A method for reduction of losses in an integrated inductor and an integrated inductor

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The invention presents a method for reducing energy losses in an integrated inductor and the integrated inductor intended for use in resonant power converters that allows minimization of losses in a ferromagnetic core and reduction of parasitic capacitances. To put it simply, the method relies on the phenomenon of superposition of magnetic flux density vectors in portions of the combined magnetic circuit. Directions of winding of the integrated inductor windings and resulting current flow directions, as well as air gaps widths in magnetic circuits are chosen so that the superimposing magnetic flux density vectors associated with different inductive elements reduce the resulting magnetic flux density vector, while maintaining the minimum required magnetic coupling between the resonant inductor and other inductive elements.

In addition, in a power converter topology based on a LLC series resonant circuit, which is currently becoming more and more popular, it is possible to employ a multi-winding inductor as an output transformer, thus minimizing thermal losses in inductive elements of the resonant circuit. Moreover, by selecting a proper ratio of the output transformer primary winding (L11) inductance to the inductance of the resonant inductor secondary (L21+L22) windings, it is possible to shape the frequency characteristics and maximum operating voltage for the power components.

The technology

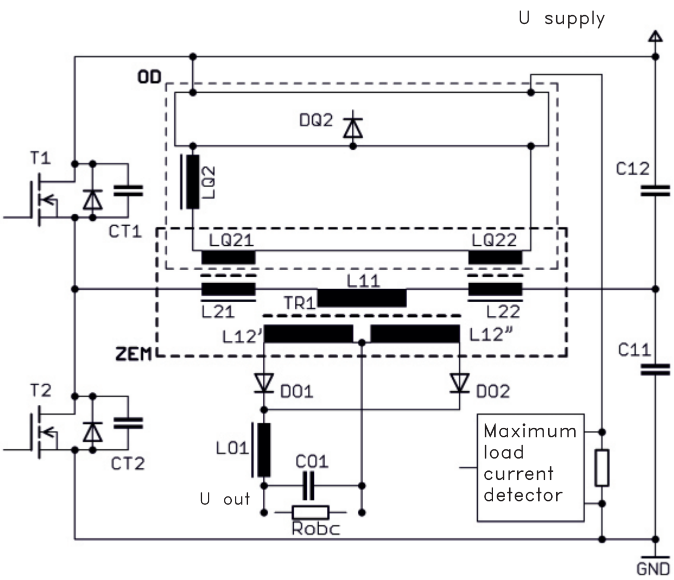

Fig.1 Schematic of a power converter with LLC series resonant circuit, operating in DE class, based on an integrated inductor (ZEM) with a Q-factor limiter OD.

Exemplary integrated inductor (ZEM), in which superimposing alternating magnetic flux densities, from multi-winding inductor TR1, acting as output transformer, and from resonant inductors L21 and L22 are in opposite phase.

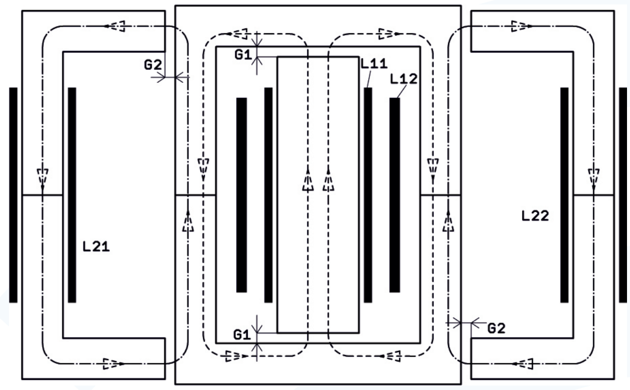

Fig. 2a Integrated magnetic element schemat

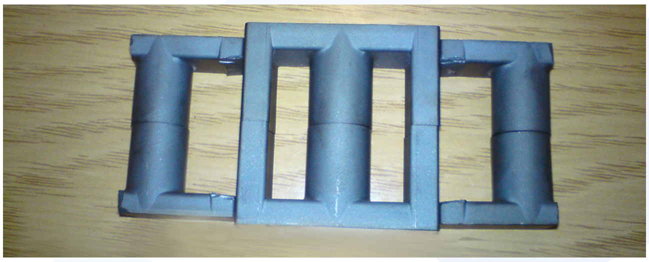

Fig. 2b Integrated magnetic element physical model

In the presented solution the reduction of thermal losses in magnetic material of the integrated inductive element is achieved by means of superposition of magnetic flux density vectors in outer columns of the transformer TR1 magnetic circuit and by selection of air gaps G1 and G2 in magnetic circuits, so that the superimposing magnetic flux density vectors, associated with different inductive elements, are reducing the resulting magnetic flux density vector while maintaining the minimum required magnetic coupling between the resonant inductor and other inductive elements. Such structure ensures also maintaining minimum magnetic coupling between resonant inductors (L21 and L22) and remaining inductive elements (L11, L21, L22). The integration of magnetic elements reduces the volume occupied by inductive elements and yields quantifiable benefits increasing the transferred power to volume ratio [W/dm3]. Additionally, with appropriate sizing of magnetic circuit, e.g. increasing the length of a central column, the primary winding can be wound as a single-layer winding thus significantly reducing unwanted parasitic capacitances.

Approximate calculations regarding an integrated inductive element are given below. In the subject literature core losses are usually described as:

$$P_V = P_{V,\,hysteresis} + P_{V,\,eddycurrent} + P_{V,\,residual}$$

According to manufacturers specifications losses in a ferromagnetic core PV(B,f,T) depend mainly on the magnetic flux density B, magnetic field frequency f and the core temperature T, while:

$P_V(B) \approx B^{2+y}$ where $y \in [0,1]$; $Pv(f) \approx f^{1+x}$ where $x \in [0,1]$; $P_v(T)$

has a minimum at the vicinity of 90°C.

Given sinusoidal waveforms and assuming magnetic flux density vectors are on the same plane but opposite in phase (180° phase shift), and also assuming the same amplitude of magnetic flux densities associated with transformer windings TR1 – L11 and resonant inductors windings L21 and L22 - $B_{A1}=B_{A2}=B_A$ we obtain the resultant magnetic induction $B_{12}(t)$ will in certain areas be equal B_{A12} :

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

This is a highly desirable feature since two inductive elements L21 and L22, are formed utilizing portions of the multi-winding inductor TR1 magnetic circuit, moreover, it is a possible to considerably reduce losses in common branches of magnetic circuits due to reduction in the magnetic flux density vector amplitude.

The simulation below shows magnetic induction distribution in the integrated inductor where the current in the resonant inductor L2=L2A+L2B 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 shifted in phase by 180°. In the external branches of the ferromagnetic core, the magnetic induction current value has been decreased from 0.8 arbitrary units to 0.45 arbitrary units. It is therefore possible to evaluate a relative change in the power of losses, assuming that there is a square relationship between the value of power losses in the core and the value of the magnetic induction:

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

If, for instance, the magnetic induction amplitude is reduced within 33% of the core volume and the magnetic induction amplitude decreases from 0.8 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 in the whole core by more than 20%.

Example applications:

All kinds of resonant energy-conversion systems where reduction of thermal losses in core as well as parasitic capacitances, are required.

Proposal

The method for reduction of losses in an integrated inductor and an integrated inductor is protected by a patent. The University of Science and Technology, Krakow offers:

- Nonexclusive licence for the technology in selected areas of application;
- Services within the scope of the technology adaptation to the customer needs, in collaboration with the patent authors.

Interested persons are kindly requested to contact with:

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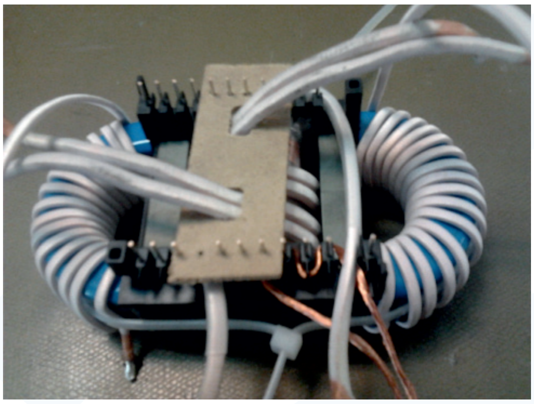

Fig. 3a Practical integrated inductor structure ZEM dedicated for 3kW power supply based on ETD59 and R50 cores.

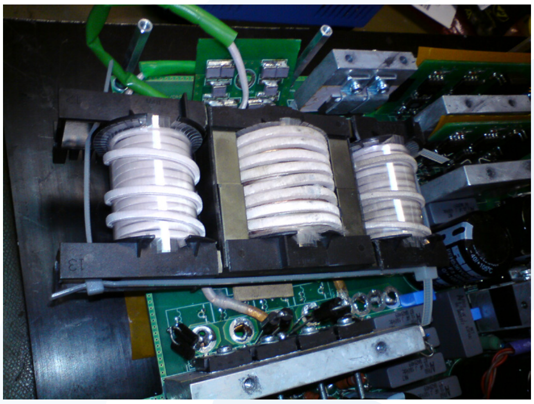

Fig. 3b Practical integrated inductor structure ZEM dedicated for 3kW power supply based on ETD59 cores.

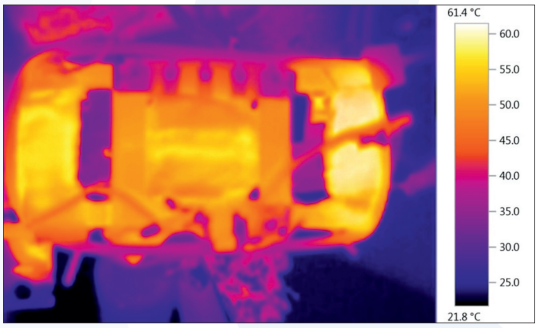

Fig. 4a Experimental results of temperature distribution in integrated inductor ZEM working in 120W power supply (EF25 cores) when used proper magnetic flux directions (field subtraction)

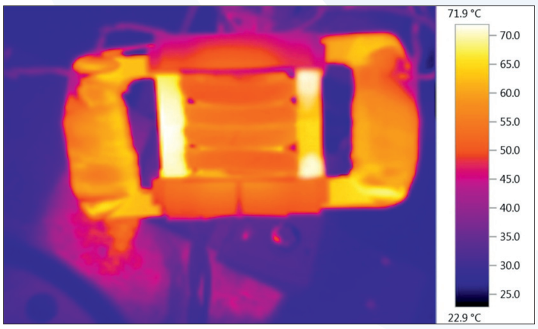

Fig. 4b Experimental results of temperature distribution in integrated inductor ZEM working in 120W power supply (EF25 cores) when used improper magnetic flux direction (field subtraction and addition)

Patent pending:
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