(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
26 November 2015 (26.11.2015)

WIPO | PCT

(10) International Publication Number
WO 2015/178780 A1

(51) International Patent Classification: *H01F 38/14* (2006.01)

(21) International Application Number: PCT/NZ2015/050055

(22) International Filing Date: 14 May 2015 (14.05.2015)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/000,232 19 May 2014 (19.05.2014) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

(54) Title: MAGNETICALLY PERMEABLE CORE AND INDUCTIVE POWER TRANSFER COIL ARRANGEMENT

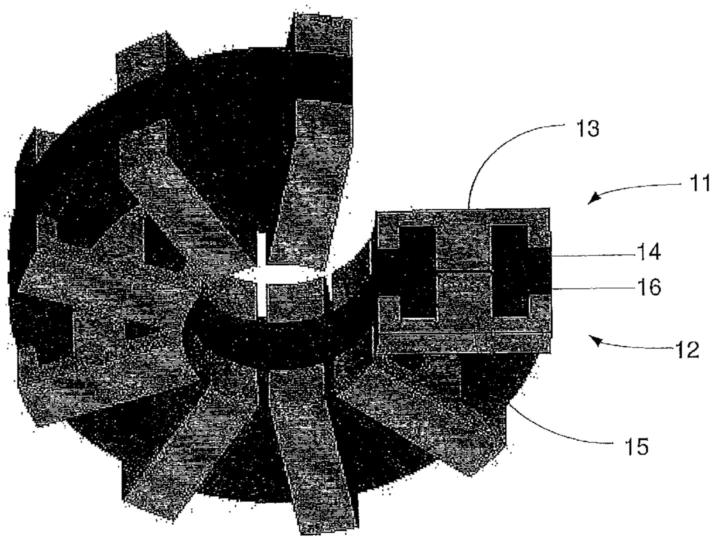

Figure 6

(57) Abstract: An inductive power transfer coil arrangement comprising: a first coil assembly including: at least a first magnetically permeable core including a base having first and second limbs extending away therefrom, wherein the first limb is located between two second limbs and extends further from the base than the second limbs, and at least one coil wound about at least one limb; and a second coil assembly including: at least a second magnetically permeable core for use in an inductive power transfer system, including a base having first and second limbs extending away therefrom, wherein the first limb is located between two second limbs that extend further from the base than the second limbs; and at least one coil wound about at least one limb; the first and second magnetically permeable cores being arranged in relatively moveable relationship such that in some relative positions the first and second magnetically permeable cores are opposed such as to provide effective magnetic coupling.

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MAGNETICALLY PERMEABLE CORE AND INDUCTIVE POWER TRANSFER COIL ARRANGEMENT

FIELD OF THE INVENTION

The present invention is in the field of wireless power transfer systems. More particularly, the invention relates to magnetically permeable cores incorporated into transmitters and receivers in wireless power transfer systems and coil arrangements utilising the cores.

BACKGROUND OF THE INVENTION

Mechanical slip rings utilising direct contact electrical connections are still utilised in a large number of applications. These suffer from contact losses, contact failure and high maintenance costs.

Inductive Power transfer (IPT) systems have been developed which address these drawbacks. A basic problem that must be overcome in wireless power transfer system design is ensuring that power can be transferred between coil arrangements over sufficient displacements (i.e. between the primary side and the secondary side), while maintaining sufficient power transfer.

Introducing magnetically permeable elements into either the transmitting coils or receiving coils can improve the performance of the system. Magnetically permeable elements increase the inductance of the transmitter or receiver coils. This means that less coil turns are required to achieve the same inductance value as a transmitter or receiver without magnetically permeable elements. Magnetically permeable elements can also be configured to 'shape' the magnetic field, which can be directed from the transmitter to the receiver. By directing the magnetic field, the coupling factor between the transmitter and receiver can be increased, thus improving the performance of the system.

Current IPT coil arrangements often suffer from a low magnetic coupling coefficient *k*, which results in limited power transfer capability, particularly for large air gaps, due to magnetic flux leakage between the limbs of the magnetically permeable cores. Decreased power transfer capability results in low efficiency, greater size and greater cost for a given power transfer capacity.

The physical space available for a wireless power transfer system is often limited, including in rotary applications for robotic joints and wind power pitch control. Further, a large air gap is often required for mechanical clearance. When the air gap is large, the magnetic flux tends to leak within the core limbs instead of linking to the other side, which can result in low magnetic field coupling.

It is an object of the invention to provide a magnetically permeable core and an inductive power transfer coil arrangement having improved magnetic coupling, or to at least provide the public with a useful choice.

SUMMARY OF THE INVENTION

According to one exemplary embodiment there is provided an inductive power transfer coil arrangement comprising:

i. a first coil assembly including:
    a. at least a first magnetically permeable core including a base having first and second limbs extending away therefrom, wherein the first limb is located between two second limbs and extends further from the base than the second limbs, and
    b. at least one coil wound about at least one limb;

and

ii. a second coil assembly including:

a. at least a second magnetically permeable core for use in an inductive power transfer system, including a base having first and second limbs extending away therefrom, wherein the first limb is located between two second limbs that extend further from the base than the second limbs; and

b. at least one coil wound about at least one limb,

the first and second magnetically permeable cores arranged in relatively moveable relationship such that in some relative positions the first and second magnetically permeable cores are opposed such as to provide effective magnetic coupling

According to another exemplary embodiment there is provided a magnetically permeable core for use in an inductive power transfer system, including a base having one or more first and two or more second limbs arranged along annular paths extending away from the base, wherein the one or more first limb is located between second annular limbs that extend further from the base than the second limbs.

It is acknowledged that the terms "comprise", "comprises" and "comprising" may, under varying jurisdictions, be attributed with either an exclusive or an inclusive meaning. For the purpose of this specification, and unless otherwise noted, these terms are intended to have an inclusive meaning – i.e. they will be taken to mean an inclusion of the listed components which the use directly references, and possibly also of other non-specified components or elements.

Reference to any prior art in this specification does not constitute an admission that such prior art forms part of the common general knowledge.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings which are incorporated in and constitute part of the specification, illustrate embodiments of the invention and, together with the general description of the invention given above, and the detailed description of embodiments given below, serve to explain the principles of the invention.

Figure 1	shows the magnetic flux paths for two standard U cores;
Figure 2	shows a reluctance model of the arrangement shown in Figure 1;
Figure 3	shows an inductance based T-equivalent circuit of the arrangement shown in Figure 1;
Figure 4	shows the cross-sectional area and length of the leakage flux lines for the arrangement of Figure 1;
Figure 5	shows the general configuration of an inductive power transfer coil arrangement according to one embodiment;
Figure 6	shows a partially cut away slip ring type arrangement utilising the general configuration shown in Figure 5;
Figure 7	shows the relationship between the magnetic coupling coefficient and the length of the ratio of the height of the outer limbs to the height of the central limb;

Figure 8	shows the relationship between the magnetic coupling coefficient and the air gap;
Figures 9	shows the relationship between the mutual inductance and the air gap;
Figures 10	shows magnetic flux lines for a conventional design; and
Figures 11	shows magnetic flux lines for the embodiment shown in Figure 5.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

Figure 1 shows the flux paths of a contactless slip ring system using a UU core arrangement. Note that in the case of EE arrangements, the center-leg flux is divided into two equal portions through the outer legs encircling the coils. Thus because of this symmetry, the whole EE structure can be divided into two identical UU layouts, so only the UU configuration is presented here for theoretical description.

In Figure 1 the total flux linked by each coil can be divided into two components; a mutual component φ_m that is common to both coils and leakage flux components (φ_{lk1} and φ_{lk2}) that links only the coil itself. When a magnetic force (Ampere-Turns) is applied to a magnetic element (such as a section of the core, or an air gap), the amount of flux is determined by the reluctance of that magnetic element. The reluctance of each region of the structure is calculated from its area, length and permeability ($\mathcal{R} = l/\mu A$), and inserted with its specific value into the appropriate location in the reluctance models as shown in Figure 2.

The reluctances of the regions between the cores limbs ($\mathcal{R}_{lk1}$ and $\mathcal{R}_{lk2}$) are of key importance, the magnetic fields in these regions translate into leakage inductance. Relative permeability equals 1.0 in these non-magnetic regions and in the copper conductors. The primary and secondary leakage inductances can be expressed in terms of their relevant reluctances as:

$$L_{lk1} = \frac{N_1^2}{\mathcal{R}_{lk1}} = \frac{N_1^2 \mu_0 A_{lk1}}{l_{lk1}} \qquad \text{Equation (1)}$$

$$L_{lk2} = \frac{N_2^2}{\mathcal{R}_{lk2}} = \frac{N_2^2 \mu_0 A_{lk2}}{l_{lk2}} \qquad \text{Equation (2)}$$

where A_{lk1} and A_{lk2} are the cross-section areas of the leakage flux lines and l_{lk1} and l_{lk2} are the length of the leakage flux lines path which is the distance between the core limbs.

The mutual inductance on the other hand depends on both coils and can be expressed by:

$$M = \frac{N_1 N_2}{\mathcal{R}_m} \qquad \text{Equation (3)}$$

where $\mathcal{R}_m$ is the total mutual reluctance between two sides expressed by:

$$\mathcal{R}_m = \mathcal{R}_{c1} + \mathcal{R}_{c2} + \mathcal{R}_{c3} + \mathcal{R}_{c4} + \mathcal{R}_{c5} + \mathcal{R}_{c6} + \mathcal{R}_{g1} + \mathcal{R}_{g2} \cong \mathcal{R}_{g1} + \mathcal{R}_{g2} \qquad \text{Equation (4)}$$

Generally, the air gap reluctances are much greater than the adjacent ferrite core legs in Figure 2, meaning that the core reluctances could be eliminated from Equation (4). Thus for a total air gap $l_g = l_{g1}+l_{g2}$, the mutual inductance is:

$$M = {N_1 N_2}/{\mathrm{R}_m} = {N_1 N_2 \mu_0 A_g}/{l_g} \qquad \text{Equation (5)}$$

The reluctance models finally translate to the inductance-based electrical model based on the duality principle as shown in Figure 3. From Figure 3 the magnetic coupling coefficient *k* is calculated based on the system inductances from:

$$k = \sqrt{\frac{M}{L_1} \cdot \frac{M}{L_2}} = \sqrt{\frac{M}{(L_{lk1} + M)} \cdot \frac{M}{(L_{lk2} + M)}} \qquad \text{Equation (6)}$$

Substituting Equations (1), (2) and (5) into Equation (6) gives the coupling coefficient *k* based on the system geometry as:

$$k = \sqrt{\frac{1}{\left(\frac{\mathrm{R}_m}{\mathrm{R}_{lk1}} + 1\right)} \cdot \frac{1}{\left(\frac{\mathrm{R}_m}{\mathrm{R}_{lk2}} + 1\right)}} \qquad \text{Equation (7)}$$

For a system with identical primary and secondary sides Equation (7) can be rewritten as:

$$k = \frac{1}{\left(\frac{\mathrm{R}_m}{\mathrm{R}_{lk1}} + 1\right)} = \frac{1}{\left(\frac{\mathrm{R}_m}{\mathrm{R}_{lk2}} + 1\right)} \qquad \text{Equation (8)}$$

The magnetic coupling coefficient of Equation (8) can be improved by reducing the ratios $\mathcal{R}_m/\mathcal{R}_{lk1}$ and $\mathcal{R}_m/\mathcal{R}_{lk2}$. Increasing the reluctance of the leakage flux path ($\mathcal{R}_{lk1}$ and $\mathcal{R}_{lk2}$) can be achieved by either increasing the length of the leakage flux path l_{lk1} and l_{lk2} (the distance between the core limbs) or reducing the leakage cross-section areas A_{lk1} and A_{lk2} (see Figure 4). To improve the magnetic coupling coefficient within fixed structural dimensions, the distance between the core limbs

(l_{lk1} and l_{lk2}) is kept the same. Thus $\mathcal{R}_{lk1}$ and $\mathcal{R}_{lk2}$ increase by reducing A_{lk1} and A_{lk2} (by reducing the length of the cores limbs as illustrated in the embodiments of Figures 5 and 6).

For the mutual reluctance $\mathcal{R}_m$ (the air gap reluctance) as the length of the limbs of the cores is reduced, the size of the air gap increases which results in greater reluctances and accordingly reduced mutual inductance. The mutual inductance is then improved by filling the available provided space (due to the shortened core limbs) with a greater number of turns.

Figure 5 shows an exemplary configuration of an inductive power transfer coil arrangement utilizing the topology of the present invention. A first E core is formed by a base 1 and two outer limbs 2 and 3 and a central limb 4 extending from the base 1. Windings 5 are provide between the limbs and above the outer limbs 2 and 3 of the E core. A second E core is formed by a base 6 and two limbs 7 and 8 and a central limb 9 extending from the base 6. Windings 10 are provide between the limbs and above the limbs 7 and 8 of the second E core.

Counterintuitively this arrangement provides improved coupling due to:

1. increased M due to increasing N_1 and N_2 as stated in Equation (3), and
2. two loops of coils being provided on each side in proximity which enhances the flux linkage between the two sides as shown in Figure 5. This results in the ratios $\mathcal{R}_m/\mathcal{R}_{lk}$ in Equation (8) being reduced and an increased coupling coefficient k.

Figure 6 shows an exemplary slip ring embodiment utilising the topology of Figure 5. In this embodiment the coil arrangement includes a first coil assembly 11 that is relatively rotatable with respect to a second coil assembly 12, as per a slip ring arrangement. In this embodiment the first coil assembly 11 includes a plurality of magnetically permeable cores 13 (only one of which is indicated) arranged along an annular path. A first coil 14 is wound following the annular path between central and outer limbs of each core 13 so as to form loops on either side of the central core. The second coil assembly 11 includes a plurality of magnetically permeable cores 15 (only one of which is indicated) arranged along an annular path. A second coil 16 is wound following the annular path between central and outer limbs of each core 15 so as to form loops on either side of the central core.

It will be appreciated that the plurality of cores 13 and 15 could each be replaced by a single core of annular form, although this form may be more expensive to produce. It will also be appreciated that this arrangement may also be implemented in linear form – either with a plurality of cores 13 and 15 in parallel linear arrangements or utilizing single opposed elongate cores. Further, it will be appreciated that rather than having the coil assemblies axially opposed they may be concentrically arranged with the limbs being generally radially directed. It will be appreciated that the design may be implemented with or without a through hole.

The coil arrangement of Figure 6 was modelled using Litz wire, an air gap of about 5 mm between the first and second coil assemblies (considered a typical value) and the values specified in Table 1 below:

Table 1

Parameter	**Value**
f (kHz)	50
N_1=N_2 (Typical design)	20
N_1=N_2 (Present embodiment)	28
Ferrite Mn-Zn with B_s (T)	0.5

3D-FEM models were used to compare coil assemblies utilizing cores with outer limbs ranging in length from a core with no outer limbs (0%) to a core with outer limbs of the same length as the central limb (100%). The results shown in Figure 7 show that the magnetic coupling coefficient changes non-linearly versus with the ratio of the length of the outer core limbs to the central core. The maximum magnetic coupling coefficient of about 0.48 is achieved when the length of the outer limbs is reduced to about 50% of the length of the central limb. As compared to a conventional design with full length outer limbs with a coupling coefficient *k* of about 0.4, the magnetic coupling coefficient is improved by about 20%. The graphs of Figure 8 show the simulation results for a range of air gaps from about 0.5 mm to about 50 mm. As can be seen from Figure 8, for the air gaps smaller than about 3 mm, the coupling coefficient of a conventional ("typical") design is greater than the coupling coefficient of the present embodiment ("proposed" design). After about 3 mm, the magnetic coupling coefficient of the present embodiment is greater for all the air gaps. This similarly happens for the mutual inductance between both sides as shown in Figure 9. The maximum of about 45% improvement in magnetic coupling coefficient is achieved for an EE core topology with an air gap of about 9 mm.

As shown in figure 7 any value less than about 90% (i.e. outer limbs less than about 90% of the length of the central limb) is advantageous with values below about 80% being more advantageous. Ratios between about 20% and about 80% are seen to be particularly advantageous with values between about 40% and about 60% being most advantageous with a maximum at about 50%.

In Figure 10 it can be seen that for a typical layout the flux lines tend to circulate between the core limbs for their low reluctance path which gets worse with increased air gap. As the core limbs are shortened as shown in Figure 11 the cross-sectional area of the flux leakage reduces and accordingly the reluctances of the flux leakage path reduce. After reducing the leakage inductances due to short cores limbs, the mutual inductance then is improved by increasing the number of turns of both sides using the provided available space. Applying these two modifications together reduces $\mathcal{R}_m/\mathcal{R}_{lk}$ and enhances the coupling coefficient k as seen in Figure 8.

The invention may find application in wide range of inductive power transfer applications including slip rings, linear arrangements such as are used for electric vehicles on roadways and automation, biomedical applications etc. Further, it is understood by those skilled in the art that the invention is applicable to IPT systems having materials other than air in the 'gap' between the transmitter and receiver coils.

The arrangements described provide improved magnetic coupling for a given physical size. This results in improved efficiency, a more compact construction and reduced cost.

While the present invention has been illustrated by the description of the embodiments thereof, and while the embodiments have been described in detail, it is not the intention of the Applicant to restrict or in any way limit the scope of the appended claims to such detail. Additional advantages and modifications will readily appear to those skilled in the art. Therefore, the invention in its broader aspects is not limited to the specific details, representative apparatus and method, and illustrative examples shown and described. Accordingly, departures may be made from such details without departure from the spirit or scope of the Applicant's general inventive concept.

CLAIMS:

1. An inductive power transfer coil arrangement comprising:
    i. a first coil assembly including:
        a. at least a first magnetically permeable core including a base having first and second limbs extending away therefrom, wherein the first limb is located between two second limbs and extends further from the base than the second limbs, and
        b. at least one coil wound about at least one limb; and
    ii. a second coil assembly including:
        a. at least a second magnetically permeable core for use in an inductive power transfer system, including a base having first and second limbs extending away therefrom, wherein the first limb is located between two second limbs that extend further from the base than the second limbs; and
        b. at least one coil wound about at least one limb,

    the first and second magnetically permeable cores being arranged in relatively moveable relationship such that in some relative positions the first and second magnetically permeable cores are opposed such as to provide effective magnetic coupling.

2. An inductive power transfer coil arrangement wherein the first and second magnetically permeable cores are arranged along annular paths.

3. An inductive power transfer coil arrangement as claimed in claim 2 including a plurality of cores.

4. An inductive power transfer coil assembly as claimed in claim 2 wherein each magnetically permeable core is an annular core.

5. An inductive power transfer coil assembly as claimed in any one of the preceding claims wherein the first and second coil assemblies are axially opposed.

6. An inductive power transfer coil assembly as claimed in any one of the preceding claims wherein the first and second coil assemblies are concentrically arranged.

7. An inductive power transfer coil assembly as claimed in any one of claims 2 to 4 having a through hole at the centre of the annular path.

8. An inductive power transfer coil assembly as claimed in any one of the preceding claims wherein the second limbs are less than about 90% of the length of the first limb.

9. An inductive power transfer coil assembly as claimed in any one of the preceding claims wherein the second limbs are less than about 80% of the length of the first limb.

10. An inductive power transfer coil assembly as claimed in any one of the preceding claims wherein the second limbs are between about 20% and about 80% of the length of the first limb.

11. An inductive power transfer coil assembly as claimed in any one of the preceding claims wherein the second limbs are between about 40% and about 60% of the length of the first limb.

12. An inductive power transfer coil assembly as claimed in any one of the preceding claims wherein the second limbs are about 50% of the length of the first limb.

13. An inductive power transfer coil assembly as claimed in any one of the preceding claims wherein the transition from the base to each limb is curved.

14. A magnetically permeable core for use in an inductive power transfer system, including a base having one or more first and two or more second limbs arranged along annular paths extending away from the base, wherein the one or more first limb is located between second annular limbs that extend further from the base than the second limbs.

15. A magnetically permeable core as claimed in claim 14 wherein the core is a unitary annular core.

16. A magnetically permeable core as claimed in claim 14 including a plurality of cores arranged along an annular path.

17. A magnetically permeable core as claimed in any one of claims 14 to 16 including a winding wound following the annular path.

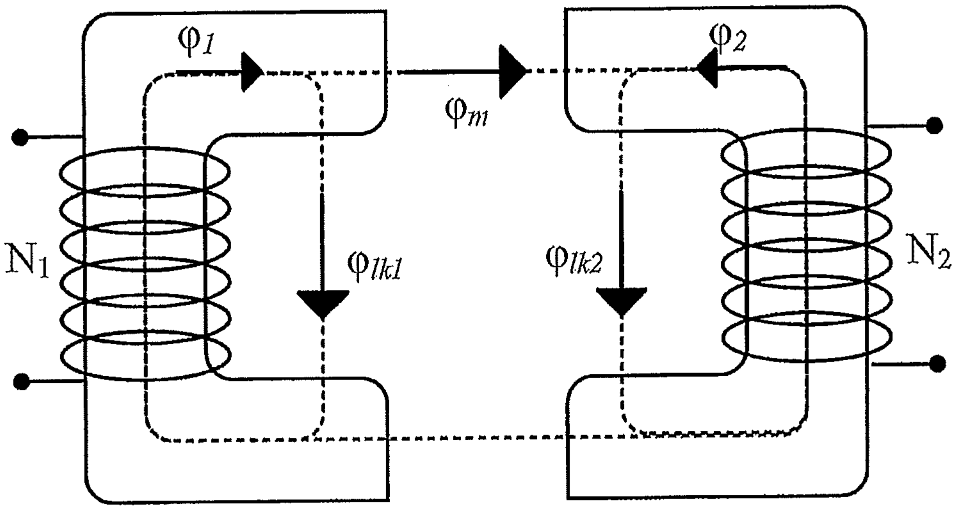

Figure 1

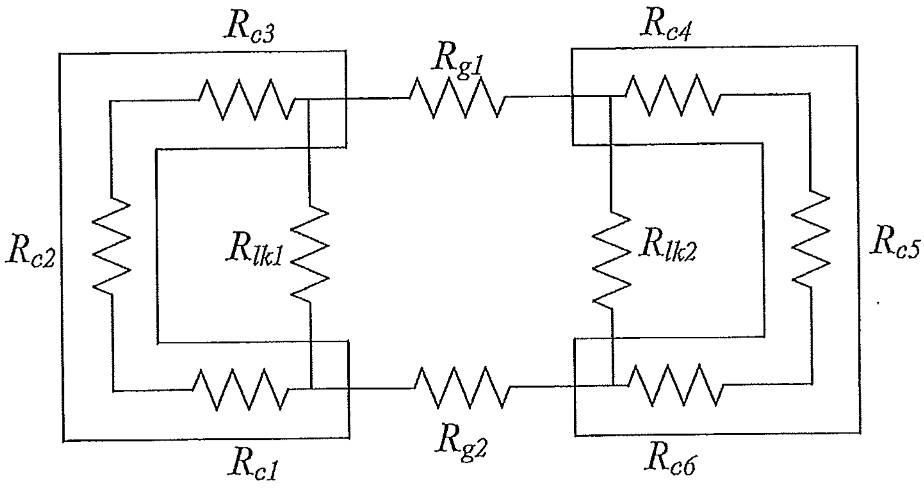

Figure 2

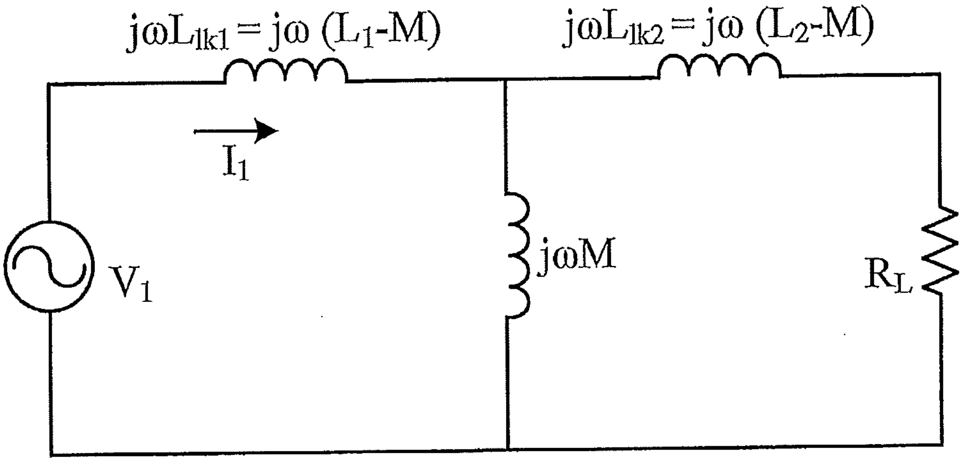

Figure 3

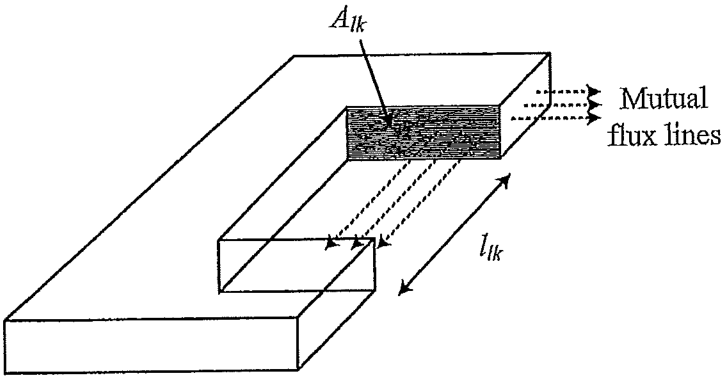

Figure 4

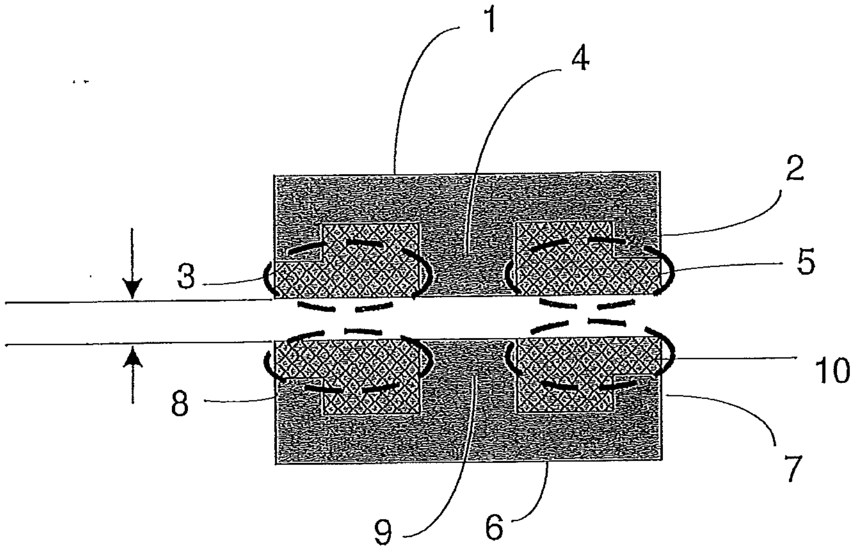

Figure 5

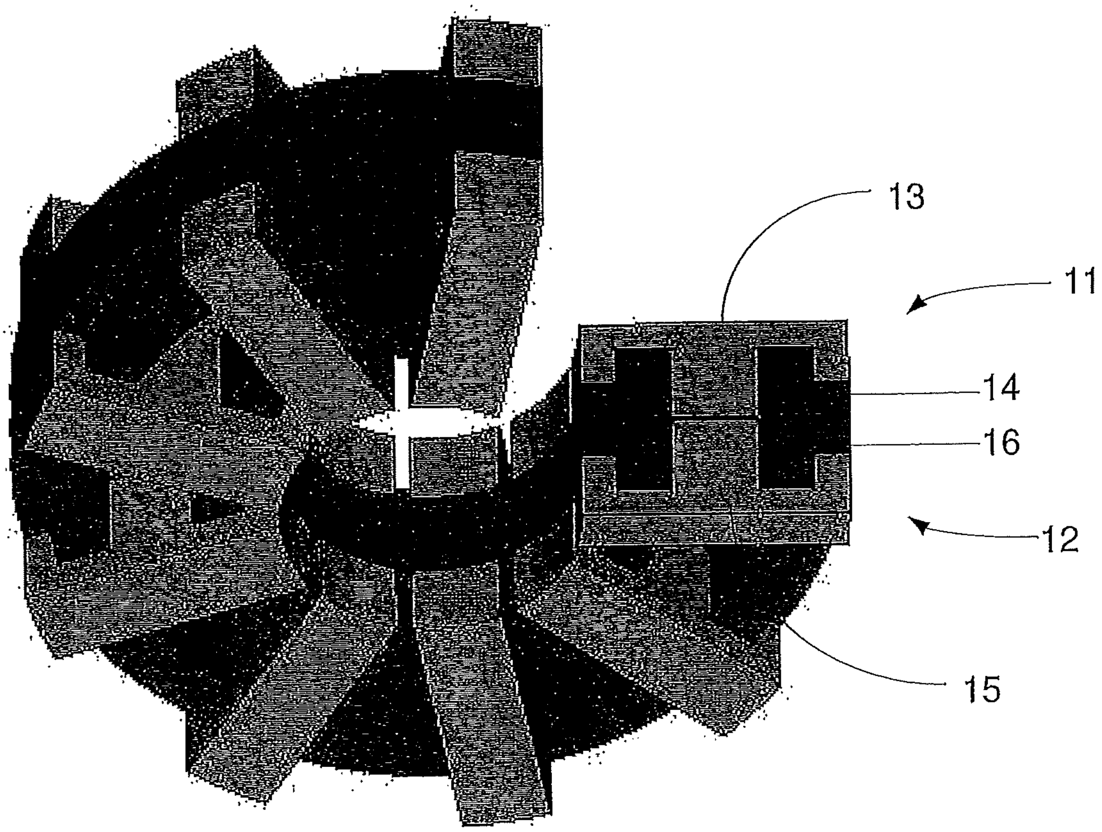

Figure 6

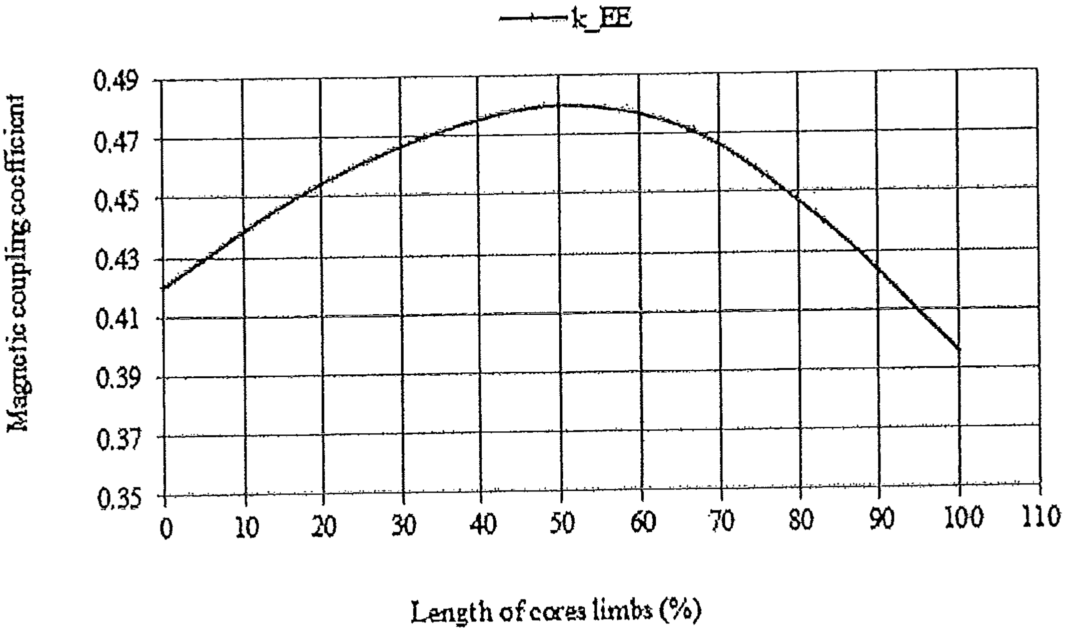

Figure 7

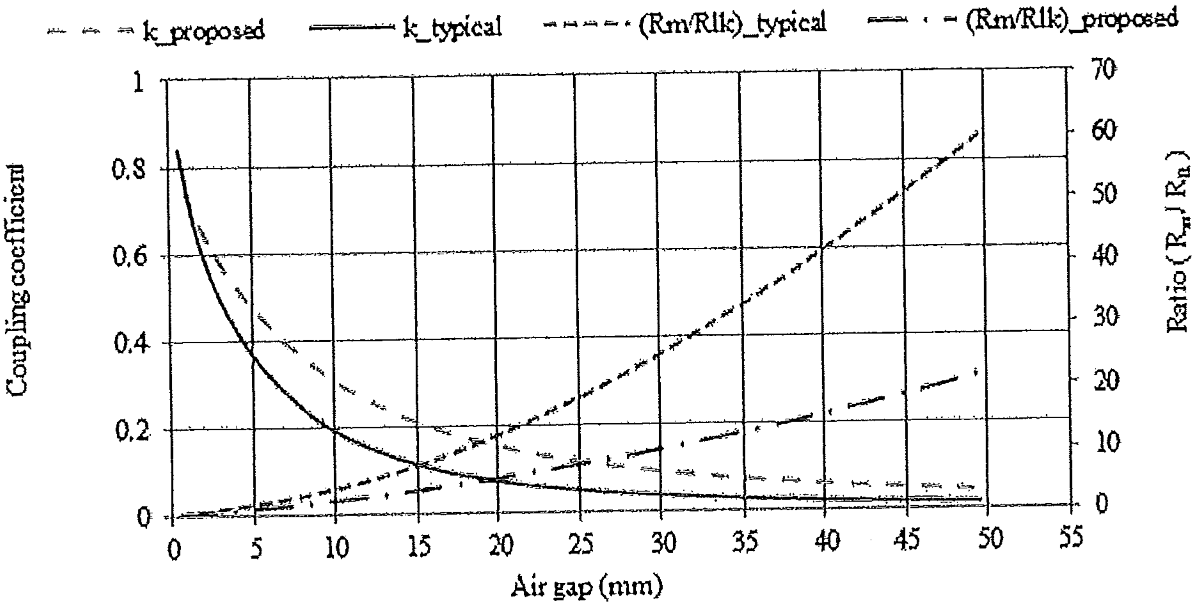

Figure 8

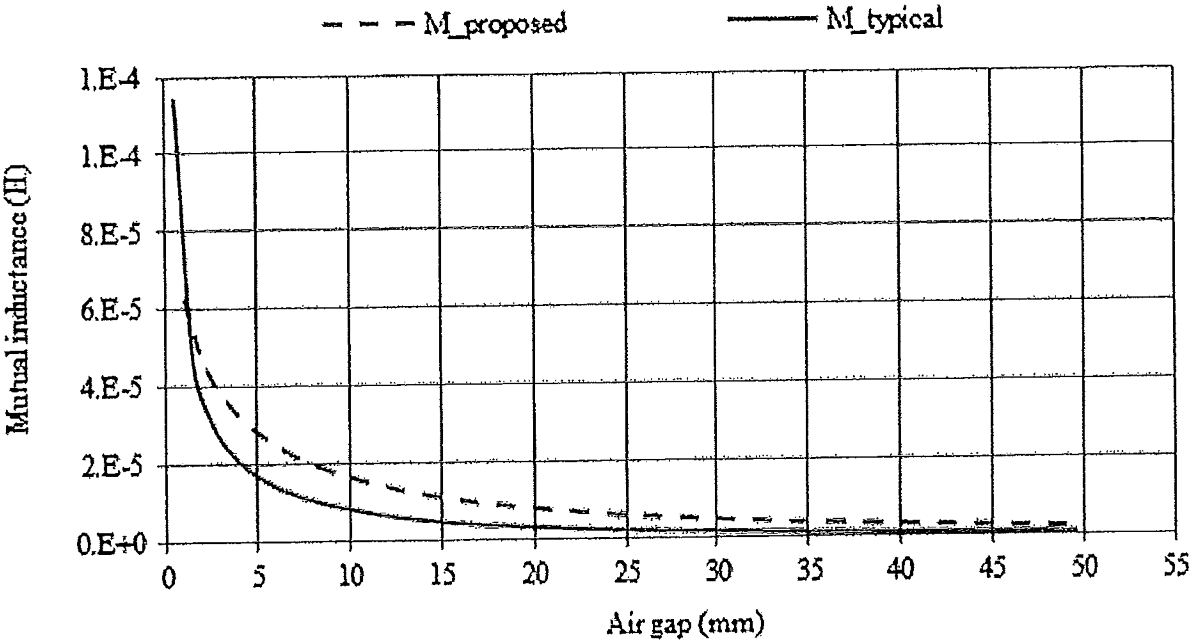

Figure 9

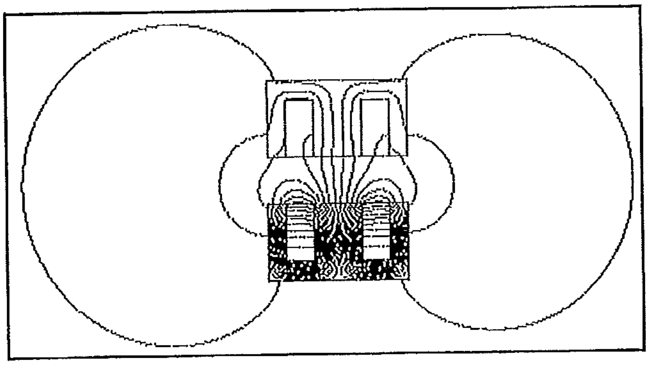

Figure 10

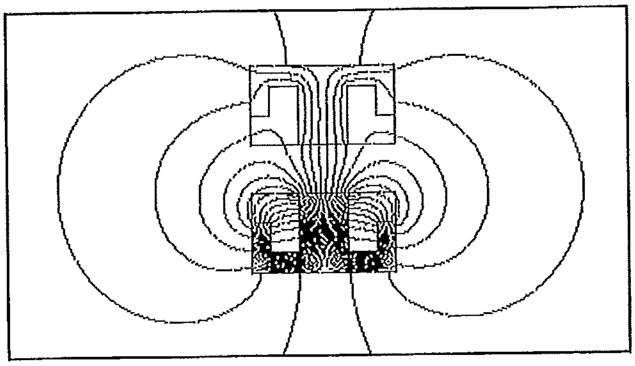

Figure 11

INTERNATIONAL SEARCH REPORT	International application No. **PCT/NZ2015/050055**

A. CLASSIFICATION OF SUBJECT MATTER

H01F 38/14 (2006.01)

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)

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)

Applicant(s)/Inventor(s) name searched in Google Patents, Espacenet, Auspat and internal databases provided by IPAustralia. Performed ultraCombi on select document from the same applicant and inventor, and performed ultraCombi on select patent family member of the document from the same applicant and inventor, using EPODOC database.

Searched Google Patents and Google Images using keywords: e-core, inductive power transfer, limbs, extension, middle, annular, mutual inductance and other similar terms.

Searched databases EPODOC, WPI using keywords: inductive, wireless, core, winding, magnet, limb, annular and other similar terms. Performed ultraCombi using EPODOC database on the most relevant document found from the search in EPODOC, WPI.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

☒ Further documents are listed in the continuation of Box C ☒ See patent family annex

* Special categories of cited documents:

"A"	document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search	Date of mailing of the international search report
17 August 2015	17 August 2015

Name and mailing address of the ISA/AU	**Authorised officer**
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INTERNATIONAL SEARCH REPORT C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		International application No. **PCT/NZ2015/050055**
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 7197113 B1 (KATCHA et al.) 27 March 2007 See the whole document, in particular, the abstract, fig. 2, col. 4 line 46 - col. 5 line 40.	1-17
Y	WO 2013/186180 A1 (TYCO ELECTRONICS NEDERLAND B.V.) 19 December 2013 See the whole document, in particular, the abstract, fig. 1-3 and page 2 line 30 - page 3 line 30.	1-17

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/NZ2015/050055**

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Patent Document/s Cited in Search Report		**Patent Family Member/s**	
Publication Number	**Publication Date**	**Publication Number**	**Publication Date**
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End of Annex

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.