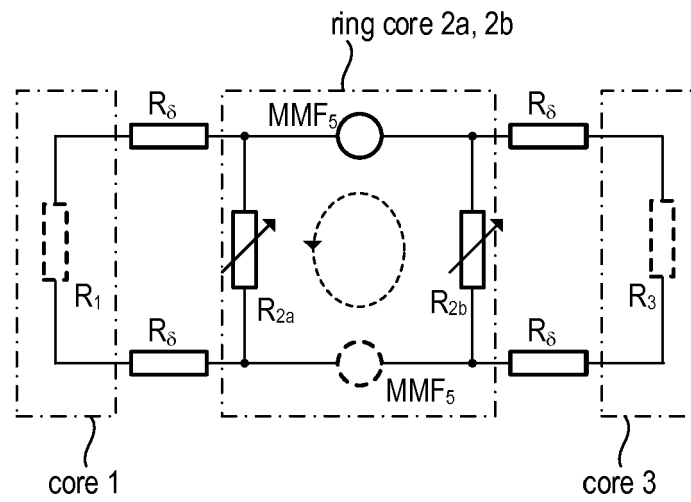


FIG. 7

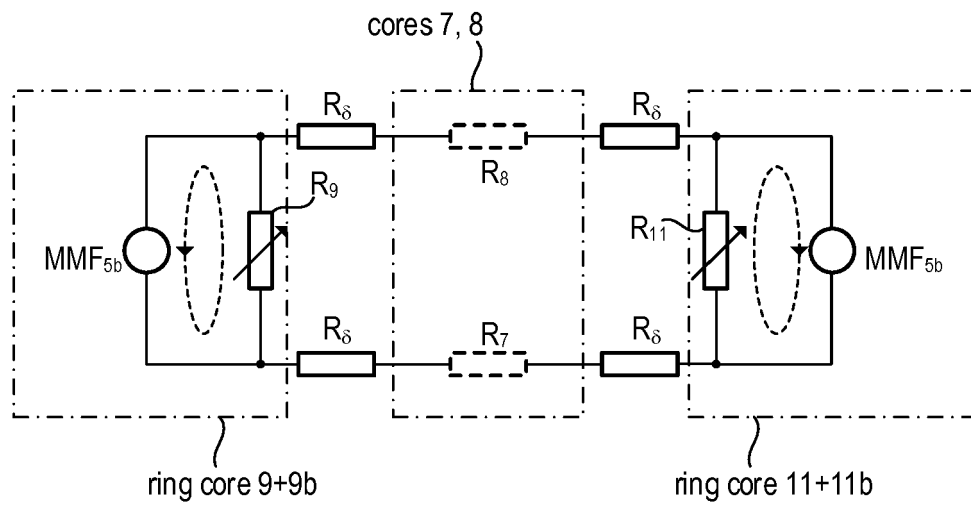


FIG. 8



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Application Number
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