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(54) **INDUCTIVE POWER TRANSFER USING DIVERTED MAGNETIC FIELD**

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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2017/0018947 A1* 1/2017 Chien H02J 7/025

OTHER PUBLICATIONS

L. C. Meng, K. W. Eric Cheng, and K. W. Chan, "Systematic Approach to High-Power and Energy-Efficient Industrial Induction Cooker System: Circuit Design, Control Strategy and Prototype Evaluation", IEEE Transactions on Power Electronics, vol. 26, No. 12, pp. 3754-3765, Dec. 2011.

(Continued)

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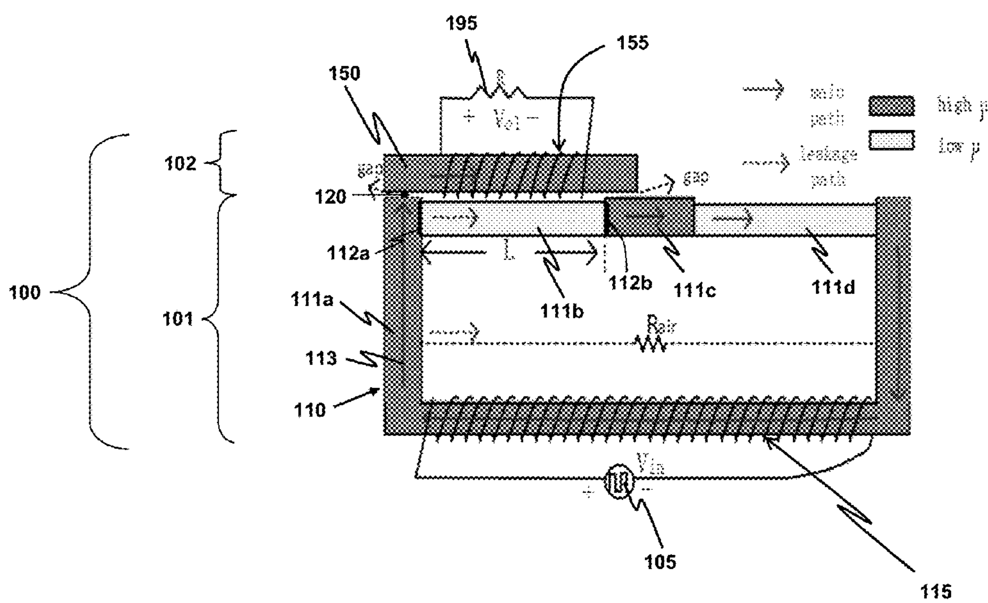
(57) **ABSTRACT**

In a wireless power transfer (WPT) system, a power-transmitting unit has a loop-shaped magnetic core formed by alternately arranging high-permeability (HP) and low-permeability (LP) core sections to give an interleaving pattern. A primary coil wound on the magnetic core provides a magnetic flux traveling therein when excited by an AC power source. A power-receiving unit has a pickup core shaped and dimensioned to overlie one or any LP core section, and to partially overlap HP core sections immediately adjacent to the LP core section that is overlay. The pickup core has a relative permeability higher than that of the aforesaid LP core section, causing at least a part of the magnetic flux to divert from this LP core section to the pickup core. The diverted part of magnetic flux generates electrical power in a secondary pickup coil wound on the pickup core to achieve WPT.

18 Claims, 5 Drawing Sheets



(51) **Int. Cl.**
H02J 3/46 (2006.01)
H01F 38/14 (2006.01)
H01F 3/10 (2006.01)
H02J 50/40 (2016.01)

(52) **U.S. Cl.**
CPC ***H02J 3/46*** (2013.01); *H01F 2003/106* (2013.01); *H02J 50/40* (2016.02)

(56) **References Cited**

OTHER PUBLICATIONS

D. Mishra, S. De, and K. R. Chowdhury, "Charging Time Characterization for Wireless RF Energy Transfer", IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 62, issue 4, pp. 362-366, 2015.

J. Madawala and D. Thrimawithana, "A Bidirectional Inductive Power Interface for Electric Vehicles in V2G Systems," IEEE Transactions on Industrial Electronics, vol. 58, No. 10, pp. 4789-4796, Oct. 2011.

C. J. Chen, T. H. Chu, C. L. Lin, and Z. C. Jou, "A Study of Loosely Coupled Coils for Wireless Power Transfer," IEEE Transactions on Circuits and Systems, vol. 57, No. 71, pp. 536-540, Jul. 2010.

D. Ahn and S. Hong, "Effect of Coupling Between Multiple Transmitters or Multiple Receivers on Wireless Power Transfer," IEEE Transactions on Industrial Electronics, vol. 60, No. 7, pp. 2602-2613, Jul. 2013.

S. Y. Hui, "Planar Wireless Charging Technology for Portable Electronic Products and Qi", Proceedings of the IEEE, vol. 101, issue 6, pp. 1290-1301, 2013.

X. Mou, O. Groling, and H. Sun, "Energy-Efficient and Adaptive Design for Wireless Power Transfer in Electric Vehicles", IEEE Transactions on Industrial Electronics, vol. 64, issue 9, pp. 7250-7260, 2017.

* cited by examiner

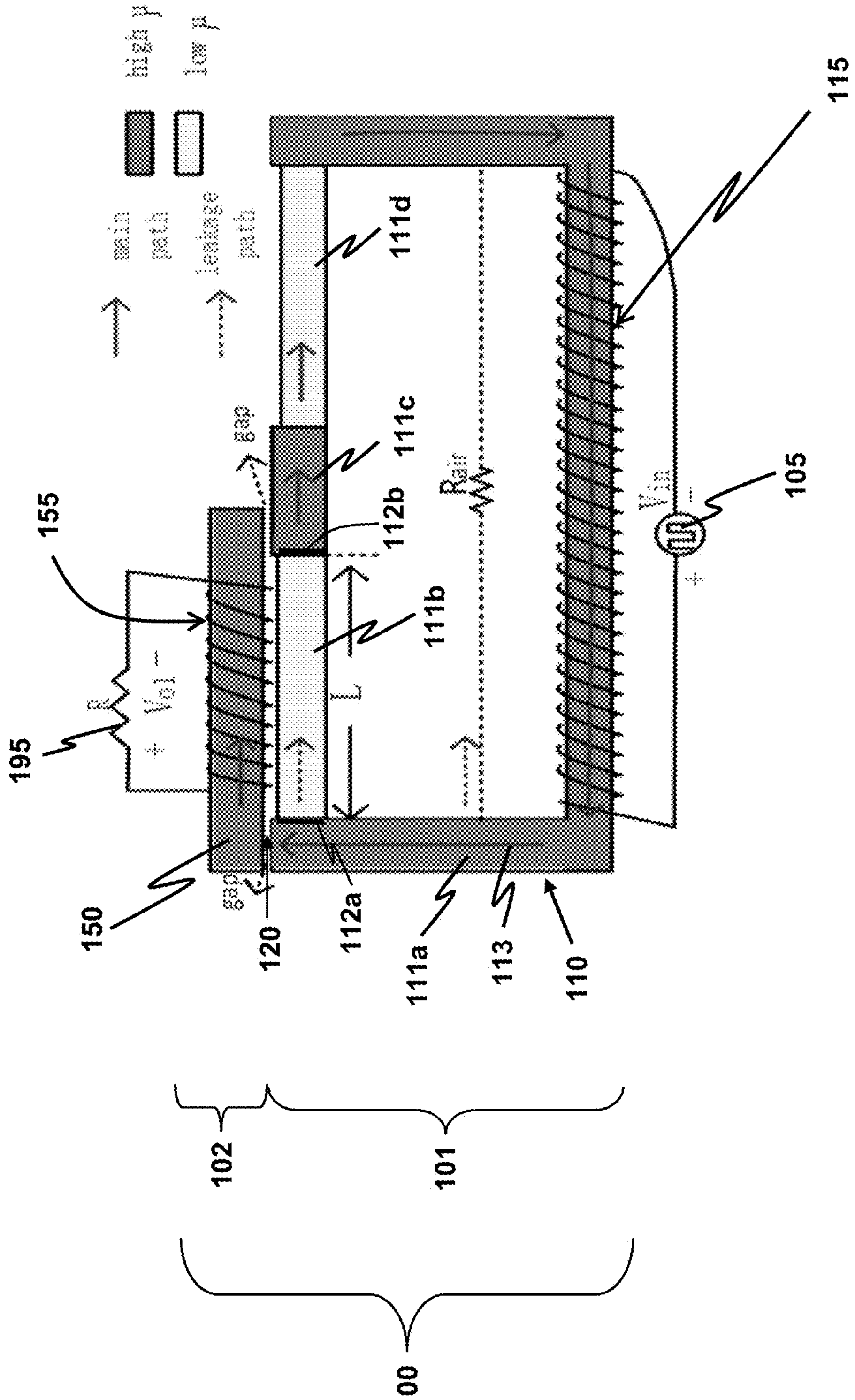
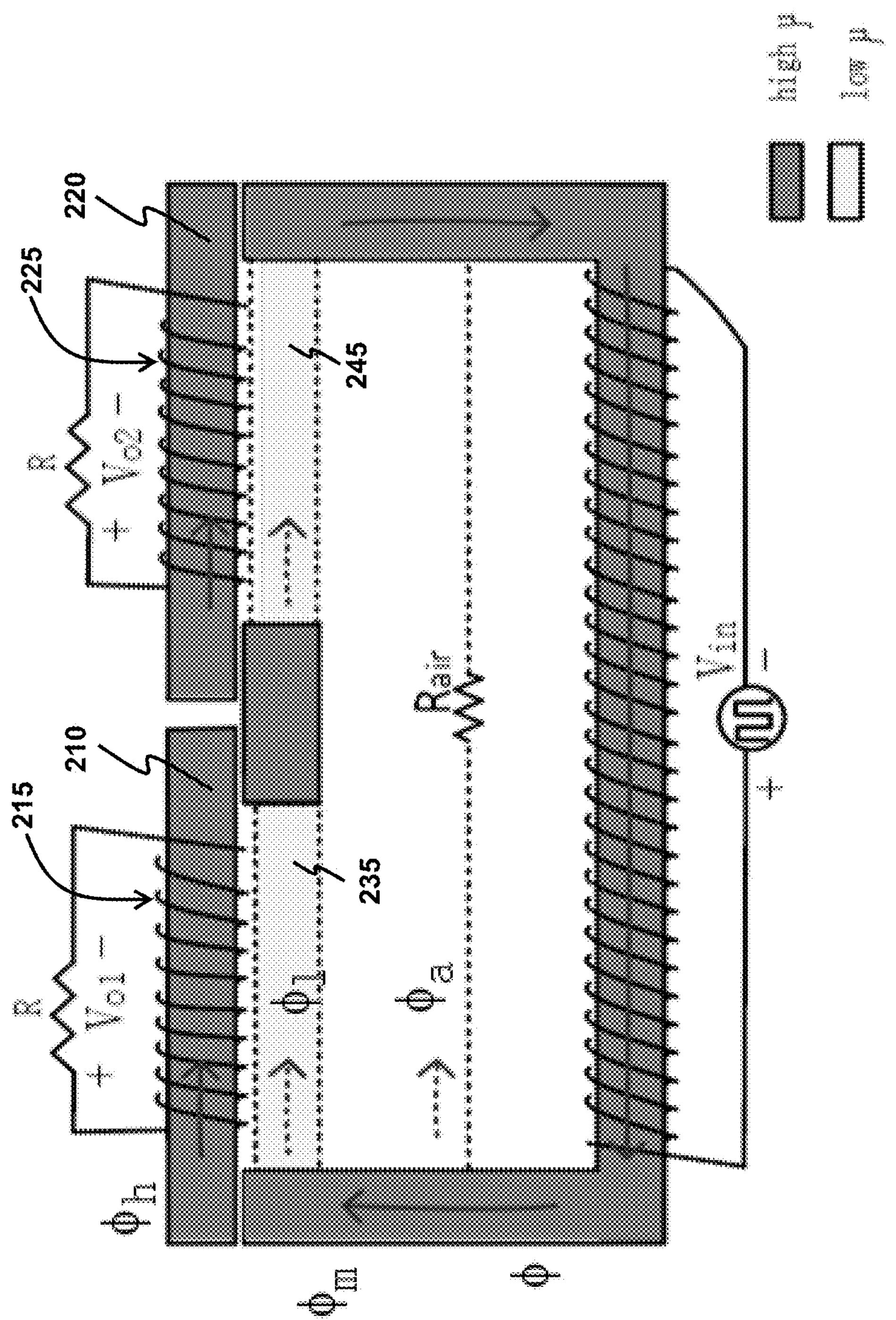

main path
leakage path
high μ
low μ
gap
155
195
150
120
112a
111a
113
110
111b
112b
111c
111d
L
R_{air}
V_{in}
105
115
102
101
100

FIG. 1


220
225
245
210
215
235
R
V_{o2}
R
V_{o1}
R_{air}
V_{in}
ϕ_h
ϕ_m
ϕ
ϕ_l
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high μ
low μ

FIG. 2

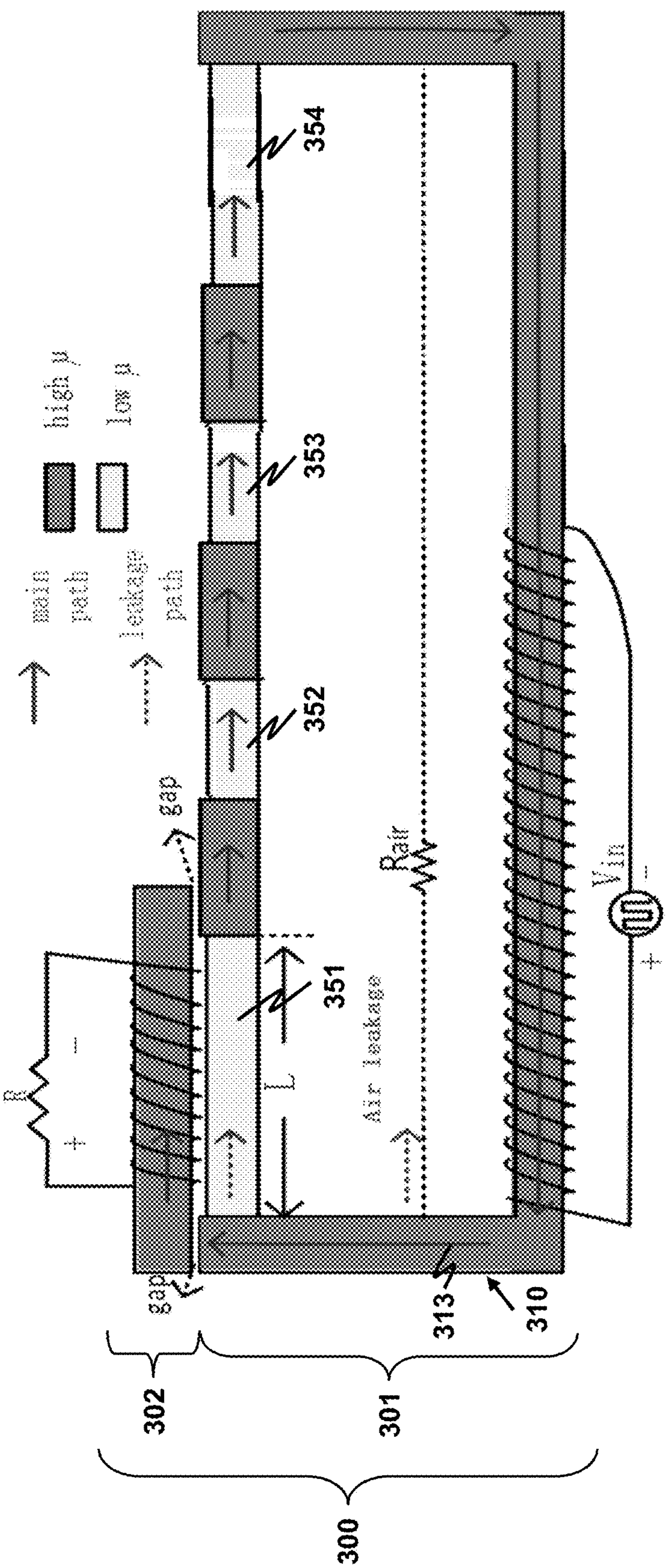
high μ
low μ
main path
leakage path
gap
gap
354
353
352
351
R
L
Air leakage
R_{air}
V_{in}
313
310
302
301
300

FIG. 3

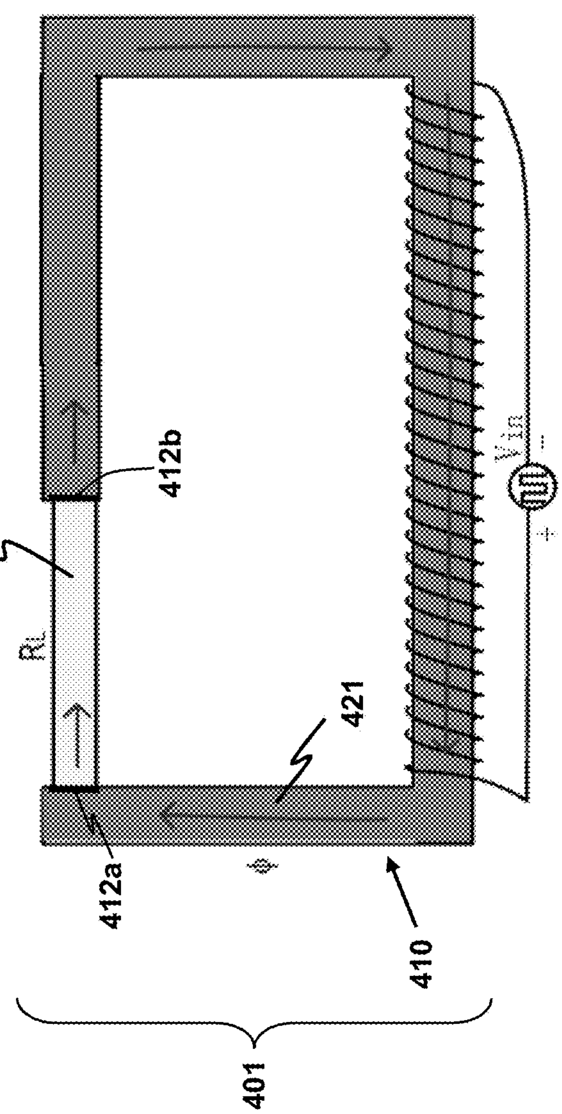

FIG. 4

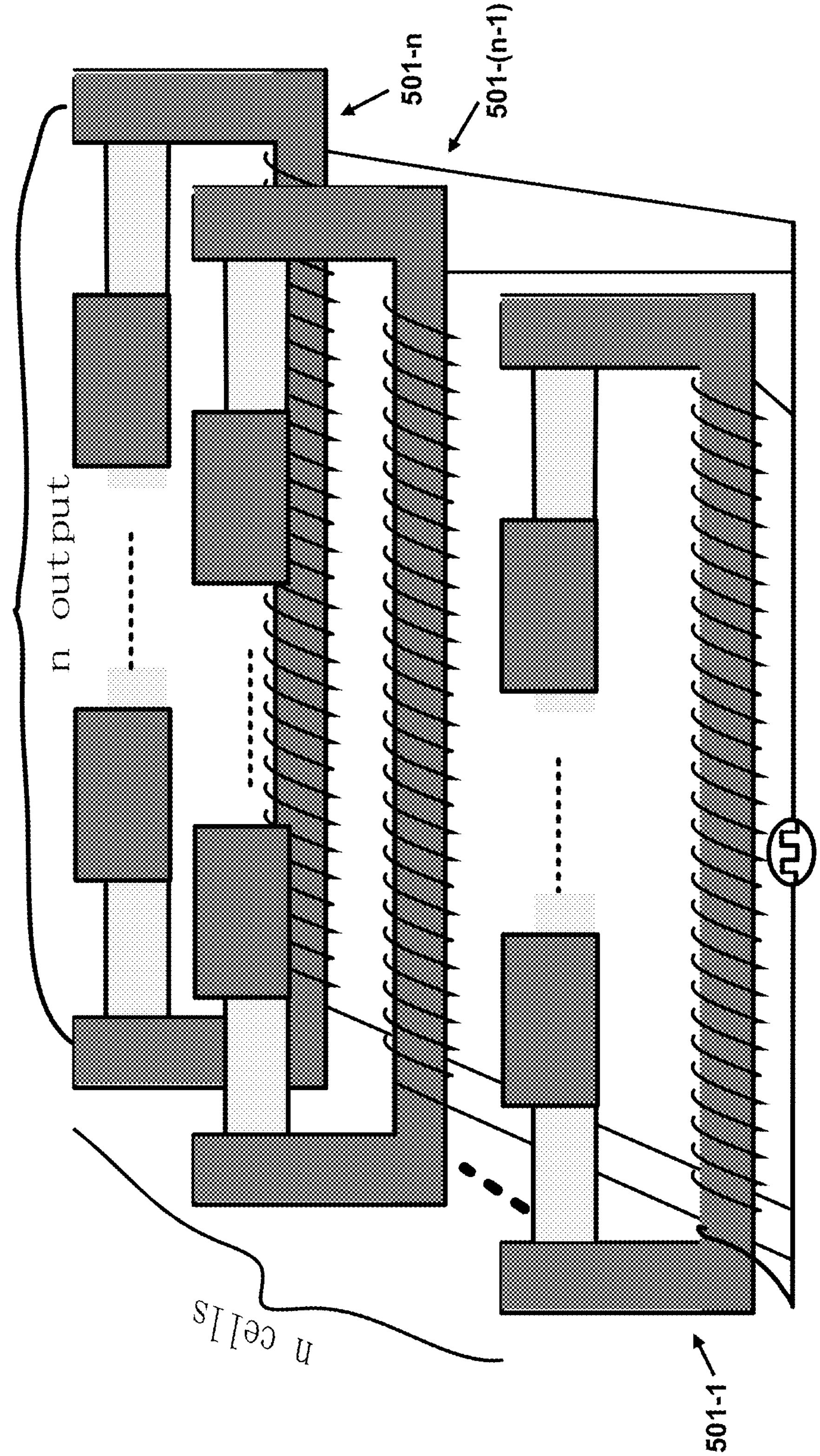

FIG. 5

500

INDUCTIVE POWER TRANSFER USING DIVERTED MAGNETIC FIELD

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Patent Application No. 62/587,546, filed on Nov. 17, 2017, the disclosure of which is incorporated by reference herein in its entirety.

LIST OF ABBREVIATIONS

AC alternating current
HP high-permeability
LP low-permeability
WPT wireless power transfer

BACKGROUND

Field of the Invention

The present invention relates to a WPT system using induction and capable of providing multiple electrical power outputs from the same magnetic flux source. The technical field is in the area of WPT using magnetic induction under the near field instead of the radio field.

List of References

There follows a list of references that are occasionally cited in the specification. Each of the disclosures of these references is incorporated by reference herein in its entirety.

[1] L. C. Meng, K. W. Eric Cheng, and K. W. Chan, "Systematic Approach to High-Power and Energy-Efficient Industrial Induction Cooker System: Circuit Design, Control Strategy and Prototype Evaluation", *IEEE Transactions on Power Electronics*, vol. 26, no. 12, pp. 3754-3765, December 2011.

[2] Deepak Mishra, Swades De, and Kaushik R. Chowdhury, "Charging Time Characterization for Wireless RF Energy Transfer", *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 62, issue 4, pp. 362-366, 2015.

[3] U. Madawala and D. Thrimawithana, "A Bidirectional Inductive Power Interface for Electric Vehicles in V2G Systems," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, pp. 4789-4796, October 2011.

[4] C. J. Chen, T. H. Chu, C. L. Lin, and Z. C. Jou, "A Study of Loosely Coupled Coils for Wireless Power Transfer," *IEEE Transactions on Circuits and Systems*, vol. 57, no. 71, pp. 536-540, July 2010.

[5] D. Ahn and S. Hong, "Effect of Coupling Between Multiple Transmitters or Multiple Receivers on Wireless Power Transfer," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 7, pp. 2602-2613, July 2013.

[6] S. Y. Hui, "Planar Wireless Charging Technology for Portable Electronic Products and Qi", *Proceedings of the IEEE*, vol. 101, issue 6, pp. 1290-1301, 2013.

[7] Xiaolin Mou, Oliver Groling, and Hongjian Sun, "Energy-Efficient and Adaptive Design for Wireless Power Transfer in Electric Vehicles", *IEEE Transactions on Industrial Electronics*, vol. 64, issue 9, pp. 7250-7260, 2017.

Description of Related Art

Electric power transfer based on conductors is a conventional method. Recently, the use of WPT provides an alternative method that can be classified into the near-field power transfer and the far-field power transfer. The near-field power transfer is usually via magnetic induction similar to operating a transformer, and the power is transferred from the primary side to the secondary side through an air gap. A similar technology is the induction heating or heating cooker (L. C. MENG, K. W. E. CHENG, and K. W. CHAN, "Systematic Approach to High-Power and Energy-Efficient Industrial Induction Cooker System: Circuit Design, Control Strategy and Prototype Evaluation", *IEEE Transactions on Power Electronics*, vol. 26, no. 12, pp. 3754-3765, Dec. 2011). The far-field power transfer is based on the use of radio wave. The power is transmitted through air or vacuum space by electromagnetic radiation and the receiver is operated similar to a radio receiver to receive the power transferred from the transmitter (D. MISHRA, S. DE, and K. R. CHOWDHURY, "Charging Time Characterization for Wireless RF Energy Transfer", *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 62, issue 4, pp. 362-366, 2015). As the power transfer is closely related to the distance between the source and the load (or the output), the former one usually has a higher efficiency of power transfer.

The latter power transfer approach is similar to radio power and because the efficiency is low, it is not discussed here. The former one is like a near distance magnetic field transfer. Therefore, the conventional design is still based on a transformer. Various methods have been used (U. MADAWALA and D. THRIMAWITHANA, "A Bidirectional Inductive Power Interface for Electric Vehicles in V2G Systems," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, pp. 4789-4796, Oct. 2011; C. J. CHEN, T. H. CHU, C. L. LIN, and Z. C. JOU, "A Study of Loosely Coupled Coils for Wireless Power Transfer," *IEEE Transactions on Circuits and Systems*, vol. 57, no. 71, pp. 536-540, Jul. 2010). Most of them are concerned with one-to-one power transfer, but multiple coils can also be used to pick up power [5]. Therefore, for high-efficiency power transfer and when there are many outputs, current technology has difficulty to provide such skills.

Even one may use a large primary coil to couple to a few secondary coils, the leakage is significant and the overall efficiency is poor. When the leakage is significant, the adverse effect to nearby people and animals becomes a concern. Another approach is to use many primary coils and one or a few secondary coils to provide WPT (S. Y. HUI, "Planar Wireless Charging Technology for Portable Electronic Products and Qi", *Proceedings of the IEEE*, vol. 101, issue 6, pp. 1290-1301, 2013; X. MOU, O. GROLING, and H. SUN, "Energy-Efficient and Adaptive Design for Wireless Power Transfer in Electric Vehicles", *IEEE Transactions on Industrial Electronics*, vol. 64, issue 9, pp. 7250-7260, 2017), but this method still needs a large coverage of primary coils and the secondary coil pickup requires good and accurate magnetic design to receive the magnetic energy. Although the efficiency may not be important for low-power applications as these applications are to provide low power battery charging, it does matter for high-power applications. When there are high-power applications such as tens or hundreds of watts or even higher, the results have not been reported.

There is a need in the art to have an improved WPT technique that achieves a high power-transfer efficiency for an application that requires transfer of high power. Such technique is advantageous for many practical applications, such as wireless charging of an electric vehicle.

SUMMARY OF THE INVENTION

In the present invention, a novel magnetic topology design for facilitating WPT from a single primary coil to one or more secondary circuits is provided. A WPT system employing such design is disclosed.

The disclosed WPT system comprises at least one power-transmitting unit and at least one power-receiving unit.

An individual power-transmitting unit comprises a loop-shaped magnetic core and a primary coil. The magnetic core comprises one or more HP core sections and one or more LP core sections. The one or more HP core sections has a relative permeability higher than a relative permeability of the one or more LP core sections. In particular, all the HP and LP core sections are alternately arranged to form an interleaving pattern in forming the magnetic core. The primary coil is wound on the magnetic core for generating a magnetic flux in the magnetic core upon the primary coil being excited by an AC power source.

An individual power-receiving unit comprises a pickup core and a secondary pickup coil. The pickup core is configured at least in shape and dimension to overlie a first LP core section selected from the one or more LP core sections. The first LP core section connects to two connecting surfaces of respective one or two HP core sections immediately adjacent to the first LP core section. Furthermore, the pickup core is further configured at least in shape and dimension to partially overlap said respective one or two HP core sections around the two connecting surfaces. The pickup core has a relative permeability higher than the relative permeability of the first LP core section, causing at least a part of the magnetic flux to divert from the first LP core section to the pickup core when the individual power-receiving unit is parked adjacent to the individual power-transmitting unit such that the pickup core overlies the first LP core section and partially overlaps said respective one or two HP core sections. The secondary pickup coil is wound on the pickup core for inductively generating electrical power from the diverted part of magnetic flux, enabling electrical power supplied by the AC power source to be wirelessly delivered to the individual power-receiving unit.

Preferably, the primary coil is wound on a predetermined HP core section selected from the one or more HP core sections. The primary coil may also be wound on a predetermined LP core section selected from the one or more LP core sections.

The primary coil may be made of copper or other conductor.

In one embodiment, the one or more LP core sections consist of plural identical LP core sections. The first LP core section is selected to be any one of the identical LP core sections such that the pickup core of the individual power-receiving unit is enabled to park on any one of the identical LP core sections for wirelessly receiving electrical power from the AC power source.

Usually, the relative permeability of an individual HP core section is at least 400, preferably from 500 and 5000 or even higher. Generally, the relative permeability of an individual LP core section is at most 500, preferably in a range of 5 to 200.

In certain embodiments, the disclosed WPT system further comprises the AC power source. The AC power source may be configured to supply a sine wave or a square wave to the primary coil. Preferably, the AC power source has a working frequency of 20 kHz or above.

In performing WPT by positioning the pickup core to overlie the first LP core section and to partially overlap said respective one or two HP core sections, the first LP core section may be separated from the pickup core by the air gap of length between 0.05 mm to 3 cm, or by the air gap of length within 0.1% to 10% of a length of the pickup core.

According to one embodiment of the disclosed WPT system, there are plural HP core sections and plural LP core sections in the individual power-transmitting unit. As such, the pickup core in the individual power-receiving unit is configured to overlie the first LP core section and to partially overlap two HP core sections immediately adjacent to the first LP core section.

Other aspects of the present invention are disclosed as illustrated by the embodiments hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** depicts an exemplary design of a WPT system as disclosed herein.

FIG. **2** depicts, as an illustration, a situation that a magnetic path having two loads, showing how the main flux is divided into two paths through a LP core section and a pickup core having a relative permeability higher than that of the LP core section.

FIG. **3** depicts, as one embodiment of the present invention, a WPT system having a power-transmitting unit equipped with four LP core sections so that there are four ports available for a power-receiving unit to park on.

FIG. **4** depicts, as another embodiment of the present invention, a power-transmitting unit having a magnetic core formed by a single LP core section and a single HP core section.

FIG. **5** depicts, in accordance with one embodiment of the present invention, a WPT system comprising plural power-transmitting units for providing a large pickup in current or electrical power.

DETAILED DESCRIPTION

According to the present invention, a novel magnetic topology design is provided for facilitating WPT from a single primary coil to one or more secondary circuits. Particularly, a WPT system employing such design is disclosed. The disclosed WPT system is advantageously useful for achieving a high power-transfer efficiency for an application that requires wireless transfer of high power. Nonetheless, the present invention is not limited only for high-power WPT applications; the present invention is also usable for low-power WPT applications. Although the disclosed WPT system can be advantageously used when the system provides many electrical-power output ports, the present invention is not limited to a general case of providing more-than-one output ports; the present invention is also applicable to a specific case of providing one output port.

The disclosed WPT system is illustrated with the aid of FIG. **1**. FIG. **1** depicts an exemplary WPT system **100** for wirelessly transmitting electrical power from an AC power source **105** to a load **195** through an air gap **120**. In the system **100**, the approach of near-field power transfer is used. The system **100** is configured to be similar to a transformer. Power is transferred from a primary coil **115**, which is excited by the AC power source **105**, to a secondary pickup coil **155**, which is connected to and thereby drives the load **195**, via magnetic induction. Operationally, the system **100** comprises a power-transmitting unit **101** for generating a magnetic flux **113** upon excitation by the AC power source **105**, and a power-receiving unit **102** for drawing at least a part of the magnetic flux **113** from the power-transmitting unit **101** to inductively generate an electrical power. The generated electrical power is deliverable to the load **195** to achieve WPT.

The power-transmitting unit **101** comprises a magnetic core **110** and the primary coil **115**. The magnetic core **110** is used to guide traveling of the magnetic flux **113** produced by the primary coil **115** upon excitation by the AC power source **105**. The magnetic core **110** is realized as a closed-circuit magnetic loop, and is hence a loop-shaped magnetic core. The magnetic core **110** is wound with the primary coil **115** for receiving the magnetic flux **113** produced therefrom. In particular, the magnetic core **110** comprises plural core sections (or segments) **111***a-d*. The core sections **111***a-d* are sequentially arranged and integrated to form the closed-circuit magnetic loop. The core sections **111***a-d* are classified into two types of core sections according to their relative permeability values. Each type of core sections is uniquely identified by having a same relative permeability. For example, core sections of one type are made of a certain material or composite having a certain relative permeability. In another example, core sections belonging to one type are made of different materials but these different materials have the same nominal value of relative permeability as reported by manufacturers of these different materials. Among the core sections **111***a-d*, the core sections **111***a* and **111***c* belong to one type and the core sections **111***b* and **111***d* belong to another type. In particular, the relative permeability of the core sections **111***a* and **111***c* is higher than the relative permeability of the core sections **111***b* and **111***d*. Hence, hereinafter the core sections **111***a* and **111***c* are referred to as HP core sections, and the core sections **111***b* and **111***d* are referred to as LP core sections. Note that all the HP core sections **111***a*, **111***c* and the LP core sections **111***b*, **111***d* are alternately arranged to form an interleaving pattern such that each of the HP core sections **111***a*, **111***c* is end-to-end connected to two of the LP core sections **111***b*, **111***d*, and vice versa.

It is desired to wirelessly receive power from the magnetic core **110** through magnetic induction to drive the load **195**. The power-receiving unit **102** achieves this WPT function by including a pickup core **150**, which is a segment of material having a high relative permeability, and the secondary pickup coil **155**. In particular, the relative permeability of the pickup core **150** is higher than the relative permeability of the LP core sections **111***b*, **111***d*. Without loss of generality, consider a representative situation that the pickup core **150** is positioned to overlie the LP core section **111***b* and to partially overlap the two HP core sections **111***a*, **111***c* (both of which are immediately adjacent to the aforesaid LP core section **111***b*). In this regard, a requisite is that the pickup core **150** is at least shaped and dimensioned to overlie the LP core section **111***b* and to partially overlap the two HP core sections **111***a*, **111***c*. Note that the LP core section **111***b* connects to a first connecting surface **112***a* and a second connecting surface **112***b* of the two immediately-adjacent HP core sections **111***a*, **111***c*, respectively. As used herein in the specification and appended claims, a connecting surface of a core section is a surface that connects to another core section immediately adjacent to the former core section. The pickup core **150** is further arranged such that the two immediately-adjacent HP core sections **111***a*, **111***c* are partially overlapped respectively around the first and second connecting surfaces **112***a*, **112***b*. Since the pickup core **150** has a higher relative permeability than the LP core section **111***b* does, and since the pickup core **150** partially overlaps the two HP core sections **111***a*, **111***c* around their respective connecting surfaces **112***a*, **112***b*, a part of the magnetic flux **113** in the magnetic core **110** is diverted from the LP core section **111***b* to the pickup core **150**. Particularly, the part of the magnetic flux **113** is drawn from the magnetic core **110** to passing through the pickup core **150** via the air gap **120**. An ideal scenario is that an entire amount of the magnetic flux **113** is diverted to the pickup core **150**. In practice, it is desirable to optimize the design of the system **100** so as to have a substantial part of the magnetic flux **113** to be received by the pickup core **150**. For instance, the air gap **120** may be kept as short as possible by means of appropriate alignment techniques (e.g., US2016/0001669 and US2017/0259680), and the pickup core **150** may be formed by a material having a much higher relative permeability than the LP core section **111***b*. The pickup core **150** is wound with the secondary pickup coil **155**. The magnetic flux **113** traveling inside the pickup core **150** produces a voltage at the secondary pickup coil **155** via induction. The induced voltage is used to drive the load **195**, thereby achieving WPT from the AC power source **105** to the load **195**.

The theory that supports the realization of WPT by the system **100** is elaborated as follows.

Refer to FIG. **2**, which shows a magnetic path having two pickup cores **210**, **220** overlying two LP core sections **235**, **245**, respectively. Based on Ampere circuital law, the magnetic path consisting of a flux ϕ passing through a loop satisfies

$$\oint B dl = \mu_0 \iint_S J \cdot ds$$

where B is the magnetic field density of the magnetic circuit, l is the magnetic path length, J is the current density of the excited current and S is the area of the current excited in the circuit. The right hand side of the aforementioned equation defines the current excited in the circuit. The left hand side defines the enclosed magnetic field in the closed circuit path. Because of the leakage of air, a portion of the magnetic flux is channeled to the air (denoted as ϕ_a). The remaining flux, given by $\phi_m = \phi - \phi_a$, is then divided into two paths. One path is a HP path (e.g., via the pickup core **210**) and the other path is a LP path (e.g., via the LP core section **235**. The HP path has a magnetic flux ϕ_h and the LP path has a magnetic flux ϕ_l.

If the pickup core **210** has a reluctance of R_h and the LP core section **235** has a reluctance of R_l, the magnetic flux ϕ_m is divided into two paths of ϕ_h and ϕ_l according to the magnetic flux sharing, which is in turn according to the reluctance values. The reluctance can be measured or calculated according to the magnetic section property. In short, it is given by

$$R = \frac{L}{\mu_r A_e \mu_0}$$

where R, the reluctance, depends on the dimension and physical parameters of a section such that L is the length of the section, and A_e is the cross-sectional area of the section.

The magnetic flux received by the pickup core **210** is transformed into electric energy by

$$\oint E \cdot dl = -\int \frac{\partial B}{\partial t} \cdot dA$$

where E is the electric field induced in the secondary side, l is the displacement and A is the area of the magnetic path concerned. The left hand side gives the voltage induced in a coil **215** wound on the pickup core **210**, and the right hand side gives the change of magnetic flux ϕ_h. For a high frequency switching circuit, the frequency of the primary current is to provide the rate of change of the flux.

The sharing of magnetic flux ϕ_m among the pickup core **220** and the LP core section **245** and the generation of voltage at a coil **225** that winds on the pickup core **220** are similar to the previous case for the pickup core **210** and the LP core section **235**.

The WPT system **100** may be extended to give a variety of different implementations adapted to practical situations. Different configurations of the disclosed WPT system are elaborated as follows.

Refer to FIG. **1**. Each of the LP core sections **111***b*, **111***d* may serve as an individual port on which the power-receiving unit **102** is parked so as to wirelessly receive power from the power-transmitting unit **101**. Although FIG. **1** depicts that the power-transmitting unit **101** provides two ports, a power-transmitting unit may be equipped with any positive number of ports as long as practically implementable.

As an example of configuration of the disclosed WPT system, FIG. **3** depicts a WPT system **300** having a power-transmitting unit **301** equipped with four LP core sections **351-354**. It follows that there are four ports available for a power-receiving unit **302** to park on. Additionally, the power-transmitting unit **301** may be used to wirelessly transmit power to two to four separate power-receiving units simultaneously. Note that the magnetic flux **313** in the magnetic core **310** of the power-transmitting unit **301** is not reduced even if any additional core sections are inserted. Anyway, the pickup energy received by any power-receiving unit is reduced when the magnetic core **310** is long because the core loss increases.

As another example of configuration, FIG. **4** depicts a power-transmitting unit **401** having a magnetic core **410** where the magnetic core **410** is formed by end-to-end connecting a single HP core section **421** to a single LP core section **422** to form a loop. Note that the LP core section **422** connects to a first connecting surface **412***a* and a second connecting surface **412***b*, where the first and second connecting surfaces **412***a*, **412***b* are of the HP core section **421**.

In one embodiment, plural power-transmitting units are installed in a WPT system such that a large pickup of current or electrical power for a power-receiving unit is obtainable. FIG. **5** depicts, in accordance with this embodiment of the present invention, a WPT system **500** installed with n power-transmitting units **501-1**:*n*, where n>1. For simplicity, a power-receiving unit is not shown in FIG. **5**. By having a plurality of power-transmitting units **501-1**:*n*, each power-transmitting unit provides a certain amount of current or electrical power to the power-receiving unit. Aggregating respective amounts of current or electrical power, the power-receiving unit is capable to obtain a large amount of current or electrical power for driving a load. As a result, the power-provision capability of the WPT system **500**, or the power transfer rate thereof, is increased as n increases, facilitating high-power transfer. According to the present embodiment, each of the n power-transmitting units **501-1**:*n* is realized as an independent power-transmitting unit according to any embodiment of the WPT system as disclosed above. As one example for illustration, each of the n power-transmitting units **501-1**:*n* is installed with n output ports for WPT.

Although FIG. **1** depicts that the system **100** has one power-receiving unit (i.e. the power-receiving unit **102**), it is possible that the disclosed WPT system includes a plurality of power-receiving units. Each of the power-receiving units may be realized as an independent power-receiving unit according to any embodiment of the WPT system as disclosed above.

Other operational aspects of the disclosed WPT system are provided as follows.

Refer to FIG. **1**. The primary coil **115**, which is wound on the magnetic core **110**, may be wound on a predetermined HP core section selected from the set of the HP core sections **111***a*, **111***c*, or a certain LP core section selected from the set of the LP core sections **111***b*, **111***d*. Preferably, the primary coil **115** is wound on the predetermined HP core section (e.g., the HP core section **111***a* as shown in FIG. **1**) since each LP core section may be more advantageously used as an electrical-power output port for the power-receiving unit **102** to park on.

The shape of the magnetic core **110** can be square, circular or of another shape provided that such shape can conduct magnetic flux.

Each of the core sections **111***a-d* is essentially made up of one or more magnetic materials, such as ferrite, a magnetic composite, powdered iron or a material exhibiting magnet properties. Those skilled in the art will appreciate that each of the core sections **111***a-d* may be additionally encapsulated by protection materials, such as an insulating film for preventing an individual core section, which may be electrically conductive, from accidentally contacting the AC power source **105**.

The relative permeability of the HP core sections **111***a*, **111***c* is usually at least 400, and is preferably from 500 to 5000 or even higher. The relative permeability of the LP core sections **111***b*, **111***d* is usually selected to be at most 500, and may be selected to be within a range of 5 to 200.

The relative permeability of the pickup core **150** may also be selected to be the same as the relative permeability of the HP core sections **111***a*, **111***c*. It is implementable by fabricating the HP core sections **111***a*, **111***c* and the pickup core **150** with the same material.

In one embodiment, the LP core sections **111***b*, **111***d* are identical LP core sections in the sense that the two LP core sections **111***b*, **111***d* are the same in dimension and in shape. Since the pickup core **150** is shaped and dimensioned according to the LP core section **111***b*, it follows that the pickup core **150** is enabled to park on any one of the LP core sections **111***b*, **111***d* for wirelessly receiving electrical power from the AC power source **105**.

Usually, a wire used in forming the primary coil **115** and/or the secondary pickup coil **155** is made of copper. Other conductor may also be used for the wire.

The number of turns of the primary coil **115** may be selected according to an output power intended to be delivered to the load **195**. As a general rule, the higher the current in the primary coil **115** and the higher the number of turns, the higher the magnetic flux **113** that is generated so as to provide a higher output power.

Generally, the power-transmitting unit **101** and the power-receiving unit **102** are manufactured to be physically disjoint, but it is possible in certain applications, e.g., educational applications involving toys, the two units may be integrated.

In performing WPT by positioning the pickup core **150** to overlie the LP core section **111***b* and to partially overlap the two HP core sections **111***a*, **111***c*, the LP core section **111***b* may be separated from the pickup core **150** by the air gap **120** of length between 0.05 mm to 3 cm, or of length within 0.1% to 10% of a length of the pickup core **150**.

According to one embodiment of the present invention, the AC power source **105** is included in the system **100**. The

AC power source **105** is used to supply a high frequency signal to excite the primary coil **115** to thereby generate the magnetic flux **113** in the magnetic core **110**. Preferably, the working frequency of the AC power source **105** is set to be 20 kHz or above in order to ensure that the working frequency is beyond the normal audible range of human beings. The signal can be a sine wave or a square wave, or any other AC signal considered appropriate for practical situations by those skilled in the art. In case of using the square wave, it may be generated by a power electronics switching circuit. The duty cycle of the square wave is usually set to be 50% for avoiding saturation of the magnetic core **110**.

The present invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The present embodiment is therefore to be considered in all respects as illustrative and not restrictive. The scope of the invention is indicated by the appended claims rather than by the foregoing description, and all changes that come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

What is claimed is:

1. A wireless power transfer (WPT) system comprising at least one power-transmitting unit and at least one power-receiving unit, an individual power-transmitting unit comprising:
- a loop-shaped magnetic core comprising one or more high-permeability (HP) core sections and one or more low-permeability (LP) core sections, the one or more HP core sections having a relative permeability higher than a relative permeability of the one or more LP core sections, all the HP and LP core sections being alternately arranged to form an interleaving pattern in forming the magnetic core; and
- a primary coil wound on the magnetic core for generating a magnetic flux in the magnetic core upon the primary coil being excited by an alternating current (AC) power source;

an individual power-receiving unit comprising:
- a pickup core configured to overlie a first LP core section selected from the one or more LP core sections, the first LP core section connecting to two connecting surfaces of respective one or two HP core sections immediately adjacent to the first LP core section, the pickup core being further configured to partially overlap said respective one or two HP core sections around the two connecting surfaces, the pickup core having a relative permeability higher than the relative permeability of the first LP core section so as to cause at least a part of the magnetic flux to divert from the first LP core section to the pickup core when the individual power-receiving unit is parked adjacent to the individual power-transmitting unit such that the pickup core overlies the first LP core section and partially overlaps said respective one or two HP core sections; and
- a secondary pickup coil wound on the pickup core for inductively generating electrical power from the diverted part of magnetic flux, enabling electrical power supplied by the AC power source to be wirelessly delivered to the individual power-receiving unit.

2. The WPT system of claim **1**, wherein the primary coil is wound on a predetermined HP core section selected from the one or more HP core sections.

3. The WPT system of claim **1**, wherein the primary coil is wound on a predetermined LP core section selected from the one or more LP core sections.

4. The WPT system of claim **1**, wherein:
- the one or more LP core sections consist of plural identical LP core sections; and
- the first LP core section is selected to be any one of the identical LP core sections such that the pickup core of the individual power-receiving unit is enabled to park on any one of the identical LP core sections for wirelessly receiving electrical power from the AC power source.

5. The WPT system of claim **1**, wherein the relative permeability of an individual HP core section is at least 400.

6. The WPT system of claim **5**, wherein the relative permeability of the individual HP core section is in a range of 500 to 5000.

7. The WPT system of claim **5**, wherein the relative permeability of the individual HP core section is at least 500.

8. The WPT system of claim **1**, wherein the relative permeability of an individual LP core section is at most 500.

9. The WPT system of claim **8**, wherein the relative permeability of the individual LP core section is in a range of 5 to 200.

10. The WPT system of claim **1**, wherein the primary coil is made of copper.

11. The WPT system of claim **1** further comprising the AC power source.

12. The WPT system of claim **11**, wherein the AC power source is configured to supply a sine wave to the primary coil.

13. The WPT system of claim **11**, wherein the AC power source is configured to supply a square wave to the primary coil.

14. The WPT system of claim **11**, wherein the AC power source has a working frequency of 20 kHz or above.

15. The WPT system of claim **1**, wherein the first LP core section is separated from the pickup core by an air gap of length between 0.05 mm to 3 cm when the pickup core overlies the first LP core section and partially overlaps said respective one or two HP core sections.

16. The WPT system of claim **1**, wherein the first LP core section is separated from the pickup core by an air gap of length within 0.1% to 10% of a length of the pickup core when the pickup core overlies the first LP core section and partially overlaps said respective one or two HP core sections.

17. A wireless power transfer (WPT) system comprising at least one power-transmitting unit and at least one power-receiving unit, an individual power-transmitting unit comprising:
- a loop-shaped magnetic core comprising plural high-permeability (HP) core sections and plural low-permeability (LP) core sections, the HP core sections having a relative permeability higher than a relative permeability of the LP core sections, all the HP and LP core sections being alternately arranged to form an interleaving pattern in forming the magnetic core; and
- a primary coil wound on the magnetic core for generating a magnetic flux in the magnetic core upon the primary coil being excited by an alternating current (AC) power source;

an individual power-receiving unit comprising:
- a pickup core configured to overlie a first LP core section selected from the LP core sections and to partially overlap two HP core sections immediately adjacent to the first LP core section, the pickup core having a

relative permeability higher than the relative permeability of the first LP core section so as to cause at least a part of the magnetic flux to divert from the first LP core section to the pickup core when the individual power-receiving unit is parked adjacent to the individual power-transmitting unit such that the pickup core overlies the first LP core section and partially overlaps the two immediately-adjacent HP core sections; and

a secondary pickup coil wound on the pickup core for inductively generating electrical power from the diverted part of magnetic flux, enabling electrical power supplied by the AC power source to be wirelessly delivered to the individual power-receiving unit.

18. The WPT system of claim **17**, wherein:

the LP core sections are identical; and

the first LP core section is selected to be any one of the identical LP core sections such that the pickup core of the individual power-receiving unit is enabled to park on any one of the identical LP core sections for wirelessly receiving electrical power from the AC power source.

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