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(54) Title: ROD CORE INDUCTORS

(57) Abstract: The invention relates to a rod core inductor having a length L and a width W comprising a) a coil having a length L_{coil} and a width W_{coil}, and b) core having a length of at least L_{coil}, width W_{core}, wherein the core comprises a polymer bonded soft magnetic material (PBSMM) comprising a polymer and at least 30 vol% soft magnetic material with a saturation magnetization of at least 1Tesla to as measured according to IEC 60401-3 and IEC 62044.

ROD CORE INDUCTORS

This invention relates to rod core inductors, also known as rod coil inductors, rod core chokes and rod coil chokes, as well as drum core inductors. These devices are widely applied in electronic filter circuits or as circuit element to temporarily store electrical energy in power electronics, such as, for examples, switch-mode power supplies and DC-DC converters used in Light Emitting Diode (LED) drivers.

Rod core inductors are well known and comprise at least a coil and a rod-shaped core. A coil, also known as solenoid, is herein defined as at least one winding comprising an electrical conductive material around a rod-shaped core. The coil has a length L_{coil} and a width W_{coil}, wherein the length is defined as parallel to the axis of the core, and the width is defined as perpendicular to the axis of the core. A rod-shape is herein meant being an elongated member having a length of at least the length of the coil, thus at least L_{coil}. Preferably the length is larger than its width.

The rod-shaped core is generally made from soft magnetic materials, such as ferrite, to enhance the inductance of the rod core inductor. The soft magnetic material is chosen to meet the requirements of the end-use of the rod core inductors, such as the current rating, the operation frequency range and operation temperature range. It is well known in the art that soft magnetic metals and alloy with a low resistivity can only be used in applications up to about 1 kHz. For applications > 1 kHz soft magnetic materials with a higher resistivity are applied, specifically mostly MnZn and NiZn ferrites.

Rod core inductors with a ferrite core are known in the art, but suffer from a number of problems. First, as a result of the poor mechanical properties of ferrites (low strength, brittleness) these inductors have poor mechanical stability. For example, ferrite cores are prone to cracking and chipping both during manufacture and final application. Second, the production process of ferrite cores generally involves sintering steps and does not allow for easy manufacture of complex shapes. Third, the production process of ferrite cores does not allow for tight dimensional tolerance levels. Fourth, the poor mechanical properties of ferrites do not allow for machining operations as (post) shaping step in manufacture. Finally, ferrite cores are not stable in corrosive environments leading to deterioration of the ferromagnetic magnetic properties and functionality of the inductors. These problems can be solved by rod core inductors comprising a core of Polymer Bonded Soft Magnetic Materials (PBSMMs). In addition, PBSMMs generally have a lower mass per unit volume than ferrites, thus offering the possibility to make lighter inductors.

PBSMMs are known in the art as a general class of materials comprising a polymer and a soft magnetic material as filler, see for example, L. Svensson *et al*., Journal of Magnetism and Magnetic Materials, 324 (2012), pp 2717–2722. However, inductors with a PBSMM core suffer from a decrease of their inductance value as a function of the applied current when increasingly higher currents are applied. Therefore, this solution is not satisfactory for applications that require high current ratings. Current rating is herein defined as the maximum amount of current passed through the inductor by which the inductance will drop by no more than 10% of the initial inductance at low current.

It is thus an object of the present invention to have rod core inductors comprising a PBSMM core which can attain a high current rating. This object has been achieved by a Rod core inductor having a length L and a width W comprising

a) a coil having a length L_{coil} and a width W_{coil}, and
b) core having a length of at least L_{coil}, width W_{core},

wherein the core comprises a polymer bonded soft magnetic material (PBSMM) comprising a polymer and at least 30 vol% soft magnetic material with a saturation magnetization of at least 1Tesla to as measured according to IEC 60401-3 and IEC 62044. The saturation magnetization is herein defined as being equivalent to the saturation magnetic flux density referred to in IEC 60401-3. Volume percentages (vol%) is herein meant with respect to the total volume of the PBSMM, unless denoted otherwise.

The length (L) of the inductor is hereby defined as the distance parallel to the core axis (35), and the width (W) is defined as the distance perpendicular to the core axis (35). Minimal dimensions are defined as the minimal length and the minimal width of the inductor, which thus includes shapes wherein parts of the length and/or width are larger than its minimal length and/or width.

Coil

Preferably, the coil comprises at least 3 windings, more preferably at least 10 windings. The coil may comprise as many windings as convenient for end-use, for example at most 50 windings, more preferably at most 30 windings.

The windings comprise an electrical conductive material which can be any of the well-known electrically conductive materials such as nickel, copper, gold, silver, platinum, lead or aluminum. Preferably the windings comprise nickel or copper or blends thereof since these materials are not scarce and provide a high electrical conductivity.

The windings can have any cross-sectional shape such as circular, rectangular and ellipsoidal. The windings may comprise an insulation material around an electrical conductive material. The insulation material is known in the art and may be a thermoset or a thermoplastic material with a degradation or melting point higher than the melting point of the PBSMM. The windings may also be made from Litz wire. Litz wire reduces skin effects at higher frequencies and decrease resistance.

The diameter of a winding (22) is herein defined as the largest dimension of the cross-section of the electrical conductive material of the winding. Preferably, the diameter of the electrical conductive material in the windings is at least 1mm, more preferably 1.5 mm and most preferably at least 2.5 mm, as this allows high currents to pass through the winding with lower ohmic loss. The maximum diameter of the electrical conductive material in the winding is chosen to allow for the total number of windings around the core as desired in the end-use, for example at most 5 mm, more preferably at most 4 mm.

<u>Soft magnetic materials – general</u>

The term soft magnetic material is known in the art and is distinguished from hard magnetic materials. Herein, soft magnetic materials are understood to be magnetic materials with a coercivity < 1000 A/m in accordance to IEC 60404-1:2000.

Soft magnetic materials are further described, for example, in the following handbooks: (1) Feynman, R.P., Leighton, R.B., Sands, M. *The Feynman lectures on Physics*; The New Millennium Edition, Basic Books: New York, 2010, Vol. 2, pp 37-1 – 37-13; describes Magnetic Materials; (2) Williams. B.W. *Power Electronics: Devices, Drivers, Applications and Passive Components*. McGraw-Hill; 2nd edition, 1992; pp 617-679, describes Soft Magnetic Materials; and (3) Herzer, G. in *Handbook of Magnetic Materials*; Vol. 10. Buschow, K.H.J. Ed. Elsevier Science B.V.: 1997, pp 415-462, describes Nanocrystalline Soft Magnetic Alloys.

Typical values for the saturation magnetization of common soft magnetic materials are given in Table 1.

Table 1: Saturation magnetization of common soft magnetic materials

Material (class)	**Saturation magnetization (T)**
$Fe_{49}Co_{49}V_2$ (alloy); FeCoV	2.34
Fe (metal); Iron	2.15
Co (metal)	1.82
$Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ (nanocrystalline alloy)	1.25
$Ni_{80}Fe_{20}$ (alloy)	1.04
Ni (metal)	0.61
NeoSid, F02 (MnZn ferrite); Ferrite 2	0.34
NeoSid, F5is (NiZn ferrite); Ferrite 1	0.30

The saturation magnetization of the soft magnetic materials is measured according to IEC 60401-3 and IEC 62044 using the following basic measurement conditions and parameters:

- Ring-shaped sample
- Temperature 23 °C
- Sinusoidal excitation signal
- Excitation frequency of 50 Hz
- Maximum applied field strength as prescribed in Table 2 of IEC 60401-3.

Core

The rod core inductors according to the present invention comprise a rod-shaped core.

A rod-shape is herein meant as an elongated member having a length of at least the length of the coil, which is larger than its width (W_{core}, 32). For the purpose of this invention, drum-cores are also considered to comprise a rod-shaped core. The shape of the core outside the coil may be different from the shape inside the coil.

As depicted schematically in Figure 2, the diameter of the rod-shape core may be of any form, such as circular (36), rectangular (37) and ellipsoidal (38). For cores with a non-circular cross-section the width (32) is defined as the largest dimension of its cross-section.

The length of the core must be at least the length of the coil, and may be larger than the length of the coil, and thus be extended with respect to the coil. This is exemplified in Figure 1 by the hatched area (33). The length of the optional core extension (L_e, 34) may be the same or different on both sides of the coil.

Preferably, the length of the core extension is at least 0.01 times the length of the core and more preferably at least 0.05 times the length of the core. The advantage of having a core extension is that it allows easier applications and more robust fixation of the windings to the core by means of chemical or physical bonding agents. The maximal length of the core extension may be chosen as dictated by the space requirements of the inductor in the end-use, and may be for example at most 0.25 times the length of the core, more preferably at most 0.15 times the length of the core.

The core of the rod core inductor according to the invention comprises a polymer bonded soft magnetic material (PBSMM) comprising a polymer and at least 30 vol% of a soft magnetic material with a saturation magnetization of at least 1 Tesla as measured according to the method described above. The polymer in the PBSMM can be chosen from a wide range of thermoplastic polymers. These include, for example, (co)polyamides, polyphthalamides, polyolefins, polyesters, polyimides, polyetherimides, polyaryletherketones, polyphenylene sulfides, liquid crystalline polymers, polycarbonates and a thermoplastic elastomer, as well as mixtures thereof.

Suitable polyamides include, for example, PA6, PA6,6 and PA4,6, as well as (co)polyamides and blends thereof. Suitable polyphthalamides include PA10T,PA9T and PA6T/6I, as well as (co) polyphthalamides and blends thereof. Suitable thermoplastic elastomers include segmented block-copolymers comprising a soft block such as for example polyethylene glycol or polytetrahydrofuran and a polyester hard block such as polyethylene terephthalate or polybutylene terephthalate. The advantage of using thermoplastic elastomers is that PBSMMs based on these polymers show higher ductility and offer the possibility to make embedded inductors according to the present invention with higher mechanical robustness.

Preferably, the thermoplastic polymer is chosen from a material that is reflow solderable. This has the advantage that the embedded inductor according to the invention can be reflow soldered to a printed circuit board (PCB).

The soft magnetic material comprised in the PBSMM of the core in the rod core inductor of the present invention can be any soft magnetic material having a saturation magnetization of at least 1 Tesla, more preferably at least 1.2 Tesla, even more preferred at least 1.5 Tesla. Suitable soft magnetic materials are, for example, ferromagnetic metals and alloys ferromagnetic amorphous alloys and ferromagnetic nanocrystalline alloys with the provision that their saturation magnetization is at least 1 Tesla more preferably at least 1.2 Tesla, even more preferred at least 1.5 Tesla as measured in accordance to the method described above. A suitable soft magnetic material having a saturation magnetization of at least 1 Tesla is, for example, $Ni_{80}Fe_{20}$ (alloy). Suitable soft magnetic materials having a saturation magnetization of at least 1.2 Tesla are, for example, $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ (nanocrystalline alloy) and $Ni_{50}Fe_{50}$ (alloy). Suitable soft magnetic materials having a saturation magnetization of at least 1.5 Tesla are, for example, Iron (metal), Cobalt (metal), $Fe_{49}Co_{49}V_2$ (alloy) and $Fe_{65}Co_{35}$ (alloy).

The PBSMM is made by techniques as known in the art and include blending of the polymer with the soft magnetic material and optionally other components. The amount of soft magnetic material in the PBSMM of the core is at least 30 vol%, with respect to the total volume of the PBSMM. Preferably, the amount is at least 40 vol%, more preferred at least 50 vol%. The advantage of increasing the amount of soft magnetic material in the PBSMM is that the magnetic properties (*e.g.*, relative magnetic permeability and saturation magnetization) of the PBSMM improve. The maximum amount of soft magnetic material in the PBSMM of the core depends on the process of preparing the core. When the core according to the invention is manufactured using injection molding, the maximum is around 80 vol% as above these amounts the flow behavior of the PBSMM is insufficient for the injection molding process. When compression molding is employed, the maximum amount of soft magnetic material can be as high as 90 vol%.

In one embodiment the PBSMM of the core has a saturation magnetization of at least 0.4 Tesla as measured according to IEC 60401-3 and IEC 62044 using the measurement conditions and parameters as described above with the proviso that the maximum applied field strength is 100 kA/m.

The reason to choose this maximum applied field strength for PBSMM, which deviates from the norm IEC 60401-3, is that the relative magnetic permeability of the PBSMMs used in the rod core inductors according to the current invention is generally less than 50 and can even be lower than 15, which is much lower than for typical soft magnetic materials. As a result, saturation occurs at much higher applied field strength for these PBSMMs compared to typical soft magnetic materials for which the aforementioned norm was specifically developed.

Preferably, the PBSMM has a saturation magnetization of at least 0.6 Tesla and even more preferred of at least 0.8 Tesla as measured according to IEC 60401-3 and IEC 62044 using the measurement conditions and parameters as described above with the proviso that the maximum applied field strength is 100 kA/m. Having a PBSMM with a higher saturation magnetization allows for inductors with a higher current rating. Optionally, the rod core inductor according to the invention may also be embedded with an embedding of a PBSMM having a saturation magnetization of at least 0.4 Tesla as measured according to IEC 60401-3 and IEC 62044 using the measurement conditions and parameters as described above with the proviso that the maximum applied field strength is 100 kA/m, preferably at least 0.6 Tesla and even more preferred at least 0.8 Tesla. An embedding of this kind of PBSMM allows for higher current ratings.

PBSMM embedment

In a preferred embodiment, the rod core inductor has an embedment of a polymer bonded soft magnetic material with a saturation magnetization of at least 1 Tesla and the inductor has a length L of at least L_{coil}+0.001xW_{coil}, and a width W of at least 1.001xW_{coil}. The embedment according to the present invention can have any shape as desired for the end-used as long as L is at least L_{coil}+0.001xW_{coil}, and W is at least 1.001xW_{coil}.

Preferably, the core is centered with respect to the embedment in the direction perpendicular to the core axis (35) and, thus, the perpendicular thickness of the embedment (11) is at least 0.0005xW_{coil}. Herein, the perpendicular thickness (11) is defined as the minimum distance from an outer diameter of the windings to the outer surface of the embedment in the direction perpendicular to the axis of the core (35).

Preferably, the core is centered with respect to the embedment in direction parallel to the core axis (35) and, thus, the longitudinal thickness of the embedment (12) is at least 0.0005xW_{coil}. The longitudinal thickness (12) is defined as the minimum distance from a terminal winding to the outer surface of the inductor in the direction parallel to the axis of the core (35). The longitudinal thickness of the inductor (12) may be made from PBSMM, if the core has the same length as the coil. If the core is longer than the coil, the longitudinal thickness may be a combination of core and PBSMM.

More preferably, the inductor has a length L being at least L_{coil}+0.01xW_{coil} and the width W being at least 1.01xW_{coil}. Even more preferably, the inductor has length L being at least L_{coil}+0.1xW_{coil} and the width W being at least 1.1xW_{coil}. The advantage of having a thicker embedment is that the inductance of the inductor according to the invention is enhanced and the stray magnetic field is shielded to a higher extent. The maximum embedment thickness may be chosen as dictated by the space requirements of the inductor in the end-use. For example, the inductor may have maximum dimensions of for example the length L being at most L_{coil}+2xW_{coil} and the width W being at most 3xW_{coil}, more preferably the length L being at most L_{coil}+1xW_{coil} and the width W being at most 2xW_{coil}.

The embedment can be manufactured by any shaping technique known in the art, such as, for example, injection molding, compression molding, extrusion or selective laser sintering (SLS). Preferably, injection molding is used to manufacture of the embedment, as it allows rapid, large scale manufacture and complex product shapes.

In another preferred embodiment of the present invention, the perpendicular thickness (11) and longitudinal thickness (12) of the embedment are preferably at least 0.1 mm, more preferably at least 0.2 mm and most preferably at least 0.5 mm. The maximum perpendicular thickness (11) and longitudinal thickness (12) of the embedment are chosen as dictated by the space requirements of the inductor in the end-use. For example, the thickness (11) and longitudinal thickness (12) of the embedment may be at most 10 mm, more preferably at most 5 mm.

In yet another preferred embodiment of the present invention, the inductor has a number of windings per unit (n) length of the coil of the inductor (L_{coil}) is between 400 and 900 and can be calculated by the formula:

$$n=N/L_{coil},$$

wherein L_{coil} is in meters, and N is the total number of windings.

The current rating of the inductor according to the invention is preferably at least 1 A, more preferably at least 5 A and most preferred at least 10 A.

The advantage of having inductors with a higher current rating is that these devices have a wider operating window and may be applied in applications where high (peak) currents occur.

In another embodiment of the present invention the soft magnetic material in the PBSMM of the core and/or embedment is chosen to also have a high Curie temperature (T_c). The Curie temperature is the temperature above which soft magnetic materials lose their ferromagnetic properties and is herein defined as the temperature at which the relative magnetic permeability drops to less than 10% of the value at 23 °C. Preferably, the Curie-temperature of the soft magnetic material is at least 150 °C, more preferably at least 250 °C and most preferably at least 350 °C. The advantage of having a PBSMM comprising a soft magnetic materials with a higher Curie-temperature is that the inductance of the rod core inductors remains high over a wider temperature range. This embodiment of the present invention provides additional advantages compared to rod core inductors with a ferrite core. The ferrite core inductors generally have a relatively limited operating temperature range, because many common ferrites have Curie temperatures lower than 250 °C.

Suitable soft magnetic materials with a Curie temperature of at least 350 °C are found in the group of ferromagnetic metals and alloys, such as, for example, Iron, Cobalt, Nickel, Iron-Nickel alloys and Iron-Cobalt alloys.

The rod core inductor according to the invention can suitably be employed in applications which require high currents; alternatively, the rod core inductor can be designed smaller while still allowing the same amount of current.

Yet another preferred embodiment of the present invention is a rod core inductor having a length L and a width W comprising:

a. a coil having a length L_{coil} and a width W_{coil}, and
b. a core having a length of at least L_{coil}, width W_{core},

wherein the core comprises a polymer bonded soft magnetic material (PBSMM) comprising a polymer and at least 30 vol% soft magnetic material with a saturation magnetization of at least 1Tesla as measured according to IEC 60401-3 and IEC 62044, and wherein L is at least $L_{coil}+0.001xW_{coil}$, and W is at least $1.001xW_{coil}$, and wherein the coil is embedded in an embedment of a polymer bonded soft magnetic material comprising a polymer and at least 30 vol% soft magnetic material with a saturation magnetization of at least 1Tesla as measured according to IEC 60401-3 and IEC 62044 wherein

- the polymer for the PBSMM of the core and the embedment is independently chosen from (co)polyamides, polyphthalamides, polyolefins, polyesters, polyimides, polyetherimides, polyaryletherketones, polyphenylene sulfides, liquid crystalline polymers, polycarbonates and a thermoplastic elastomer, as well as mixtures thereof, and
- the soft magnetic material for the PBSMM of the core and the embedment with a saturation magnetization of at least 1 Tesla is independently chosen from

$Ni_{80}Fe_{20}$ (alloy)., $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ (nanocrystalline alloy), $Ni_{50}Fe_{50}$ (alloy), Iron (metal), Cobalt (metal), $Fe_{49}Co_{49}V_2$ (alloy) and $Fe_{65}Co_{35}$ (alloy).

The most preferred embodiment is a rod core inductor wherein both the core and the embedment comprise the same PBSMM comprising a polymer and at least 30 vol% soft magnetic material with a saturation magnetization of at least 1Tesla to as measured according to IEC 60401-3 and IEC 62044.

Description of the drawings

Figure 1 shows an example of a rod core inductor according to the invention. The rod core inductor comprises a coil (20), having a length L_{coil} (21), and a width W_{coil} (23). The rod core inductor also comprises a rod-shaped core (30), having a length L_{core} (31), and a width W_{core} (32). The central axis of the core is visualized by a dotted line (35). Optional core extension is visualized by the hatched area (33), with a length of core extension L_e (34). A winding is denoted by (24), with coil winding diameter (22). The optional embedment is visualized by the area (10), with perpendicular thickness (11) and longitudinal thickness (12).

Figure 2 shows various examples cross-sections of a core, also referred to as diameter of the rod-shape core, being circular (36), rectangular (37) and ellipsoidal (38).

Methods

Materials

Thermoplastic polymers:

PA6	polyamide 6 (standard injection molding grade), relative solution viscosity at 23 °C in 90% formic acid in water at 1 g/100mL = 2.28, density 1.13 g/cm3.
PA46	polyamide 46 (standard injection molding grade), viscosity number according to ISO 307 at 25 °C in 96% sulphuric acid in water at 0.005 g/ml = 160 mL/g, density 1.10 g/cm3.
PBT	polybutylene terephthalate, relative solution viscosity at 23 °C in m-cresol at 0.5 g/mL = 1.85, density 1.30 g/cm3.
TPE	thermoplastic elastomer (segmented block-copolymer comprising polytetrahydrofuran soft block and a polybutylene terephthalate hard block), Hardness (3 s) = Shore D 25, MVR = 41 cm3/10 min at 230 °C and 2.16 kg, density 1.08 g/cm3.
PPS	polyphenylene sulfide, MFR = 152 g/10 min at 315 °C and 5 kg, density 1.35 g/cm3.
PP	polypropylene block copolymer (high impact resistance grade), MFR = 6.2 g/10 min at 230 °C and 2.16 kg, density 0.91 g/cm3.

Soft magnetic materials:

Ferrite 1	NiZn ferrite, Neosid F5is from the company NEOSID Pemetzrieder GmbH & CoKG, Germany, initial relative magnetic permeability = 150, saturation magnetization 0.30 T, density about 5.35 g/cm3
Ferrite 2	MnZn ferrite, Neosid F02 from the company NEOSID Pemetzrieder GmbH & CoKG, Germany, initial relative magnetic permeability = 1800, saturation magnetization 0.34 T, density about 5.09 g/cm3
Iron (Fe)	ACS 100.29 iron powder from Höganäs AB, Sweden, density = 7.83 g/cm3
FeCoV	$Fe_{49}Co_{49}V_2$ alloy, Fe-49Co-2V from Sanyo Special Steel Co., Ltd., Japan, density = 8.21 g/cm3

Preparation of PBSMM

The PBSMM were prepared using a twin-screw extruder by melt-blending the soft magnetic materials and the appropriate thermoplastic polymer as known in the art. Table 2 gives an overview of the PBSMMs prepared.

Preparation of cylindrical rod cores, rings and tensile bars

Cylindrical rod cores (diameter 4.5 mm x length 100 mm), rings with a circular cross-section (inner diameter 95 mm, outer diameter 105 mm) and ISO 527 type 1BA tensile bars were prepared by injection molding as known in the art.

Preparation of embedded rod core inductors

For the preparation of the embedded rod core inductors a standard coil was used. The coil had a length, L_{coil} (21), of 34.8 mm and a width, W_{coil} (23), of 15 mm. The coil consisted of 12.5 windings made of isolated copper wire with a diameter (22) of 2.5 mm.

The core and embedment consisted of the same PBSMM and were applied in and around the coil by a single injection molding procedure as known in the art using a dedicated mold. The coil was fixed in the mold by the terminal part of the windings. The embedded rod core inductors produced by the injection molding procedure with this mold had the following characteristics:

Core	A rod-shaped core with circular cross-section with a diameter, W_{core} (32), of 10 mm and a total length, L_{core} (31) + 2x L_e (34), of 40 mm. The length of the core extension, L_e (34), was 2.6 mm.
Embedment	The embedment had perpendicular thickness (11) of 3 mm and a longitudinal thickness (12) of 2.6 mm (equal to the length of the core extension, L_e).

Measurement of tensile properties of the PBSMM

The tensile properties of the PBSMM were measured on the injection molded tensile bars according to ISO 527 (testing speed 1 mm/min for E-modulus, 5 mm/min beyond E-modulus).

Measurement of initial relative magnetic permeability of PBSMM as function of frequency

To determine the initial relative magnetic permeability of a PBSMM, the inductance of a cylindrical coil with circular windings is measured in two configurations: *i*) with an injection molded cylindrical rod core (diameter 4.5 mm x length 100 mm) made from the material under investigation and *ii*) without core material, *i.e,*, using an air core. The initial relative magnetic permeability is then calculated as

$$\mu_r = (L_m/L_{air}-1) * (A_{coil}/A_{air}) + 1$$

wherein L_m is the inductance of the coil with the core made from the material, L_{air} is the inductance of the coil with the air core, A_{coil} is the cross sectional area of the coil $1/4\pi D^2$, wherein D is the average diameter calculated as the average diameter of inner and outer diameter of the coil and A_{core} is the cross sectional area of the core. The inductance was measured as a function of frequency with a HP4275A frequency LCR meter. The coil was hand-made from a standard isolated copper wire with a total diameter of 2.6 mm and a copper cross section with a diameter of 1.4 mm; 32 windings were used; total length of the coil was 87 mm; inner diameter of the coil was 4.5 mm. The coil was connected to the LCR meter by means of HP type 16048 test leads. A maximum of 0.1 Volt was applied.

Measurement of saturation magnetization (Bsat) of the PBSMMs

The saturation magnetization of the PBSMM is measured on injection molded rings with a Brockhaus MPG200 system according to IEC 60401-3 and IEC 62044 using the measurement conditions and parameters as described above with the proviso that the maximum applied field strength is 100 kA/m.

Measurement of inductance of rod core inductors as function of frequency

For measuring the Inductance as a function of frequency a HP4275A frequency LCR meter was used. The coil was hand-made from a standard isolated Copper wire with a total diameter of 2.6 mm and a copper cross section with a diameter of 1.4 mm; 32 windings were used; total length of the coil was 87 mm; inner diameter of the coil was 4.5 mm. The coil was connected to the LCR meter by means of HP type 16048 test Leads. A maximum of 0.1 Volt was applied.

<u>Measurement of inductance of rod core inductors as function of current</u>

For measuring the Inductance at 50 Hz as a function of the applied current a Brockhaus MPG200 system was used. The measuring cell, build by Brockhaus, had a coil with 1041 windings made by a copper wire with a cross section of 3.15 mm * 1.12 mm. This Ellipsoid Sensor corresponds to the international standard IEC 404-7.

<u>Measurement of inductance of embedded rod core inductors as a function of current</u>

The inductance of the embedded inductors was measured as function of DC bias current at 100 kHz with a input peak-to-peak voltage of 15-20 V using a MADMIX High-current apparatus manufactured by MinDCet NV, Leuven, Belgium. The detailed measurement principle of the MADMIX High-current apparatus is disclosed in WO2013110145.

Table 2: Overview of example PBSMMs and Mechanical data

#	Polymer	SMM [1]	SMM Loading		E [2]	TS [3]	EAB [4]
			[w%]	[v%]	[GPa]	[Mpa]	[%]
Example 1	PA6	Iron	86	47	10.33	60.3	1.2
Example 2	PA6	FeCoV	90	55	not measured		
Example 3	PA6	Iron	87	50	13.09	44.6	0.3
Example 4	PA46	Iron	88	50	8.42	37.9	0.6
Example 5	PBT	Iron	86	50	10.08	30.0	0.3
Example 6	TPE	Iron	88	50	0.24	6.4	6.8
Example 7	PPS	Iron	85	50	14.13	30.4	0.2
Example 8	PP	Iron	90	50	1.59	9.4	6.3
Comp. Ex A	PA6	Ferrite 1	85	55	14.51	83.5	0.9
Comp. Ex B	PA6	Ferrite 2	85	56	18.93	89.8	0.7
Comp. Ex C	PA6	Ferrite 1	83	50	11.09	77.2	0.9
Comp. Ex D	PA46	Ferrite 1	83	50	14.31	76.5	0.6
Comp. Ex E	PBT	Ferrite 1	80	50	11.30	54.6	0.6
Comp. Ex F	TPE	Ferrite 1	83	50	0.18	10.5	10.5
Comp. Ex G	PPS	Ferrite 1	80	50	17.12	60.5	0.4
Comp. Ex H	PP	Ferrite 1	86	50	3.32	22.0	0.9

[1] Soft magnetic material (SMM)

[2] E-modulus

[3] Tensile strength

[4] Elongation at break

Table 3: PBSMM magnetic data

#	**Polymer**	**SMM [1]**			**Relative magnetic permeability**		**Bsat [3]**
		type	Tc [2] [°C]	Bsat [3] [T]	10 kHz [-]	100 kHz [-]	[T]
Example 1	PA6	Iron	1044	2.15	7.9	8.5	0.66
Example 2	PA6	FeCoV	940	2.34	7.2	7.8	0.82
Example 3	PA6	Iron	1044	2.15	8.8	9.5	0.75
Example 4	PA46	Iron	1044	2.15	10.8	9.4	0.83
Example 5	PBT	Iron	1044	2.15	9.8	10.5	0.78
Example 6	TPE	Iron	1044	2.15	9.1	9.8	0.73
Example 7	PPS	Iron	1044	2.15	10.0	10.7	0.86
Example 8	PP	Iron	1044	2.15	8.9	9.7	0.74
Comp. Ex A	PA6	Ferrite 1	170	0.30	5.7	6.1	0.31
Comp. Ex B	PA6	Ferrite 2	130	0.34	9.4	10.1	0.38
Comp. Ex C	PA6	Ferrite 1	170	0.30	5.0	5.3	0.30
Comp. Ex D	PA46	Ferrite 1	170	0.30	5.0	5.4	0.29
Comp. Ex E	PBT	Ferrite 1	170	0.30	4.7	5.1	0.29
Comp. Ex F	TPE	Ferrite 1	170	0.30	5.0	5.4	0.30
Comp. Ex G	PPS	Ferrite 1	170	0.30	5.5	5.9	0.30
Comp. Ex H	PP	Ferrite 1	170	0.30	5.0	5.4	0.29

[1] Soft magnetic material (SMM)

[2] Curie-temperature

[3] Saturation magnetization

Table 4: Rod core inductor data

Core PBSMM			**L_0 [2]**	**I 90% [3]**
#	Polymer	SMM [1]	at 50 Hz, [mH]	[A]
Example 1	PA6	Iron	0.77	7.0
Example 2	PA6	FeCoV	0.74	12.1
Example 3	PA6	Iron	0.86	6.0
Example 4	PA46	Iron	1.07	4.9
Example 5	PBT	Iron	0.93	5.7
Example 6	TPE	Iron	0.83	6.2
Example 7	PPS	Iron	1.00	6.5
Example 8	PP	Iron	0.83	6.4
Comp. Ex A	PA6	Ferrite 1	0.53	3.4
Comp. Ex B	PA6	Ferrite 2	0.92	4.0
Comp. Ex C	PA6	Ferrite 1	0.49	4.1
Comp. Ex D	PA46	Ferrite 1	0.50	3.9
Comp. Ex E	PBT	Ferrite 1	0.48	4.1
Comp. Ex F	TPE	Ferrite 1	0.47	4.3
Comp. Ex G	PPS	Ferrite 1	0.54	3.9
Comp. Ex H	PP	Ferrite 1	0.47	4.2

[1] Soft magnetic material (SMM)

[2] Initial inductance at low current of 2.3 A (L_0)

[3] Current at which inductance is 90% of L_0

Table 5: Embedded rod core inductor data

Core and Embedment PBSMM			**L_0 [2]**	**I 95% [3]**	**I 90% [4]**
#	Polymer	SMM [1]	at 100 kHz, [μH]	[A]	[A]
Example 3	PA6	Iron	2.99	31.0	> 40
Comp. Ex C	PA6	Ferrite 1	2.14	8.3	14.9

[1] Soft magnetic material (SMM)

[2] Initial inductance at low DC bias current of 2.85 A

[3] DC bias current at which inductance is 95% of L_0

[4] DC bias current at which inductance is 90% of L_0

The mechanical data as shown in Table 2 clearly indicate that these are largely independent on the applied soft magnetic material. TPE and PP based PBSMM exhibit lower modulus and higher elongation at break, and are thus more soft and ductile as compared to PBSMMs based on PA6, PA46, PBT and PPS.

Table 3 clearly shows that the PBSMM according to the invention (examples 1 to 8) exhibits a high initial relative magnetic permeability, which is comparable or significantly higher as compared to the PBSMM not according to the invention with a comparable loading of soft magnetic material (comparative examples A to H). The high initial relative magnetic permeability was even observed at a frequency as high as 100 kHz. The soft magnetic material in the PBSMM according to the invention has a Curie-temperature of > 900 °C, well above 250 °C and much higher than the PBSMM not according to the invention (<200 °C). The PBSMM examples according to the invention clearly show a saturation magnetization as measured at an applied field of 100 kA/m of being higher than 0.65 T, whereas the comparative examples exhibit a saturation magnetization of lower than 0.40 T.

Table 4 provides results of rod core inductors with a PBSMM core. These results are also partly shown in Figure 3. All rod core inductors with a PBSMM core according to the invention, thus examples 1 to 8, maintain a high relative inductance up until 90% of the original inductance, as compared to rod core inductors with a PBSMM core not according to the invention, comparative examples A to H.

Figure 3 denotes the inductance as function of current, a) and c) absolute inductance, b) and d) relative inductance. The relative inductance is calculated as L/L_0 x 100%, with L_0 being the initial inductance at low current (2.3 A). The horizontal line in b) and d) represents the 90% inductance value referenced to L_0.

The rod core inductors according to the invention using examples 1 to 8 as core, show a stable inductance up to a frequency as high as $5 \cdot 10^5$ Hz, clearly in the > 1 kHz range where high resistivity materials such as ferrites are commonly applied as core material for rod core inductors.

In Figure 3 the inductance value is plotted as a function of applied current for six rod core inductors made from the set of PBSMMs listed in Table 2. From Figure 3a and 3c it is clear that the inductance value of Examples 1 to 3 decreases much less and at higher current as compared to the comparative examples A to C.

The difference between the rod core inductors according to the invention and the two comparative examples becomes even clearer when looking at the relative inductance (Figure 3b and 3d). The rod core inductors according to the invention using PBSMM examples 1 and 2 as core, maintain a relative inductance up until 90% of the original inductance, until an applied current of about up to 7 A and 12 A for Example 1 and Example 2, respectively. This is in stark contrast to the rod core inductors with a core of the PBSMM of comparative examples A and B, which only maintain a relative inductance up until 90% of the original inductance, until an applied current of less than 5 A.

Similarly, the rod core inductor according to the invention using PBSMM example 3 as core, maintains a relative inductance up until 90% of the original inductance, until an applied current of about up to 6 A. Again, this is in stark contrast to the rod core inductor with a core of PBSMM of comparative example C, which only maintains a relative inductance up until 90% of the original inductance, until an applied current of less than 4.5 A.

Table 5 provides results of embedded rod core inductors with a core and embedment made from the same PBSMM. These results are also shown in Figure 4. Figure 4 denotes the relative inductance as function of DC bias current. The relative inductance is calculated as L/L_0 x 100%, with L_0 being the initial inductance at low DC bias current (2.85 A).

The embedded rod core inductor according to the invention with an embedment and core of a PBSMM of example 3, exhibited a higher initial inductance, as compared to the inductor not according to the invention, thus with core and embedment of a PBSMM of comparative example C. Surprisingly, this higher inductance could be maintained at higher currents. The rod core inductor with a core and embedment of a PBSMM of comparative example C clearly showed that the value of the inductance steeply decreased upon increasing current.

Specifically, the embedded rod core inductor according to the invention maintains a relative inductance up until 90% of the original inductance (L_0), until an applied current of > 40 A. This is in stark contrast to the embedded rod core inductor not according to the invention, which only maintains a relative inductance up until 90% of the original inductance, until an applied current of less than 15 A.

Since the PBSMMs of examples 1, 2 and 4 to 8 show similar magnetic properties as PBSMM of example 3, similar results are expected for embedded rod core inductors according to the invention prepared employing the PBSMMs of examples 1,2 and 4 to 8.

These examples clearly show that rod core inductors and embedded rod core inductors according to the present invention can attain a higher current rating in a relevant frequency range and can operate at higher temperature. The rod core inductors and embedded rod core inductors according to the invention thus show a high current rating, which makes them very suitable to be applied in applications which requires these high current rating, such as for example switch-mode power supplies and DC-DC converters.

CLAIMS

1. Rod core inductor having a length L and a width W comprising
   c) a coil having a length L_{coil} and a width W_{coil}, and
   d) core having a length of at least L_{coil}, width W_{core},

   wherein the core comprises a polymer bonded soft magnetic material (PBSMM) comprising a polymer and at least 30 vol% soft magnetic material with a saturation magnetization of at least 1Tesla to as measured according to IEC 60401-3 and IEC 62044.
2. Rod core inductor according to claim 1 in which the soft magnetic material with a saturation magnetization of at least 1 Tesla is chosen from a group comprising ferromagnetic metals and alloys, ferromagnetic amorphous alloys and ferromagnetic nanocrystalline alloys.
3. Rod core inductor according to claim 1 or 2, in which the PBSMM has a saturation magnetization of at least 0.4 Tesla as measured according to IEC 60401-3 and IEC 62044 with a maximum applied field strength being 100 kA/m.
4. Rod core inductor according to any one of the above claims, in which the polymer of the PBSMM is a thermoplastic polymer.
5. Rod core inductor according to claim 4 in which the thermoplastic polymer is chosen from a group comprising polyamides, polyphthalamides, polyolefins, polyesters, polyimides, polyetherimides, polyaryletherketones, polyphenylene sulfides, liquid crystalline polymers, polycarbonates and a thermoplastic elastomer.
6. Rod core inductor according to any one of the above claims, wherein the coil is embedded in an embedment of a polymer bonded soft magnetic material (PBSMM) comprising a polymer and at least 30 vol% soft magnetic material with a saturation magnetization of at least 1Tesla as measured according to IEC 60401-3 and IEC 62044, and wherein L is at least L_{coil}+0.001xW_{coil}, and W is at least 1.001xW_{coil}.
7. Rod core inductor according to claim 6, wherein L is at least L_{coil}+0.01xW_{coil}, and W is at least 1.01xW_{coil}
8. Rod core inductor according to claim 6 or 7, wherein the soft magnetic material of the embedment having a saturation magnetization of at least 1

Tesla is chosen from a group comprising ferromagnetic metals and alloys, ferromagnetic amorphous alloys and ferromagnetic nanocrystalline alloys.

9. Rod core inductor according to any one of the claims 6 to 8 in which the soft magnetic material of the core and of the embedment are the same.

10. Rod core inductor according to any one of the claims 6 to 9 in which the polymer of the PBSMM of the core and of the embedment are the same.

11. Rod core inductor according to any one of the above claims in which the number of windings is between 1 and 50.

12. Rod core inductor according to any one of the above claims in which the diameter of each winding is at least 0.1mm.

13. Rod core inductor according to any one of the above claims having a current rating of at least 1 Ampere.

14. Rod core inductor according to any one of the above claims, having a current rating of at least 5 Ampere.

15. Rod core inductor according to any of the above claims, wherein the Curie-temperature of the soft magnetic material in the core and/or embedment is at least 250 °C.

Figure 1

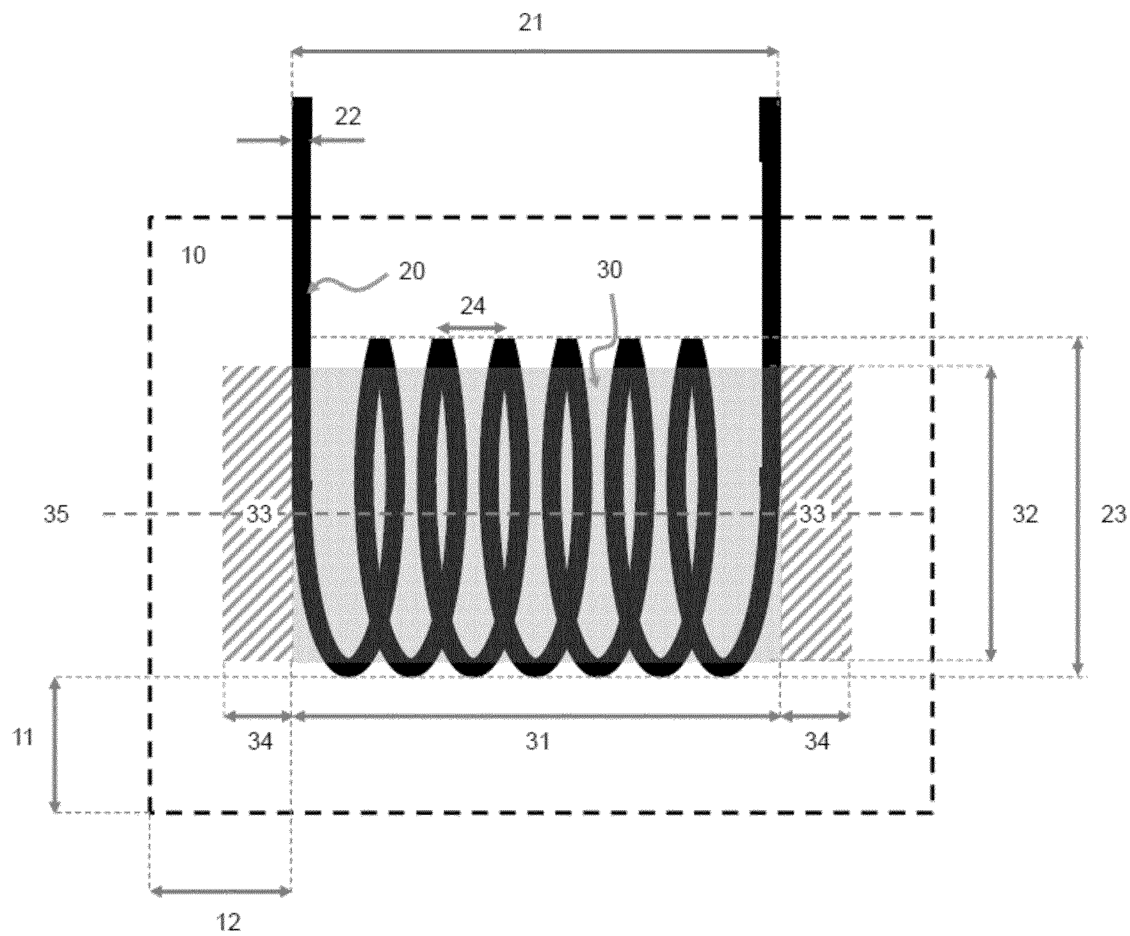


Figure 2

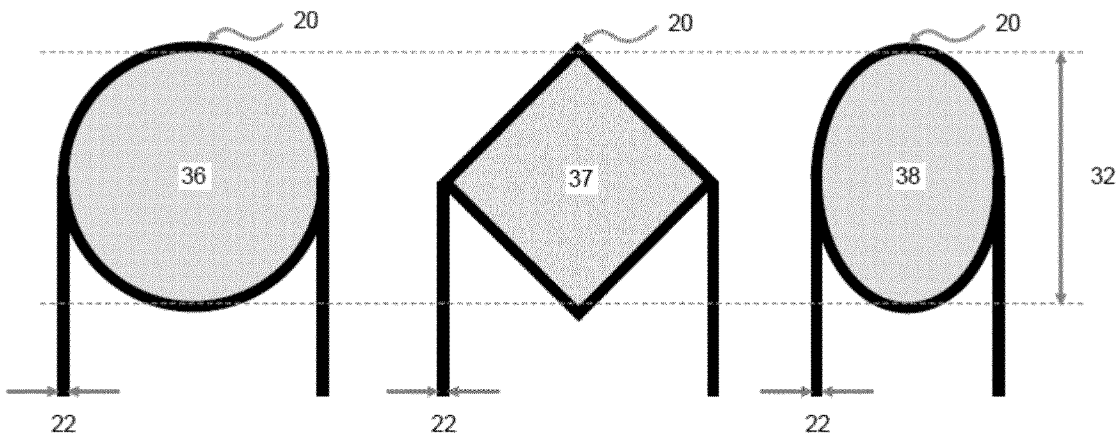
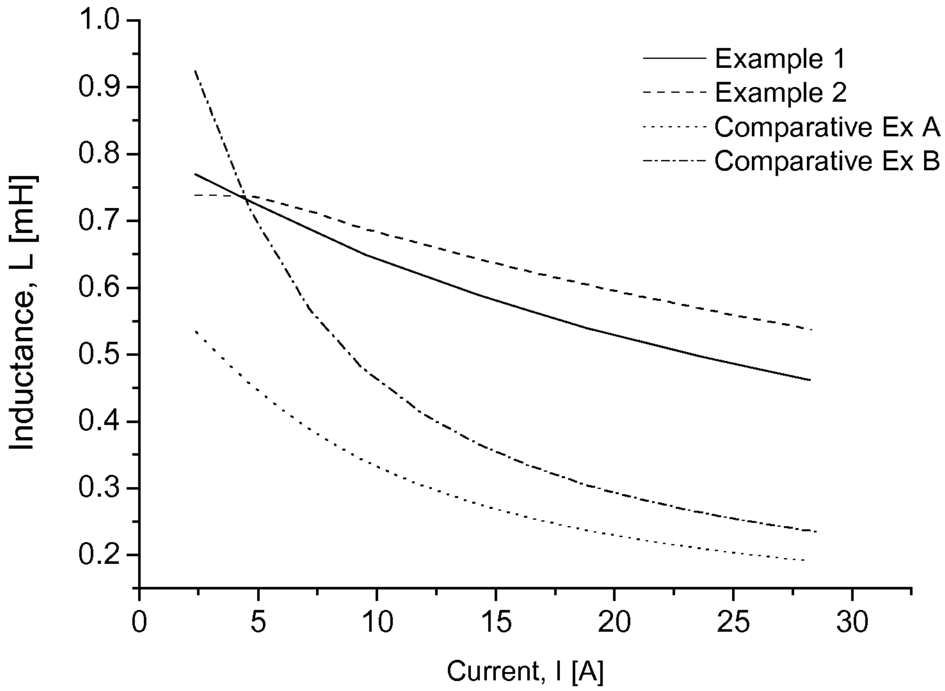
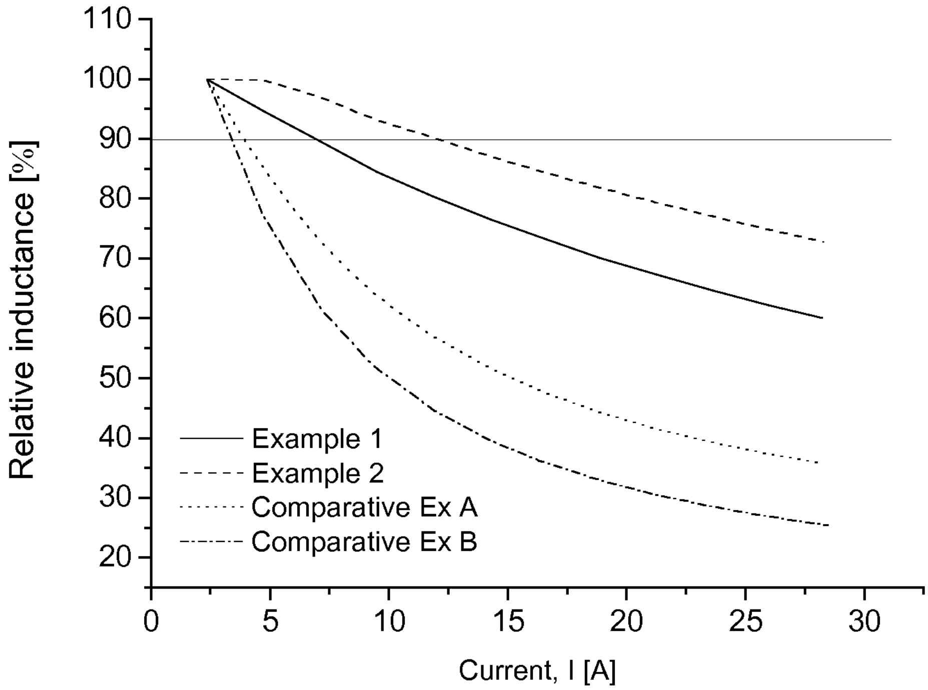


Figure 3: Inductance as function of current. a) and c) absolute inductance, b) and d) relative inductance.



a)


110
100
90
80
70
60
50
40
30
20
Relative inductance [%]
Example 1
Example 2
Comparative Ex A
Comparative Ex B
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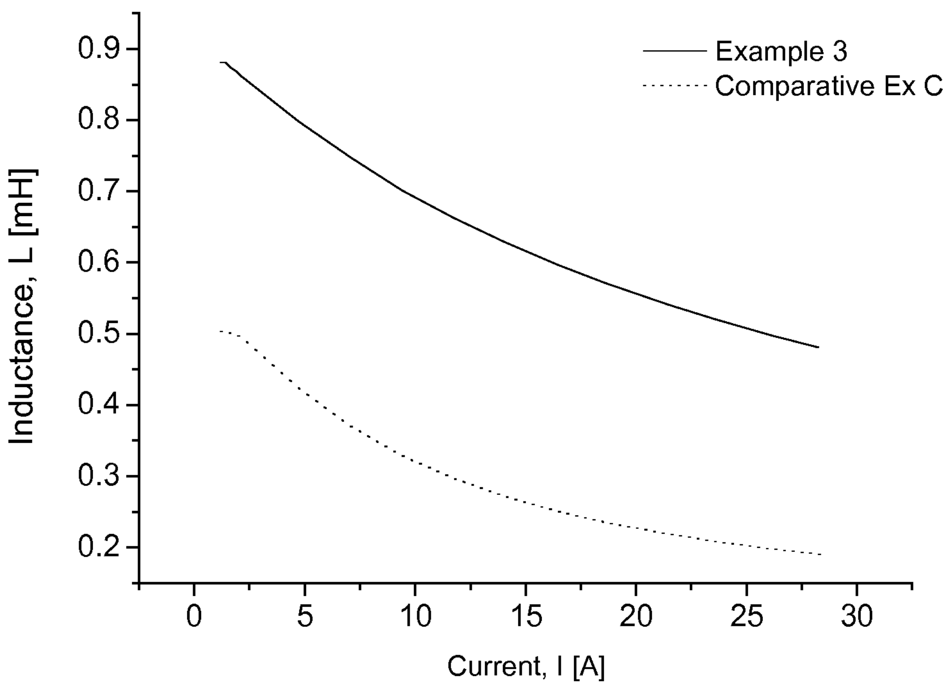
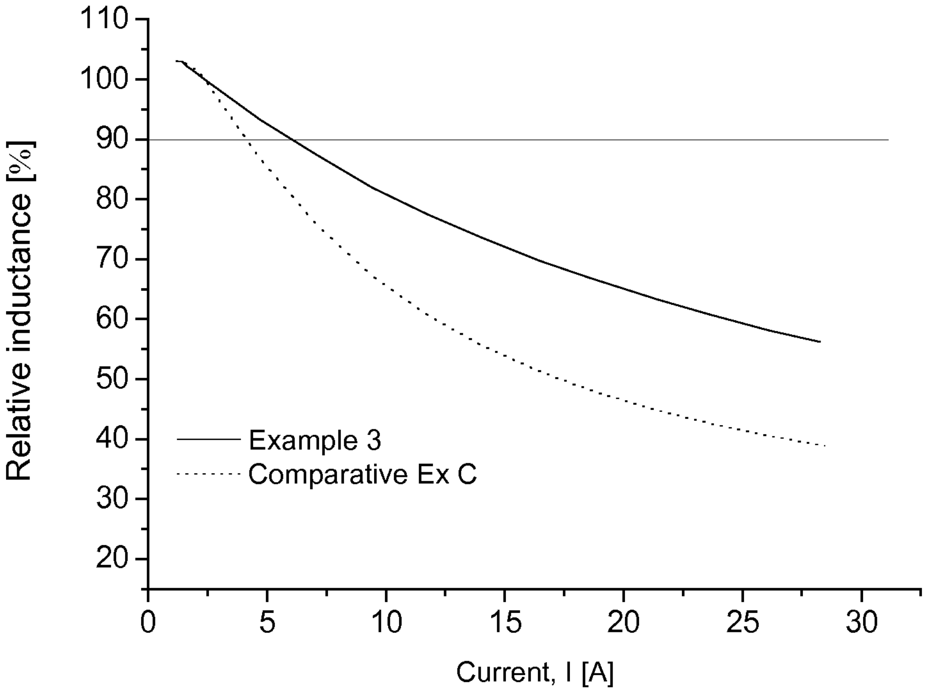
5
10
15
20
25
30
Current, I [A]

b)

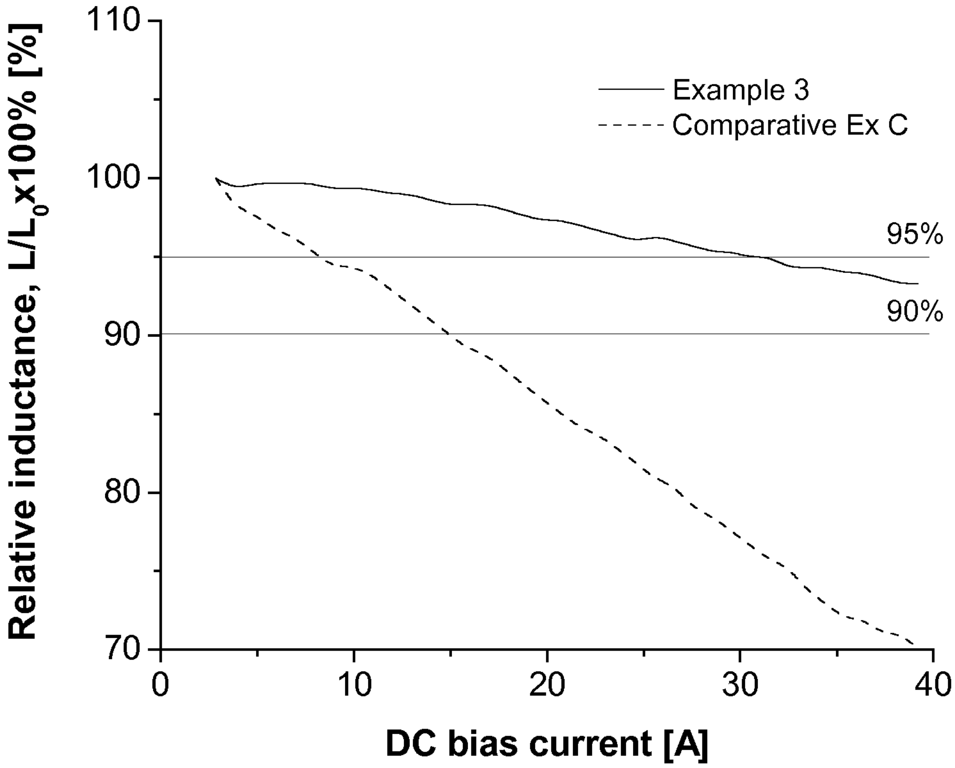

0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Inductance, L [mH]
Example 3
Comparative Ex C
0
5
10
15
20
25
30
Current, I [A]

c)


110
100
90
80
70
60
50
40
30
20
Relative inductance [%]
0
5
10
15
20
25
30
Current, I [A]
Example 3
Comparative Ex C

d)

Figure 4: Relative inductance as function of DC bias current



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2014/076188

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01F27/02 H01F27/255 H01F17/04
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 950 772 A2 (WACOM CO LTD [JP]) 30 July 2008 (2008-07-30) paragraphs [0010], [0027], [0031]; claims 2,9; figure 4 -----	1-15
X	US 6 137 390 A (TUNG MEAN-JUE [TW] ET AL) 24 October 2000 (2000-10-24) column 3, paragraph 3; figure 1 -----	1-15
A	WO 2013/051421 A1 (SUMITOMO ELECTRIC INDUSTRIES [JP]; SUMITOMO WIRING SYSTEMS [JP]; AUTON) 11 April 2013 (2013-04-11) abstract -----	1-15

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 January 2015	05/02/2015

Name and mailing address of the ISA/	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2014/076188

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