

## AN INTEGRATED INDUCTOR AND A METHOD FOR REDUCTION OF LOSSES IN AN INTEGRATED INDUCTOR

### DESCRIPTION

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### TECHNICAL FIELD

The present invention relates to an integrated inductor for use in resonant energy-conversion systems ensuring minimization of losses in a ferromagnetic core and to a method for reduction of losses in an integrated inductor.

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### BACKGROUND ART

Resonant energy-conversion systems, despite of their advantages, such as sinusoidal currents, soft switching capability, wide operating frequency range, etc., are relatively slowly superseding the classical solutions based on hard switching. The reason is that in a resonant circuit the peak current values are substantially exceeding the maximum load current. Therefore, the reactance elements, both the capacitors and inductors, shall be designed to store relatively large amounts of energy. This problem can be solved by increasing both the weight and dimensions of reactance elements. However, such approach is not economically viable, since it entails additional costs and, consequently, a higher price. A further unfavourable effect is the decrease in energy efficiency, because the increase in the inductive elements dimensions in resonant energy-conversion systems results in considerable losses in windings, particularly at frequencies above 100kHz. Also increasing the ferromagnetic core dimensions, while maintaining a constant rms value of the magnetic flux density is the reason that losses increase linearly with the core volume. Recently, due to rising electricity prices and legislative measures aimed at limitation of electric power consumption and its rational utilization, the energy efficiency becomes the crucial parameter influencing the potential success of the proposed solution.

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The US Patent No. 5,886,516 presents an integrated multi-winding magnetic element intended for operation in a series resonant converter, in which on a single "UU" gapped magnetic core there are located two windings of an isolation transformer and two additional windings constituting two inductive  
5 elements of the resonant circuit. This assembly constitutes a resonant circuit consisting of three inductances, two capacitances and the isolation transformer.

An integrated-magnetic apparatus is known from the US Patent No. 5,726,615 comprising three ferromagnetic pot cores, two of which have central core-columns carrying two flat windings placed around these columns. These two  
10 inductive elements constitute a transformer. The third ferromagnetic pot core has a shorter central core-column around which a flat winding is placed. The third core-piece located adjacent to a flat exterior surface of the transformer allows to form the third inductive element. The third inductive element is partially coupled magnetically through an air gap to the other windings and is phased to have the  
15 magnetic induction in the same direction as the magnetic induction in the un-gapped magnetic circuit.

The US Patent No. 7,525,406 presents a structure that contains a plurality of coupled and non-coupled inductive elements and at least one closed magnetic circuit comprised of mutually contiguous magnetic elements having grooves for  
20 current conductors in the X-axis and a perpendicular Y-axis. The current conductors located along the same axis exhibit mutual inductance but none between mutually orthogonal axes.

The Polish patent application No. 393133 presents a method for increasing the power transferred by an integrated inductor characterized by positioning an  
25 integrated inductor's windings orthogonally with respect to each other and the choice of induction elements values so that magnetic flux of the auxiliary magnetic circuit is transferred through at least a portion of the main magnetic circuit transferring the main magnetic flux while both magnetic induction vectors are oriented orthogonally with respect to each other, in addition both variable in time  
30 magnetic induction vectors are shifted with respect to each other in the time domain.

In the article „1MHz-1kW LLC Resonant Converter with Integrated Magnetics”, Zhang, Yanjun Xu, Dehong Mino, Kazuaki Sasagawa, Kiyooki, Applied Power Electronics Conference, APEC 2007 - Twenty Second Annual IEEE, Feb. 25 2007–March 1 2007, pp. 955-961, there is described an integrated  
5 magnetic module in which the region of magnetic induction compensation is restricted to a small portion of the magnetic core volume. Moreover, in this element there occurs a problem of large resonant induction values with respect to the transformer induction value and also a relatively large effect of increasing the resistance of copper windings being in magnetic field from air gaps in magnetic  
10 circuits.

The article “Planar Integrated Magnetics Design in Wide Input Range DC-DC Converter for Fuel Cell Application”, Ziwei Ouyang, Zhe Zhang, Ole C. Thomsen, Michael A. E. Andersen, Ole Poulsen, Thomas Björklund, Energy Conversion Congress and Exposition (ECCE), 2010 IEEE: 12-16 Sept. 2010, pp.  
15 4611-4618, also describes an integrated magnetic module in which the region of magnetic induction compensation is restricted to a small portion of the magnetic core volume. In this solution, a so-called hot spot occurs, where magnetic induction vectors produced by inductive elements of integrated magnetic circuits are summing up.

20 The above examples illustrate integrated reactances intended for use in resonant DC/DC converters. Nevertheless, said integrated reactances do not fully utilize the multi-winding inductor as an output transformer in resonant energy-conversion systems, and therefore, a reduction of thermal losses in inductive elements of the resonant circuit.

25 It would be, therefore, advisable to develop an integrated reactance element, characterized by reduced thermal losses in its resonant circuit inductive elements, and suitable for use in resonant DC/DC converters.

## DISCLOSURE OF THE INVENTION

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The object of the invention is an integrated inductor comprising a multi-winding inductor having a transformer winding and a resonant inductor, wherein

sections, of the magnetic circuit of the transformer winding are incorporated into magnetic circuits of at least two parts, of a resonant inductor so as to form common parts of magnetic circuit of the multi-winding inductor and at least two-part, resonant inductor, wherein the transformer winding of the multi-winding  
5 inductor is wound around a column, which has at least one air gap having a width adapted so that the magnetic induction produced by the at least two-part, resonant inductor does not exceed 25% of the magnetic induction produced by the transformer winding of the multi-winding inductor.

Preferably, the transformer winding of the multi-winding inductor is wound  
10 around the column in a single layer.

Preferably, the transformer winding of the multi-winding inductor is a pitched winding wound around the column.

Preferably, in that the column, over which the transformer winding of the multi-winding inductor is wound, comprises two air gaps at its ends.

15 Preferably, the integrated inductor it comprises magnetic core-pieces that constitute a magnetic circuit with parallel columns magnetically connected with the yoke whereas the transformer winding of the multi-winding inductor is wound on the column parallel to columns on which the windings, of the resonant inductor are wound.

20 Preferably, the integrated inductor further comprises columns, parallel to the yoke, with further windings of the resonant inductor which are wound around said columns.

Preferably, the integrated inductor comprises magnetic core-pieces circumferentially arranged around the column having the transformer winding,  
25 wherein windings of the resonant inductor are wound on said magnetic core-pieces.

Another object of the invention is a resonant power supply comprising the integrated inductor according to the invention, wherein the multi-winding inductor acts as the output transformer and the inductive element is connected in series  
30 through the resonant inductor with with transistor switches.

The invention also relates to a method for reduction of losses in an integrated inductor comprising a multi-winding inductor having a transformer

winding and a resonant inductor, wherein sections, of the magnetic circuit of the transformer winding are incorporated into magnetic circuits of at least two parts, of the resonant inductor so as to form common parts of magnetic circuit of the multi-winding inductor and at least two-part resonant inductor wherein the transformer winding of the multi-winding inductor is wound around a column, which has at least one air gap having a width which is adapted so that the magnetic induction produced by the at least two-part, resonant inductor does not exceed 25% of the magnetic induction produced by the transformer winding of the multi-winding inductor.

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#### BRIEF DESCRIPTION OF DRAWINGS

The invention is shown by means of exemplary embodiments on a drawing, in which:

15 Fig. 1 shows a half-bridge structure of a multi-resonance power supply with a quality-factor limiter based on an integrated inductor ZER according to the first embodiment.

20 Fig. 2 shows the first embodiment of the integrated inductor wherein variable magnetic inductions produced by the multi-winding inductor, which also functions as an output transformer, and by the resonant inductor, are oriented parallel with respect to each other in such a manner that the resultant time-variable vector of both magnetic inductions attains its minimum value.

25 Fig. 3 shows exemplary simulation of magnetic induction distribution in the integrated inductor according to the first embodiment wherein the current flowing in the resonant inductor  $L_2=L_{2A}+L_{2B}$  equals 0 arbitrary units, whereas the current flowing in the L1 coil equals 0.67 arbitrary units. The central column of the magnetic core incorporates an air gap.

30 Fig. 4 shows exemplary simulation of magnetic induction distribution in the integrated inductor according to the first embodiment, wherein the current in the resonant inductor  $L_2=L_{2A}+L_{2B}$  equals 1 arbitrary unit, whereas the current in the L1 coil equals 0.67 arbitrary units. The magnetic core central column incorporates

an air gap and the directions of currents are chosen so that they are opposite in phase (a 180° phase shift).

Fig. 5 shows schematically the second embodiment of the integrated inductor, and Fig. 6 shows the example of its application in a resonant power supply circuit.

Fig. 7 shows schematically the third embodiment of the integrated inductor, and Fig. 8 shows the example of its application in a resonant power supply circuit.

Fig. 9 shows schematically the fourth embodiment of the integrated inductor's spatial structure.

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## MODES FOR CARRYING OUT THE INVENTION

Fig. 1 shows the first example of application of the integrated inductor according to the invention in a resonant-mode power supply circuit. The integrated inductor ZER1 comprises a resonant inductor L2 consisting of two inductive elements L2A and L2B connected in series and a multi-winding inductor, which also acts as the output transformer, composed of three inductive elements L1, L3, L4 having a common magnetic circuit. The inductive element L1 is connected in series through the inductor L2=L2A+L2B with transistor switches K1, K2; the output winding L4 and the quality-factor limiter winding L3 and the inductor L5 are connected to the diode voltage limiter PD1. The primary winding is also connected with the capacitive circuit C2=C2A+C2B. Due to a series connection of the capacitive circuit C2=C2A+C2B with the inductor L2=L2A+L2B, the resulting impedance of these elements is strongly dependent on frequency, which allows controlling the voltage provided to the secondary winding L4 of the multi-winding inductor. Because at resonance, the value of the voltage at the winding of the multi-winding inductor may achieve high values, a circuit for limiting good has been employed, which forms a control winding L3 connected with the inductor L5 and a diode voltage limiter PD1.

Fig. 2 shows the first embodiment of the integrated inductor according to the invention. The integrated inductor comprises two „E” shaped core-pieces assembled with their legs joined together and two „U” shaped core-pieces whose

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legs are joined to the corners of said two „E” shaped core-pieces. These core-pieces constitute columns 11, 12, 13, 14, 15 parallel with respect to each other whereas the multi-winding inductor winding L1 is wound around the column 11. The intermediate columns 12, 13 have no windings. Around outer columns 14, 15 there are wound windings L2A, L2B of the two-part resonant inductor L2. Columns 11-15 are connected by means of yokes 21, 22 that close the magnetic circuit. Such configuration ensures minimum leakage flux from the multi-winding inductor whereof the main flux closes within the "E" core-pieces. Furthermore, the multi-winding inductor magnetic circuit comprises at least one air gap G that enables controlling the maximum magnetic induction value in the magnetic core and therefore power losses occurring in the core. The width of the air gap G is chosen so that magnetic induction produced by the at least two-part L2A, L2B resonant inductor L2 does not exceed 25% of the magnetic induction produced by the multi-winding inductor's transformer winding L1. Moreover, such construction with a single-layer, preferably pitched, winding having a break over the air gap minimizes the magnetic coupling between magnetic elements, ensures symmetry of the windings and minimizes the losses associated with the influence of magnetic field around the air gap. The resonant inductor winding utilizes two „U” shaped core-pieces on which the windings L2A and L2B are placed. In the embodiment shown in Fig. 3 and Fig. 4 the preferable directions of magnetic induction produced by the integrated inductor windings are depicted in the form of curves drawn in dashed lines with arrowheads indicating the direction, while in Fig. 3 the current flows only through the element L1, whereas in Fig. 4 through elements L1 and L2. An advantageous feature of the integrated inductor shown in Fig. 2 is the ease of adjustment to different values of power transferred by means of typical magnetic elements of a suitable size. Due to parallel positioning of the multi-winding inductor winding L1 with respect to resonant inductors' windings L2A and L2B, the magnetic inductions produced by these windings are also parallel oriented. The winding L3, most often wound over the L1 winding, is not shown in Fig. 2 to increase its clarity. Furthermore, depending on the phase shift between both magnetic induction vectors achieved by means of an appropriate choice of relative values of the reactance elements incorporated in the resonant-mode power supply

or by choice of an appropriate topology, the amplitude of magnetic induction can be reduced within a certain range and, consequently, a reduction of losses in the magnetic core can be achieved. For this purpose, the phase shifts between the magnetic inductions superimposing in a selected portion of the magnetic circuit are  
 5 chosen so as to achieve the smallest possible losses. Preferably, the phase shift between magnetic induction vectors produced by inductors L1 and L2 is basically  $180^{\circ}$ .

It is well known to describe the losses in a ferromagnetic core by the  
 10 equation:

$$P_V = P_{V,histerezy} + P_{V,prqrq-wirowe} + P_{V,resztkowe}$$

The losses  $P_V(B, f, T)$  in a ferromagnetic core depend primarily on the magnetic  
 15 induction  $B$ , the magnetic field frequency  $f$  and the core temperature  $T$ , whereas:

$$P_V(B) \approx B^{2+y} \text{ where } y \in [0,1]$$

$$P_V(f) \approx f^{1+x} \text{ where } x \in [0,1]$$

$P_V(T)$  attains its minimum near  $90^{\circ}\text{C}$ .

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In the resonant-mode power supply according to Fig. 1 it is possible to achieve a constant phase shift of ca.  $\pm 90^{\circ}$  between the current in the inductor L2A and L2B and the current in the multi-winding inductor winding L1. Assuming equal amplitudes of the magnetic induction vectors, the resultant magnetic induction  
 25 amplitude in the magnetic circuit portion where both magnetic fluxes are superimposing is:

$$B_{12}(t) = B_A \cdot (\sin \omega t + \cos \omega t) = B_A \cdot \sqrt{2} \cdot \sin(45^{\circ} + \omega t) = B_{A12} \cdot \sin(45^{\circ} + \omega t)$$

$$B_{A12} = B_A \cdot \sqrt{2}$$

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Assuming both induction vectors are on the same plane but opposite in phase (a 180° phase shift) and assuming for sinusoidal waveforms the same amplitude of the inductions associated with coils (L1) and (L2=L2A+L2B)  $B_{A1}=B_{A2}=B_A$ , and if magnetic fields are shaped so that they cancel out, the resultant magnetic induction  $B_{12}(t)$  in certain regions is  $B_{A12}$  :

$$B_{12}(t) = B_A \cdot (\sin \omega t - \sin(\omega t)) = B_{A12} \cdot 0 = 0$$

The integrated inductor according to the invention has a particularly desirable feature that two inductive elements L2A, L2B utilize portions 1 and 2 of the multi-winding inductor and losses in common branches of magnetic circuits can be substantially reduced by means of reduction of the magnetic induction vector amplitude.

Fig. 3 and Fig. 4 show results of simulation of the magnetic induction vector distribution in the integrated inductor according to the invention. Fig. 3 illustrates the integrated inductor condition when the resonant inductor L2=L2A+L2B current equals 0 arbitrary units and the coil L1 current is 0.67 arbitrary units. The central column of the magnetic core incorporates an air gap. This is the initial condition, which is the basis for comparison because there are no compensating magnetic inductions from the resonant inductor.

Fig. 4 shows simulation of the magnetic induction vector distribution in the integrated inductor in which the resonant inductor L2=L2A+L2B current equals 1 arbitrary unit and the current in coil L1 is 0.67 arbitrary units. The central column of the magnetic core incorporates an air gap and directions of currents in windings L1 and L2 are chosen so that they are phase-shifted by 180°. In the external branches of the ferromagnetic core, the magnetic induction current has been decreased from a value of 0.8 arbitrary units to the value of 0.45 arbitrary units. In such a situation, it is possible to assess a relative change of the power of losses, assuming that there is a square relationship between the value of power of losses in the core and the value of the magnetic induction:

$$P_V(B) \approx B^2$$

If, for example, the magnetic induction amplitude is reduced within 33% of the core volume and the magnetic induction amplitude decreases from 0.8  
 5 arbitrary units to 0.45 arbitrary units then, due to the reduction of magnetic induction within 33% of the core volume, thermal losses in chosen portions of the magnetic circuit decrease by 67% and by 20% in the whole core.

Fig. 5 shows schematically the second embodiment of the integrated inductor, and Fig. 6 shows the example of its application in the resonant power  
 10 supply circuit. The second embodiment is equivalent to the first one except for the fact that it contains two air gaps G1 located at the ends of the column 11, between the magnetic element of column 11 and the yoke 21, 22. The advantage of this solution over the configuration comprising a single gap G in the middle of the column 11 is that it allows to achieve the self-screening effect of magnetic field  
 15 from air gaps (reduction in electromagnetic emission, minimization of losses associated with magnetic field near the air gap and minimization of couplings between magnetic elements through the external yoke) and allows to maintain a symmetry of magnetic fields distribution (equal number of volts-per-turn, independently on the position on the column). The second embodiment, similarly  
 20 as the first one, comprises air gaps G2 in the yoke connecting the column 11, around which the transformer windings are wound, with the columns 14 and 15 with the resonant inductor windings L2A, L2B. The direction of magnetic induction produced by the transformer winding L1 is shown with a dashed line and the direction of magnetic induction produced by the resonant inductor windings L2A,  
 25 L2B is represented by a dashed-and-dotted line. In the second embodiment the height of the column 11 is larger than the distance between the column 11 and columns 14, 15, and therefore the transformer winding L1 can be wound as a single-layer winding or, in the case of a larger length of the column 11, as a pitched winding. A single-layer wound transformer winding L1 allows to reduce  
 30 windings losses (reduction of the proximity effect) and also to attain as large as possible relative length of the common magnetic path (losses reduction in magnetic material) and enables a flat, planar construction. Reduction in parasitic

capacitances of the transformer windings enables to increase the operating frequency.

Fig. 7 shows schematically the third embodiment of the integrated inductor, and Fig. 8 shows the example of its application in the resonant power supply circuit. The integrated inductor according to the third embodiment differs from the integrated inductor according to the second embodiment in that it has a four-element resonant inductor which, apart of windings L2A, L2B wound around columns 14, 15 parallel to the column 11, has also windings L2C, L2D wound around columns 16, 17 parallel to the yoke 12, 13. That allows to additionally increase the volume of the magnetic material in which the reduction of magnetic induction occurs and, consequently, reduction of losses in the magnetic core.

Since under resonance conditions the voltage across the multi-winding inductor may attain large values, the solution incorporates a quality-factor limiting circuit that consists of the control winding L3 connected with inductor L5 and a diode voltage limiter PD1.

Fig. 9 shows schematically the fourth embodiment of the integrated inductor's spatial structure wherein the six-part resonant inductor's windings L2A, L2B, L2C, L2D, L2E, L2F are wound around columns 31, 32, 33, 34, 35, 36, arranged circumferentially around the column 11 carrying the transformer winding. The columns 31-36 can be curvilinear and in this embodiment they have the form of a half of a torus and thus facilitate the construction of a bobbin (also in the toroidal form) and winding of coils, and enable achieving significant reduction in core losses. The circumferential arrangement of columns 31-36 allows minimization of air gaps and thus effective reduction of magnetic flux leakage from the integrated magnetic element as well as compact, low profile construction and, consequently, substantial reduction of parasitic inter-turn capacitances.

## CLAIMS

1. An integrated inductor comprising a multi-winding inductor having a transformer winding (L1) and a resonant inductor (L2) characterized in that sections (1), (2) of the magnetic circuit of the transformer winding (L1) are  
5 incorporated into magnetic circuits of at least two parts (L2A), (L2B) of a resonant inductor (L2) so as to form common parts of magnetic circuit of the multi-winding inductor (L1) and at least two-part (L2A), (L2B) resonant inductor (L2), wherein the transformer winding (L1) of the multi-winding inductor is wound around a column  
10 (11), which has at least one air gap (G) having a width adapted so that the magnetic induction produced by the at least two-part (L2A), (L2B) resonant inductor (L2) does not exceed 25% of the magnetic induction produced by the transformer winding (L1) of the multi-winding inductor.
- 15 2. The integrated inductor according to claim 1, characterized in that the transformer winding (L1) of the multi-winding inductor is wound around the column (11) in a single layer.
3. The integrated inductor according to claim 2, characterized in that the  
20 transformer winding (L1) of the multi-winding inductor is a pitched winding wound around the column (11).
4. The integrated inductor according to any preceding claim, characterized in that the column (11), over which the transformer winding (L1) of the multi-winding  
25 inductor is wound, comprises two air gaps (G1) at its ends.
5. The integrated inductor according to any preceding claim characterized in that it comprises magnetic core-pieces that constitute a magnetic circuit with parallel columns (11-15) magnetically connected with the yoke (21, 22) whereas  
30 the transformer winding (L1) of the multi-winding inductor is wound on the column (11) parallel to columns (14, 15) on which the windings (L2A), (L2B) of the resonant inductor are wound.

6. The integrated inductor according to claim 5, characterized in that it further comprises columns (16, 17), parallel to the yoke (12, 13), with further windings (L2C, L2D) of the resonant inductor (L2) which are wound around said columns.

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7. The integrated inductor according to any preceding claim, characterized in that it comprises magnetic core-pieces (31-36) circumferentially arranged around the column (11) having the transformer winding (L1), wherein windings (L2A, L2B, L2C, L2D, L2E, L2F) of the resonant inductor (L2) are wound on said magnetic  
10 core-pieces (31-36).

8. A resonant power supply comprising the integrated inductor according to any of claims 1-7, wherein the multi-winding inductor acts as the output transformer and the inductive element (L1) is connected in series through the  
15 resonant inductor with (L2) with transistor switches (K1, K2).

9. A method for reduction of losses in an integrated inductor comprising a multi-winding inductor having a transformer winding (L1) and a resonant inductor (L2), wherein sections (1), (2) of the magnetic circuit of the transformer winding  
20 (L1) are incorporated into magnetic circuits of at least two parts (L2A), (L2B) of the resonant inductor (L2) so as to form common parts of magnetic circuit of the multi-winding inductor (L1) and at least two-part (L2A), (L2B) resonant inductor (L2) characterized in that the transformer winding (L1) of the multi-winding inductor is wound around a column (11), which has at least one air gap (G) having a width  
25 which is adapted so that the magnetic induction produced by the at least two-part (L2A), (L2B) resonant inductor (L2) does not exceed 25% of the magnetic induction produced by the transformer winding (L1) of the multi-winding inductor.

AN INTEGRATED INDUCTOR AND A METHOD FOR REDUCTION OF LOSSES  
IN AN INTEGRATED INDUCTOR

ABSTRACT

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An integrated inductor comprising a multi-winding inductor having a transformer winding (L1) and a resonant inductor (L2). Sections (1), (2) of the magnetic circuit of the transformer winding (L1) are incorporated into magnetic circuits of at least two parts (L2A), (L2B) of a resonant inductor (L2) so as to form  
10 common parts of magnetic circuit of the multi-winding inductor (L1) and at least two-part (L2A), (L2B) resonant inductor (L2), wherein the transformer winding (L1) of the multi-winding inductor is wound around a column (11), which has at least one air gap (G) having a width adapted so that the magnetic induction produced by the at least two-part (L2A), (L2B) resonant inductor (L2) does not exceed 25%  
15 of the magnetic induction produced by the transformer winding (L1) of the multi-winding inductor.

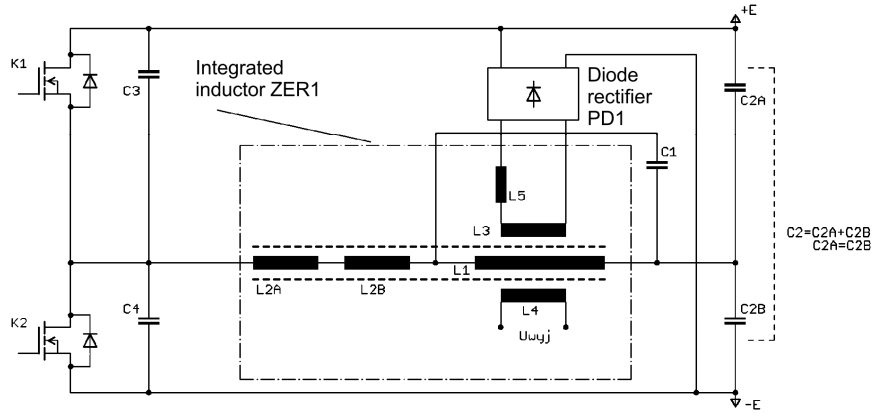


Fig. 1

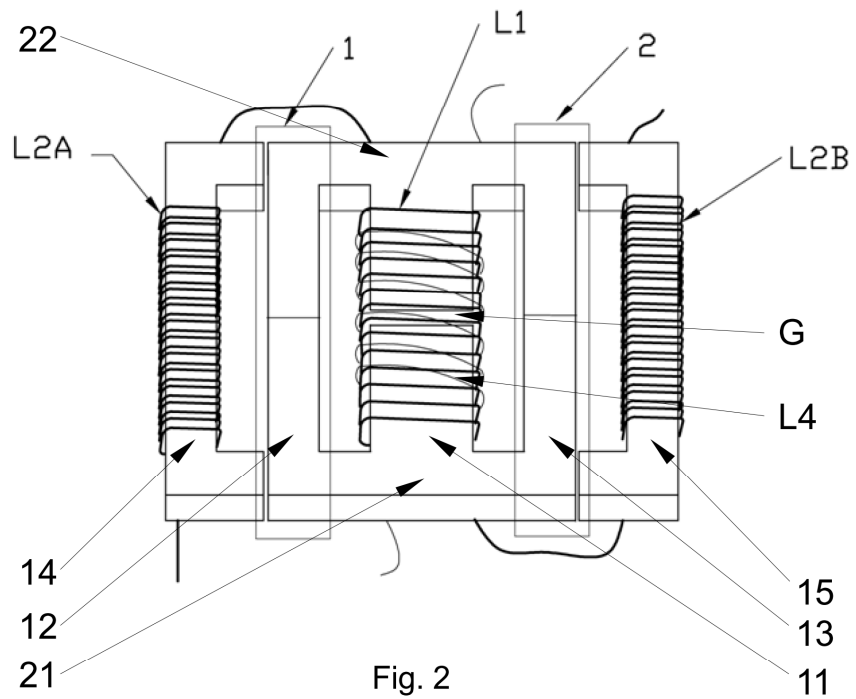


Fig. 2

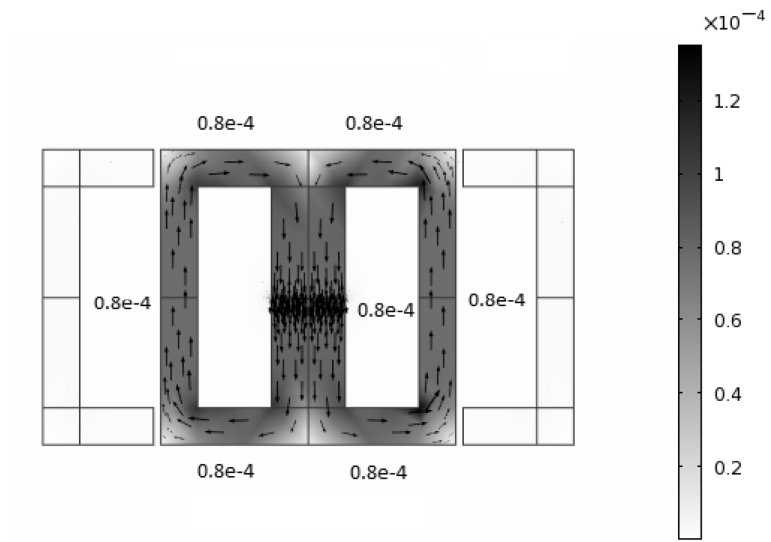


Fig. 3

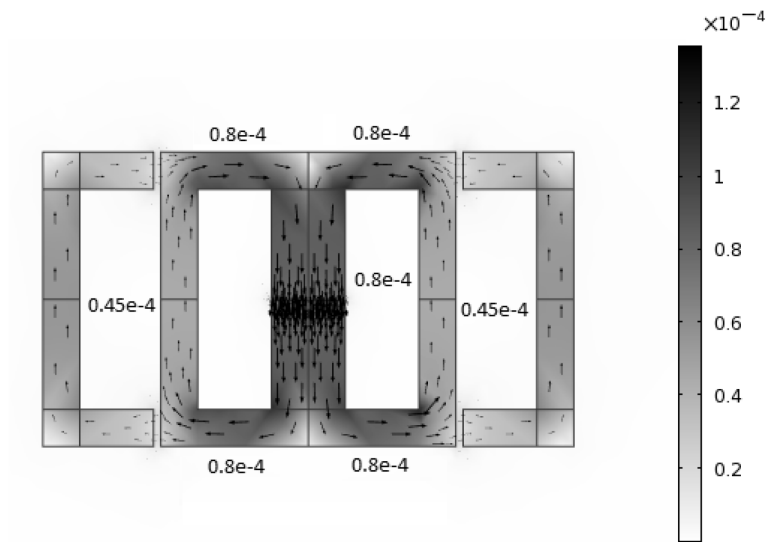


Fig. 4



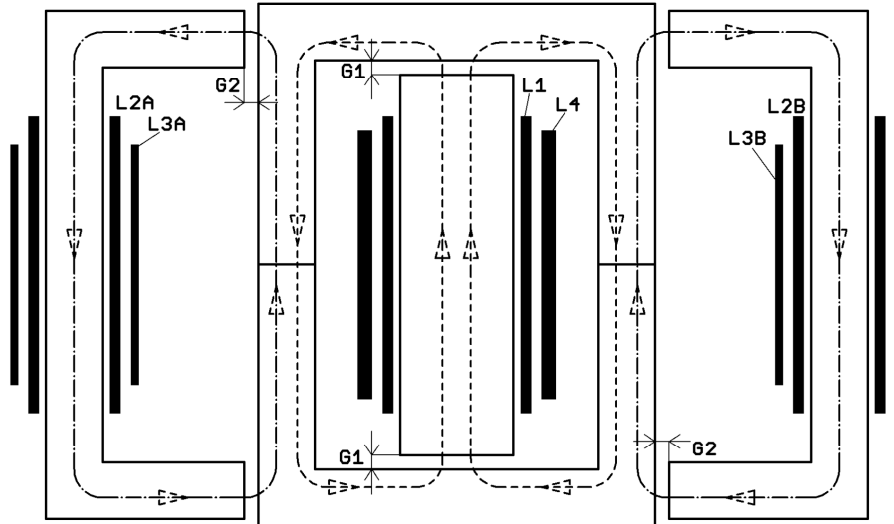


Fig. 5

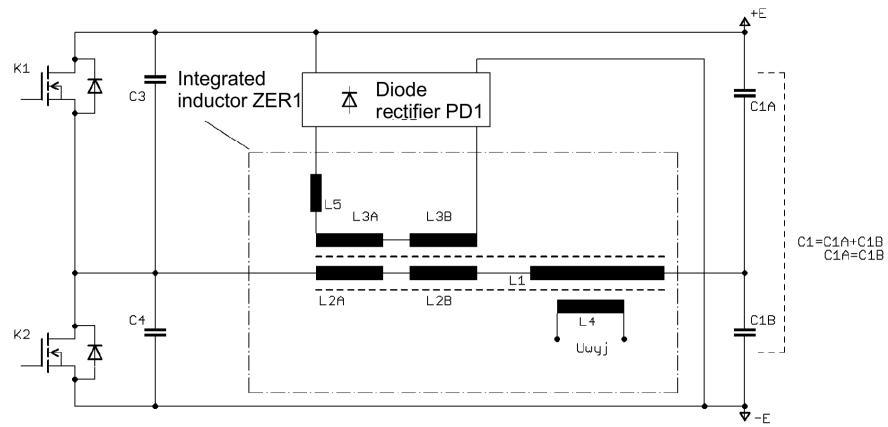


Fig. 6

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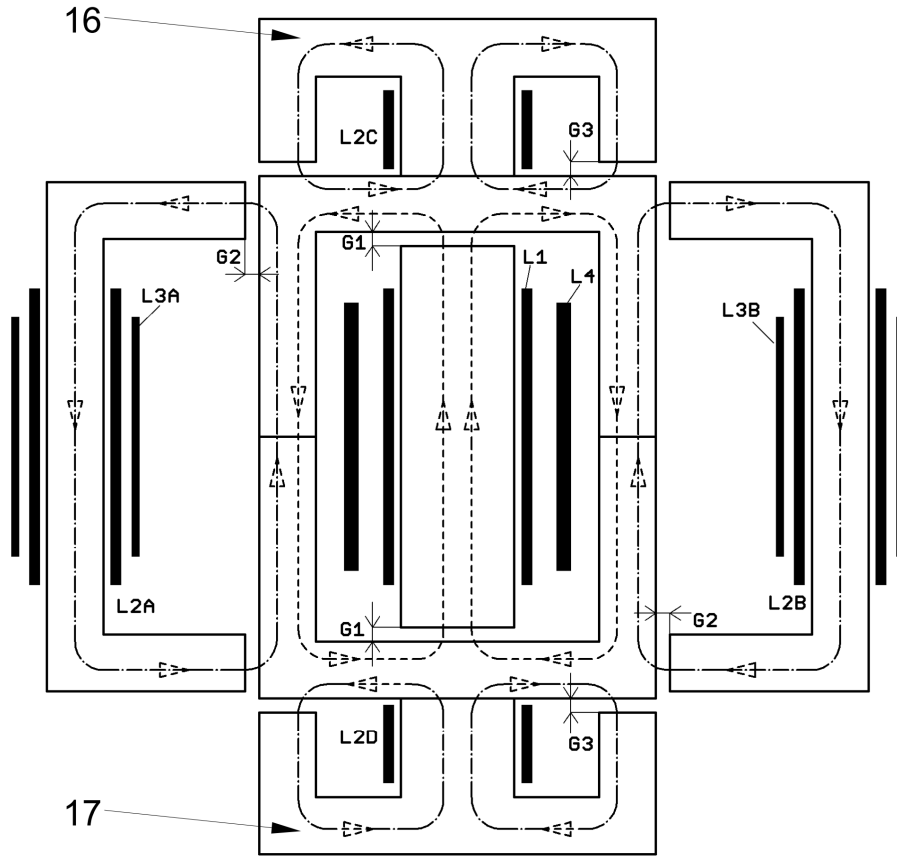


Fig. 7

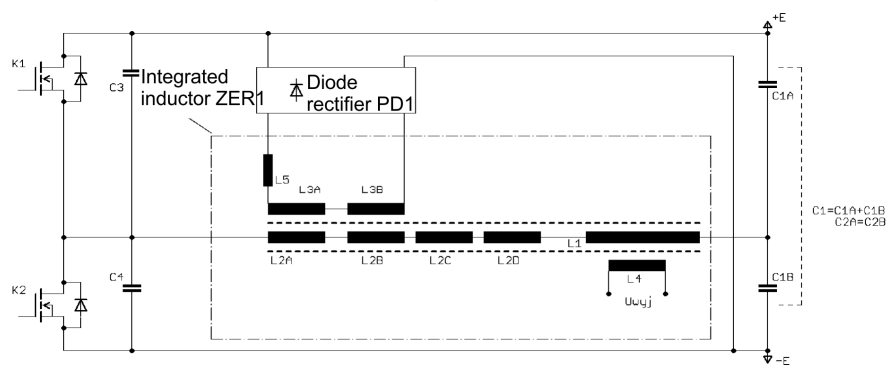


Fig. 8

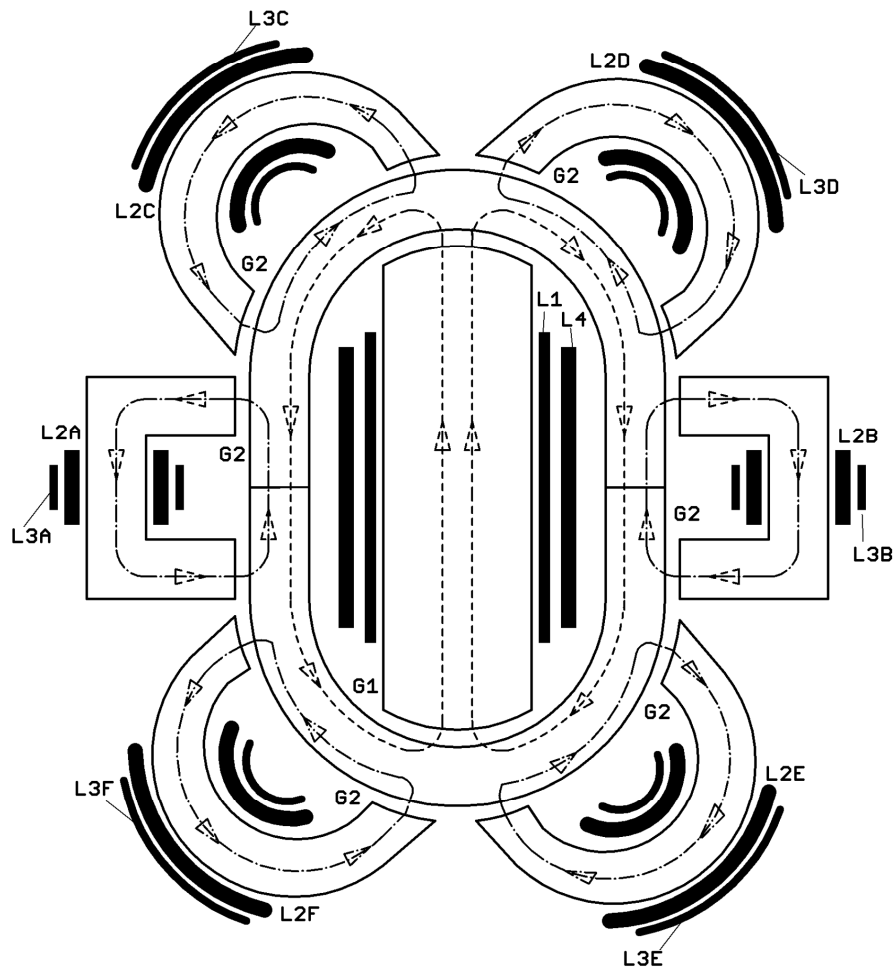


Fig. 9