Network for and method of wireless power transfer

Field

The present invention relates to wireless power transfer, particularly dynamic wireless charging.

Background to the invention

Wireless power transfer (WPT) technology has been applied to a wide variety of portable consumer electrical, medical, and industrial devices. It has attracted considerable interests and already been proposed for electric vehicles (EVs) charging. The WPT systems concerning the charging of EVs can be divided into three broad categories, namely, the static wireless charging, dynamic wireless charging (DWC) and Quasi-DWC. DWC technology can be used to charge moving EVs with advantages such as mitigating range anxiety, reducing battery size and cost.

A review of the state-of-the-art WPT for EVs indicates that maintaining high-power and high-efficiency of charging a moving EV on an electrified track is still a challenge for many DWC systems. DWC transfers the energy using the magnetic coupling between track and pick-up coils. The maximum power transfer efficiency (PTE) will only be achieved with perfect alignment, and the efficiency will decrease rapidly with misalignment. Moreover, the power null phenomena will significantly affect the transferred power level when the Rx moves to the intermediate position between two track coils, causing power pulsation. Hence, the PTE and power pulsation are the main challenges for EVs charging using DWC technique. A bipolar coil topology with a double-D (DD) shape and a quadrature coil (Q-coil) has been used as the pick-up coil to receive more power in the power null point. However, the transfer efficiency is still very low. For road-powered EVs, power pads have been proposed, reducing the amount of ferrite so as to increase efficiency. To decrease deployment cost, an ultra-slim S-type power supply rail has been proposed, having a width of 4 cm, in which a vertically-wound multi-turn coil is placed inside a thin S-shape core. However, the transfer efficiency is still very low, because only a small portion of the primary loop contributed to power transfer when the DWC system was working.

Furthermore, misalignment is a serious issue for DWC systems. Anti-misalignment WPT systems can maintain a high efficiency over a wide range of misalignment conditions. For example, a dual-loop primary controller may be used to regulate primary-side power and current against lateral misalignment. However, only 40% efficiency may be achieved in the power null point.

Hence, there is a need to improve wireless power transfer, particularly for dynamic wireless charging.

Summary of the Invention

It is one aim of the present invention, amongst others, to provide a network which at least partially obviates or mitigates at least some of the disadvantages of the prior art, whether identified herein or elsewhere. For instance, it is an aim of embodiments of the invention to provide a network having an improved power transfer efficiency, that is more tolerant to misalignment, that reduces an effect due to power null points and/or that is less susceptible to shielding.

A first aspect provides a network for inductive charging of a device, wherein the network comprises a transmitter and a receiver;
wherein the transmitter comprises:
a set of coils, including a first coil and optionally a second coil, wherein the set of coils comprises a first set of turns, including a first turn, and a second set of turns, including a first turn;
wherein the set of coils of the transmitter is arranged in a first plane;
wherein the first set of turns and the second set of turns are adjacent, defining a centre line therebetween;
wherein the first turn of the first set of turns has a first sense and wherein the first turn of the second set of turns has a second sense, opposed to the first sense; and
whereby, in use, current flows through the first turn of the first set of turns and the first turn of the second set of turns in mutually opposed senses, thereby providing a bipolar transmitter;
wherein the receiver comprises:
a set of coils, including a first coil, wherein the set of coils comprises a first set of turns, including a first turn; and
wherein the set of coils of the receiver is arranged in a second plane, transverse to the first plane substantially about the centre line.

A second aspect provides a way, for example a roadway or a railway, including the transmitter according to the first aspect.

A third aspect provides a land craft, for example a road vehicle or a train, comprising the receiver according to the first aspect.

A fourth aspect provides a method of inductive charging of a device, for example according to the third aspect, using a network according to the first aspect or a way according to the second aspect.

Detailed Description of the Invention

According to the present invention there is provided a network, as set forth in the appended claims. Also provided is way, a land craft and a method. Other features of the invention will be apparent from the dependent claims, and the description that follows.

Network

The first aspect provides a network for inductive charging of a device, wherein the network comprises a transmitter and a receiver;
wherein the transmitter comprises:
a set of coils, including a first coil and optionally a second coil, wherein the set of coils comprises a first set of turns, including a first turn, and a second set of turns, including a first turn;
wherein the set of coils of the transmitter is arranged in a first plane;
wherein the first set of turns and the second set of turns are adjacent, defining a centre line therebetween;
wherein the first turn of the first set of turns has a first sense and wherein the first turn of the second set of turns has a second sense, opposed to the first sense; and
whereby, in use, current flows through the first turn of the first set of turns and the first turn of the second set of turns in mutually opposed senses, thereby providing a bipolar transmitter;
wherein the receiver comprises:
a set of coils, including a first coil, wherein the set of coils comprises a first set of turns, including a first turn; and
wherein the set of coils of the receiver is arranged in a second plane, transverse to the first plane substantially about the centre line.

In this way, the receiver is arranged generally perpendicularly to the bipolar transmitter, thereby providing a network having an improved power transfer efficiency, that is more tolerant to misalignment, that reduces an effect due to power null points and/or that is less susceptible to shielding, as described below in more detail.

Briefly, a WPT system (i.e. a network according to the first aspect comprising a transmitter and a receiver) having a perpendicular structure is presented. The charging module (i.e. the transmitter) optionally comprises an extensible modularized array to improve the capacity of maintaining high efficiency when the receiver is moving. Another advantage of this WPT system is that any metal parts placed around the receiver have little effect on the WPT efficiency (i.e. such that the receiver is less susceptible to shielding). Much less heat would be generated on surrounding metal parts. A mathematical model is derived to calculate the maximum PTE for this WPT system.

Mathematic modelling and analysis

A typical four-coil magnetic resonance coupling-based wireless power transfer (MRC-WPT) system for an EV is shown in Figure 1. A simplified schematic is shown in Figure 2. It consists of two loops and two resonators with the same resonant frequency. The feed and load loop are connected to the input source V_s and load R_L respectively. Normally, the feed loop and the load loop are single turn loop so that their self-inductance L_1 and parasitic resistance R_1 will be small than those of the transmitter (Tx) coil and receiver (Rx) coil. The Tx or Rx coil consists of the self-inductance L_2, the parasitic resistance R_2 of the coil, and an external capacitor C_2 to form a resonator with L_2. These loops and coils are linked magnetically by k_{pq}, which is the coupling coefficient between the p^{th} and q^{th} coil or loop. $k_{12} = k_{34}$ due to symmetry. For simplicity, the internal resistance of the power source R_0 is equal to the load resistance R_L. The reflected impedance from the load loop to the Rx coil Z_{ref34} at resonant frequency ω_0 is given by Equation 1:

$$Z_{ref34} = \frac{(\omega_0 M_{34})^2}{R_L}$$

The reflected impedance from the Rx coil to the Tx coil Z_{ref23} is given by Equation 2:

$$Z_{ref23} = \frac{(\omega_0 M_{12})^2}{R_2 + Z_{ref23}} = \frac{(\omega_0 M_{12})^2}{R_2 + \frac{(\omega_0 M_{34})^2}{R_L}}$$

The PTE η can be expressed by Equation 3 as:

$$\eta = \frac{Z_{ref23}}{R_2 + Z_{ref23}} \frac{Z_{ref34}}{R_2 + Z_{ref34}}$$

$$= \frac{(\frac{\omega_0 M_{23}}{R_2})^2}{1 + \frac{(\omega_0 M_{34})^2}{R_2 R_L} + (\frac{\omega_0 M_{23}}{R_2})^2} \frac{\frac{(\omega_0 M_{34})^2}{R_2 R_L}}{1 + \frac{(\omega_0 M_{34})^2}{R_2 R_L}}$$

M_{pq} is the mutual inductance between p^{th} and q^{th} coils (q, p = 1, …, 4), defined as $M_{pq} = k_{pq}\sqrt{(L_p L_q)}$. M_{12}, M_{23} and M_{34} represent main inductive couplings in the WPT system and the cross coupling of non-adjacent coils such as M_{13}, M_{14} and M_{24} can be neglected, as they are much smaller than M_{12}, M_{23} and M_{34}. The MRC-WPT system requires the coils with high quality factors Q (unloaded) to achieve high PTE. Also, since $R_1 << R_2$, R_1 can be omitted.

For a typical four-coil MRC-WPT system, the Tx and Rx are placed coaxially in parallel as shown in Figure 1, which is described as the aligned condition. To achieve the maximum PTE, the distance d between the Tx and the Rx needs to be optimized so that the MRC-WPT system satisfies the critical coupling condition. When the charging distance is shorter than the optimal distance $d_{optimal}$, frequency splitting will occur. The PTE and transferred power will be low at the desired operating frequency. The maximum PTE can be expressed by Equation 4:

$$\eta_{max} = \left(\frac{k_{23}Q_2}{1+\sqrt{1+{k_{23}}^2{Q_2}^2}}\right)^2$$

The value of k_{23} to achieve the critical coupling condition can be obtained from Equation 5:

$$k_{23} = \sqrt{\left(\frac{{k_{12}}^2 Q_1 Q_2 + 1}{Q_2}\right)^2}$$

where Q_1 and Q_2 are the quality factors of the feed/load loop and resonator coil. They are defined as $Q_1 = \omega L_1/R_S$ and $Q_2 = \omega L_2/R_2$, respectively. Meanwhile, k_{23}varies according to the lateral displacement Δd_la*,* which is the misalignment distance when Rx is moving along rail in the x-axis direction.

Analytically, the relationship among the coupling coefficient k_{23}, d and Δd_la can be expressed using Neumann formula, numerical iterations and Biot-Savart law. In our study, Computer Simulation Technology (CST) and Maxwell, the software packages based on high precision Finite Element Analysis, are used to calculate the mutual inductances, coupling coefficients and optimal distances for convenience.

Transverse arrangement

In order to achieve high PTE for DWC, an 8-shape (i.e. figure of 8) coil structure is used. More generally, a bipolar (also known as , also known as DD) transmitter is used. Herein, a WPT system with a transverse Tx-Rx charging structure using an 8-shape feed loop is shown in Figure 3. The Rx is placed transversely above the Tx center. This is defined as the “perfectly aligned” position. The Tx includes two individual resonators and an 8-shape feed loop. The Rx includes one resonator and a load loop.

For DWC applications, the Rx will move along a rail or track (x-axis as show in Figure 3). Figure 4 shows a simplified equivalent circuit of an exemplary embodiment of WPT system (i.e. a network according to the first aspect). With alignment, Resonator 3 in the Rx is coupled to Resonator 1 and Resonator 2 in the Tx simultaneously. Similar to a conventional WPT system, the PTE of this WPT system can be expressed by Equation 6 as:

$$\begin{aligned}\eta =& \frac{Z_{ref01}}{R_s + Z_{ref01} + Z_{ref02}}(\frac{Z_{ref13}}{R_1 + Z_{ref12}+Z_{ref13}}\frac{Z_{ref34}}{R_3 + Z_{ref34}}\\ &+\frac{Z_{ref12}}{R_1 + Z_{ref12} + Z_{ref13}}\frac{Z_{ref23}}{R_2 + Z_{ref21}+Z_{ref23}}\frac{Z_{ref34}}{R_3 + Z_{ref34}})\\ &+ \frac{Z_{ref02}}{R_s + Z_{ref01} + Z_{ref02}}(\frac{Z_{ref23}}{R_2 + Z_{ref21}+Z_{ref23}}\frac{Z_{ref34}}{R_3 + Z_{ref34}}\\ &+\frac{Z_{ref21}}{R_2 + Z_{ref21} + Z_{ref23}}\frac{Z_{ref13}}{R_1 + Z_{ref12}+Z_{ref13}}\frac{Z_{ref34}}{R_3 + Z_{ref34}})\end{aligned}$$

The reflected impedance Z_{refpq} from coil q to coil p can be expressed by Equation 7 as:

$$\begin{bmatrix} Z_{ref01} \\ Z_{ref02} \\ Z_{ref12} \\ Z_{ref21} \\ Z_{ref13} \\ Z_{ref23} \\ Z_{ref34} \end{bmatrix} = \begin{bmatrix} \frac{(\omega_0 M_{01})^2}{R_1 + Z_{ref21} + Z_{ref23}} \\ \frac{(\omega_0 M_{02})^2}{R_2 + Z_{ref21} + Z_{ref23}} \\ \frac{(\omega_0 M_{12})^2}{R_2 + Z_{ref23}} \\ \frac{(\omega_0 M_{21})^2}{R_1 + Z_{ref13}} \\ \frac{(\omega_0 M_{13})^2}{R_3 + Z_{ref34}} \\ \frac{(\omega_0 M_{23})^2}{R_3 + Z_{ref34}} \\ \frac{(\omega_0 M_{34})^2}{R_L} \end{bmatrix}$$

All three resonators in the this WPT system are designed with the identical parameters L_1=L_2=L_3, R_1=R_2=R_3 and C_1=C_2=C_3 and have the same resonant frequency. When the Rx is moving along the x-direction, the whole WPT system is symmetrical with respect to the x-z plane as shown in Figure 3. Therefore, it can be approximated that the mutual inductance between the feed loop and resonator 1 (M_{01}) equals to the mutual inductance between feed loop and resonator 2 (M_{02}). The mutual inductance between resonator 1 and resonator 3 (M_{13}) is equal to the mutual inductance between resonator 2 and resonator 3 (M_{23}), M_{13} =M_{23}, due to symmetry. Then, the reflected impedance in (7) and (8) can be simplified to Z_{ref01}=Z_{ref02}, Z_{ref12}=Z_{ref21} and Z_{ref13}=Z_{ref23}. Thus, the calculated PTE of this WPT system can be further simplified by Equation 8 as:

$$\eta = \frac{2Z_{ref01}}{R_s + 2Z_{ref01}}\frac{Z_{ref13}}{R_1 + Z_{ref12}+Z_{ref13}}\frac{Z_{ref34}}{R_3 + Z_{ref34}}\left(1 + \frac{Z_{ref12}}{R_1 + Z_{ref12} + Z_{ref13}}\right)$$

Similarly, the optimal charging distance $d_{optimal}$ to achieve the critical coupling can be obtained by simulation. Hence, the maximum PTE is achieved when the Rx is placed $d_{optimal}$ above the Tx when they are aligned. The operating frequency is selected to be 13.56 MHz, which is the resonant frequency of all resonators in the system. The value of the external capacitors can be calculated according to $f = \frac{1}{2\pi\sqrt{LC}}$.

As shown in Figure 5, the Tx in a conventional four-coil WPT system as introduced in Section II. A is unipolar. The flux lines leave the top surface and enter the bottom surface of the Tx and vice versa periodically. For the Tx in the exemplary WPT system, due to the using of the 8-shape feed loop, the current goes in the-clockwise direction in one part and in the anti-clockwise direction in the other part. This results in a bipolar structure for the Tx, where the top surface of the Tx has both North Pole and South Pole as shown in. Figure 6. Magnetic flux lines leave the top region of one coil in the Tx and enter the top region of the other coil in the Tx through the Rx.

Another common issue associated with WPT is the induction-heating phenomenon. Compared with the WPT system using a unipolar Tx, the magnetic field is confined to a small area above the Tx in the exemplary WPT system. This would significantly reduce the heat induced by magnetic field leakage to any metal parts close to the WPT system. This makes the exemplary WPT system more suitable for DWC of EVs.

WPT system for DWC

Bipolar coil topology is widely used for DWC of EV applications. It not only increases the coupling coefficient between the Tx and Rx, but also reduces magnetic flux leakage. However, eliminating the power null phenomenon is still a main challenge. A typical DWC system with bipolar coil topology is shown in Figure 7. The structures of the Tx and Rx are the same when using the DD type of bipolar coils. Two Txs are placed below the Rx for DWC. When the Rx moves along the two Txs, in the middle point the net magnetic flux on the Rx becomes zero as shown in Figure 7. At this point, there is no power transferred from the Tx to the Rx.

The sum of mutual inductances between all Tx coils and the Rx can be used to evaluate the total power transferred in a multi-Tx DWC system. The mutual inductance M_{RTi} between the i^{th} Tx ($i=1,2$) and the Rx can be obtained by simulation using the software package Maxwell. The variation of the mutual inductance with respect to distance is shown in Figure 8. The absolute value of the sum of M_{RT1} and M_{RT2} is denoted as $ABS(M_{RT1}+M_{RT2})$. It can be seen that M_{RT1} varies from a high positive value to a negative value when the Rx moves along the Txs. M_{RT2} has a symmetrical varying profile with M_{RT1}. Hence, $ABS(M_{RT1}+M_{RT2})$ fluctuates from the maximum to zero and back to the maximum. When $ABS(M_{RT1}+M_{RT2})$ reaches zero, very little power is transferred in the WPT system.

One conventional method to eliminate the power null phenomenon is to add another rectangular coil (Q coil) to the Rx, which composes a DDQ type Rx. When the Rx moves to the null power point, the DD coils stop receiving power from the Tx, the net magnetic flux on the Q-coil reaches its maximum. Conversely, the net magnetic flux on the Q-coil decreases to zero when the Rx moves to the aligned position, where the DD coils on the Rx produce the maximum power. Therefore, the DDQ design can mitigate the power null phenomenon and reduce the power fluctuation. However, adding another coil to the Rx would cause other challenges and problems. Firstly, the manufacturing cost would be increased. Secondly, the Q-coil needs to be optimized carefully, making the whole WPT system much more complex. Moreover, due to the reflected impedance from the Q-coil to the Tx is different from that of the DD coil, the output of the DD coil and the Q-coil are not in phase. As a result, the Q-coil required an individual compensation and rectifier circuit. This results in more power consumption in the system and lower PTE.

An exemplary 1×2 DWC system is shown in Figure 9. The Rx in this exemplary WPT system is placed perpendicularly with the Tx and it moves along the x-axis. When the Rx moves along the travel direction, flux lines go through it from the one side to the other side. Hence, the net magnetic flux on the Rx would not be zero. These mutual inductances are calculated using Maxwell and shown in Figure 10. The mutual inductance between the Rx and the i^{th} Tx (i =1, 2) is denoted as MR_{Tci}. The absolute value of the sum of MR_{Tc1} and MR_{Tc2} is denoted as $ABS(MR_{Tc1}+MR_{Tc2})$. It can be found that MR_{Tc1} *and* MR_{Tc2} are always in-phase as shown in Figure 10. Therefore, the power null phenomenon is very significantly mitigated in the exemplary WPT system. Compared with the simulation results in Figure 8, $ABS(MR_{Tc1}+MR_{Tc2})$ varies in a much smaller range, which means the output power fluctuation can be drastically reduced in the exemplary WPT system.

The exemplary WPT system maintains the advantage of using bipolar coils by confining magnetic flux lines in a smaller space, thereby reducing the concern about filed leakage. Meanwhile, this system overcomes the disadvantages of using conventional bipolar coils by mitigating the power null phenomena very effectively.

Extensible WPT system

To further increase the wireless charging area, a multi-transmitter structure can be used. However, a traditional WPT system with multiple transmitters requires that the transmitters are synchronized in frequency, phase, and amplitude. This results in a complicated control mechanism and structure. Even though all transmitters were synchronized as required, the WPT system would still have power null phenomena as introduced above.

A planar array for the Tx may be used to increase the charging area. The planar array of a conventional MCR-WPT system has a fixed feed loop to drive resonators in the Tx. Using the network according to the first aspect, a modularized array of transmitters can be constructed with simpler track connections.

Figure 11(a) shows the exemplary bipolar Tx, as described above, which can be used as an extensible module. When an AC power source is connected between the two connection terminals, the current flowing through the feed loop can generate magnetic field of opposite directions on the two resonators of the module. If the North Pole is generated in the red region, the South Pole will be generated in the blue region. The magnetic field strength *H* on the surface of the module is simulated by using CST and shown in Figure 11(b).

The feed loops in the modules can be connected in series to form a planar 1×n Tx array. In the simplest scenario when only two modules are needed, connection of the two modules is shown in Figure 12(a). The feed loops in Module 1 and Module 2 are connected together through the connection terminals. Such connections ensure that the current flowing through the two feed loops has the same direction in the two modules. Therefore, the poles in the red region are the same, and are different from those in the blue region. The simulated magnetic field distribution is shown in Figure 12(b).

According to the same principle, the charging area of an exemplary extensible WPT can be enlarged by increasing the number of modules in the Tx. Figure 13(a) demonstrates a 1×n Tx array which can be used in an exemplary DWC system. A 1×6 Tx array is simulated to validate the principle. The magnetic contribution on the surface of this Tx array is shown in Figure 13(b). The exemplary WPT system can generate a stable magnetic field on the surface of the Tx, which ensures that the WPT system will continue to work when the Rx is moving along the symmetrical line.

Network

The network is for inductive charging of the device, for example a battery thereof and/or to power an electronic circuit and/or component thereof. It should be understood that the device includes the receiver. That is, power is transferred from the transmitter to the receiver, in use, by inductive coupling therebetween. Inductive coupling between respective coils of a transmitter and a receiver is known. That is, the WPT is a near-field technique. In one example, the transmitter is an inductively coupled resonator, for example comprising a capacitor. Inductively coupled resonators are known. In one example, the receiver is an inductively coupled resonator. In one example, the transmitter and the receiver are inductively coupled resonators.

The transmitter comprises the set of coils, including the first coil and optionally the second coil, wherein the set of coils comprises the first set of turns, including the first turn, and the second set of turns, including the first turn. It should be understood that respective coils of the set of coils comprise respective turns, for example 1 or more turns, including fractional numbers of turns. It should be understood that respective coils of the set of coils comprise continuous electrical conductors, such as wires, ribbons and/or tracks, which provide and/or are arranged as the respective turns.

It should be understood that the set of coils comprises the first turn and the second turn. In one example, the first coil comprises the first turn and the second turn. That is, the second turn may be described as looping back on the first turn, such that the first sense and the second sense are opposed. In one example, the first coil comprises the first turn and the second coil comprises the second turn. It should be understood that respective coils of the set of coils may be mutually electrically coupled and/or mutually electrically isolated. In one example, the first coil and the second coil are mutually electrically coupled. In one example, the first coil and the second coil are mutually electrically isolated. In one example, the first coil comprises the first set of turns and the second set of turns.

The set of coils of the transmitter is arranged in a first plane. In one example, the set of coils is a set of planar coils, wherein the turns thereof (for example, the first turn and the second turn) are arranged in the first plane, for example mutually parallel or substantially mutually parallel planes, preferably the same or substantially the same plane. In one example, the set of coils are coplanar.

The first set of turns and the second set of turns are adjacent, defining the centre line therebetween. That is, the first set of turns is next to the second set of turns while spaced apart therefrom, for example by an electrical insulator. In one example, the first set of turns and the second set of turns are mutually spaced apart by a first spacing, preferably a substantially constant first spacing, for example in a range from 0.01w to 100w, preferably in a range from 0.1w to 10w, more preferably in a range from 0.2w to 5w, wherein w is a width of the first set of turns and/or the second set of turns. The width w of the first set of turns and/or the second set of turns is measured orthogonally to the first sense and/or the second sense, respectively. In one example, the first spacing is greater than or equal to the width w of the first set of turns and/or the second set of turns.

It should be understood that the centre line is thus a midline of the bipolar transmitter, as understood by the skilled person. In one example, the first set of turns and the second set of turns are similar, for example having a centre of rotational symmetry on the centre line.

The first turn of the first set of turns has a first sense and the first turn of the second set of turns has a second sense, opposed to the first sense. That is, the first turn of the first set of turns and the first turn of the second set of turns are bi-directional. In one example, the first sense and the second sense are generally circular, for example around an ellipse or a polygon. In one example, the first sense is clockwise and the second sense is anticlockwise. In one example, the first sense is anticlockwise and the second sense is clockwise. In one example, the first sense and the second sense are linear, for example in opposite directions.

In use, current, for example alternating current, flows through the first turn of the first set of turns and the first turn of the second set of turns in mutually opposed senses, thereby providing the bipolar transmitter. Bipolar transmitters are known. That is, in use, current, for example alternating current, flows through the first turn in the first sense and through the second turn in the second sense. In one example, the current, for example alternating current, flowing, in use, through the first turn and the second turn in mutually opposed senses is the same current.

In one example, the first turn and/or the second turn has a width w in a range from 0.1 mm to 30 mm.

In one example, the first set of turns and the second set of turns are mutually spaced apart by a second spacing, preferably a substantially constant second spacing, for example in a range from 0.01W to 100W, preferably in a range from 0.1W to 10W, more preferably in a range from 0.2W to 5W, wherein W is a width of the first set of turns and/or the second set of turns. The width W of the first set of turns and/or the second set of turns is measured orthogonally to the first sense and/or the second sense, respectively. In one example, the width W of the first set of turns and/or the second set of turns is greater than the width w of the first turn and/or the second turn. In one example, the second spacing is greater than or equal to the width W of the first set of turns and/or the second set of turns.

In one example, the first set of turns includes N turns, including the first turn, wherein N is a natural number greater than or equal to 1 or a fractional number, optionally, wherein respective turns of the first set of turns have the first sense. By increasing the number of turns in the first set of turns, mutual inductance between the transmitter and the receiver may be increased. In one example, the second set of turns includes M turns, including the first turn, wherein M is a natural number greater than or equal to 1 or a fractional number.

In one example, respective turns of the first set of turns have the first sense. In one example, respective turns of the second set of turns have the second sense. That is, more than one turn may have the same sense, not withstanding that the adjacent first turn of the first set of turns and the first turn of the second set of turns have mutually opposed senses.

The receiver comprises the set of coils, including the first coil, wherein the set of coils comprises the first set of turns, including the first turn.

The set of coils of the receiver is arranged in the second plane, transverse to the first plane substantially about the centre line. It should be understood that the second plane is thus transverse, for example substantially orthogonal (i.e. substantially perpendicular), to the first plane, which includes the centre line. It should be understood that the second plane is thus about the centre line, for example through the centre line or proximal thereto, for example laterally and/or rotationally spaced apart therefrom. In one example, the set of coils of the receiver is a set of planar coils, wherein the turns thereof (for example, the first set of turns) are arranged in the second plane.

In one example, the second plane and the first plane are orthogonal within 10˚, preferably within 5˚. In one example, the second plane is orthogonal to the first plane. In this way, a PTE of the network is improved.

In one example, the second plane is misaligned with respect to the centre line, for example a lateral misalignment relative to the centre line and/or an rotational misalignment about the centre line and/or an angular misalignment between the first plane and the second plane with respect to an orthogonal arrangement therebetween, for example wherein the rotational misalignment about the centre line is at most 10˚, preferably at most 5˚ and/or wherein the angular misalignment between the first plane and the second plane with respect to an orthogonal arrangement is at most 10˚, preferably at most 5˚.In one example, the second plane includes the centre line. That is, the second plane may be aligned with respect to the centre line In this way, a PTE of the network is improved.

In one example, the first plane and the second plane intersect at the centre line.

In one example, the network comprises a conductor, for example a planar conductor, wherein the receiver is arranged between the transmitter and the conductor. As described herein in more detail, a PTE of the network is substantially less affect by such a conductor, for example a copper plate, compared with a conventional WPT system.

In one example, the first turn of the first set of turns has substantially a shape selected from: an ellipse for example a circle, a polygon, preferably a regular polygon, for example having P sides, where P is a natural number greater than or equal to 3 , for example a triangle, a square, a rectangle, a rhombus, a trapezium, a parallelogram, a kite, a pentagon, a hexagon, a heptagon, an octagon, a nonagon or a decagon. In one example, the first turn and/or the second turn comprises one or more arcuate portions and/or one or more linear portions. Preferably, the first turn and/or the second turn is substantially circular, such as a part of a helix. The first turn of the second set of turns may be as described with respect to the first turn.

In one example, the first turn of the first set of turns is substantially spiral, preferably helical. That is, a dimension, for example a diameter, of the first turn of the first set of turns increases or decreases in the first sense. The first turn of the second set of turns may be as described with respect to the first turn.

In one example, the receiver is configured to move relative to the transmitter along the centre line. That is, the receiver and the transmitter are configurable in a variably-spaced relationship along, for example proximal to, the centre line. It should be understood that proximal means with an acceptable amount of misalignment such that a mutual inductance is relatively constant as described below, for example a lateral misalignment relative to the centre line and/or an rotational misalignment about the centre line and/or an angular misalignment between the first plane and the second plane with respect to an orthogonal arrangement therebetween, between the transmitter and the receiver.

In one example, the network is configurable in:
a first configuration, wherein the receiver is positioned at a first position along the centre line; and
a second configuration, wherein the receiver is positioned at a second position along the centre line;
wherein the first position and the second position are mutually spaced apart.

In one example, the network includes an array, preferably a planar array, comprising a set of transmitters, including a first transmitter and a second transmitter. In one example, respective centre lines of the set of transmitters are common, such as colinear, substantially colinear and/or coincident, for example arranged along an arc.

In one example, the receiver is configured to move relative to the first transmitter and/or to the second transmitter along the centre line, for example a common centre line. That is, the receiver is configurable in a variably-spaced relationship with respect to the first transmitter and/or to the second transmitter the along, for example proximal to, the centre line. It should be understood that proximal means with an acceptable amount of misalignment, for example a lateral misalignment relative to the centre line and/or an rotational misalignment about the centre line and/or an angular misalignment between the first plane and the second plane with respect to an orthogonal arrangement therebetween, between the first transmitter and/or the second transmitter and the receiver.

In one example, the network is configurable in:
a first configuration, wherein the receiver is positioned at a first position along the centre line relatively proximal the first transmitter or the second transmitter; and
a second configuration, wherein the receiver is positioned at a second position along the centre line between the first transmitter or the second transmitter;
wherein the first position and the second position are mutually spaced apart.

Particularly, a mutual inductance between the receiver and the set of transmitters is substantially constant along the centre line, compared with a conventional DWC system.

In one example, a mutual inductance between the receiver and the set of transmitters is substantially constant along the centre line. In one example, the mutual inductance changes by at most 10%, preferably at most 5%, for example when the lateral misalignment is at most 10%, preferably at most 5% of a dimension of the transmitter and/or the receiver, wherein the rotational misalignment about the centre line (i.e. yaw) is at most 10˚, preferably at most 5˚ and/or wherein the angular misalignment between the first plane and the second plane with respect to an orthogonal arrangement (i.e. roll) is at most 10˚, preferably at most 5˚.

In one example, the network comprises a way (also known as a path, a line or a route), for example a roadway or a railway, including the transmitter, and a land craft, for example a road vehicle or a train, comprising the receiver. The way and/or the land craft may be as described with respect to the second aspect and the third aspect, respectively.

Way

A second aspect provides a way, for example a roadway or a railway, including the transmitter according to the first aspect.

In one example, the transmitter is arranged proximal to a surface of the way, for example on a surface of the way or below a surface of the way. In one example, the way is a roadway and the transmitter is arranged relatively proximal a central portion of the roadway rather than an edge portion of the roadway, upon which wheels of a vehicle may roll. In one example, the way is a railway having tracks and the transmitter is arranged between the tracks.

In one example, the way includes an array, preferably a planar array, comprising a set of transmitters, including a first transmitter and a second transmitter.

Land craft

A third aspect provides a land craft, for example a road vehicle, such as a car, a bus or a lorry, for a roadway or a train for a railway, comprising the receiver according to the first aspect.

In one example, the receiver is arranged between wheels of the land craft, extending away from an undercarriage thereof. In one example, the receiver is retractable, for example into and/or through an undercarriage. In this way, the receiver may be retracted when the land craft is moving over a conventional way, for example. In one example, the receiver is translatable, for example between the wheels. In this way, alignment of the receiver with a centre line of a transmitter may be improved, for example dynamically. In one example, the receiver is rotatable about one, two or three axes (i.e. pitch, roll and/or yaw), preferably about at least one or two axes (i.e. roll and/or yaw). In this way, alignment of the receiver with a transmitter may be improved, for example dynamically.

Method

A fourth aspect provides a method of inductive charging of a device, for example according to the third aspect, using a network according to the first aspect or a way according to the second aspect.

More generally, the fourth aspect provides a method of wireless power transfer using a network according to the first aspect or a way according to the second aspect

In one example, the method comprises resonant inductive charging.

In one example, a resonant frequency is in a range from 1 kHz to 1 GHz, preferably in a range from 100 kHz to 100 MHz, more preferably in a range from 1 MHz to 50 MHz, for example 10 MHz.

In one example, the method comprises changing a misalignment, for example a lateral misalignment relative to the centre line and/or an rotational misalignment about the centre line and/or an angular misalignment between the first plane and the second plane with respect to an orthogonal arrangement therebetween, between the transmitter and the receiver, wherein a mutual inductance therebetween is substantial constant, for example wherein the mutual inductance changes by at most 10%, preferably at most 5%, for example when the lateral misalignment is at most 10%, preferably at most 5% of a dimension of the transmitter and/or the receiver, wherein the rotational misalignment about the centre line is at most 10˚, preferably at most 5˚ and/or wherein the angular misalignment between the first plane and the second plane with respect to an orthogonal arrangement is at most 10˚, preferably at most 5˚.

Definitions

Throughout this specification, the term “comprising” or “comprises” means including the component(s) specified but not to the exclusion of the presence of other components. The term “consisting essentially of” or “consists essentially of” means including the components specified but excluding other components except for materials present as impurities, unavoidable materials present as a result of processes used to provide the components, and components added for a purpose other than achieving the technical effect of the invention, such as colourants, and the like.

The term “consisting of” or “consists of” means including the components specified but excluding other components.

Whenever appropriate, depending upon the context, the use of the term “comprises” or “comprising” may also be taken to include the meaning “consists essentially of” or “consisting essentially of”, and also may also be taken to include the meaning “consists of” or “consisting of”.

The optional features set out herein may be used either individually or in combination with each other where appropriate and particularly in the combinations as set out in the accompanying claims. The optional features for each aspect or exemplary embodiment of the invention, as set out herein are also applicable to all other aspects or exemplary embodiments of the invention, where appropriate. In other words, the skilled person reading this specification should consider the optional features for each aspect or exemplary embodiment of the invention as interchangeable and combinable between different aspects and exemplary embodiments.

Brief description of the drawings

For a better understanding of the invention, and to show how exemplary embodiments of the same may be brought into effect, reference will be made, by way of example only, to the accompanying diagrammatic Figures, in which:

Figure 1 shows a typical four-coil WPT system for EVs, where the Rx is installed on the bottom of the Ev and Txs are installed under the road surface;

Figure 2 shows a simplified schematic of a four-coil WPT system. This system consists of four element: feed loop, resonator coil as the Tx, resonator coil as the Rx and load loop;

Figure 3 shows a 3-D view of an exemplary embodiment, particularly of a perpendicular WPT structure;

Figure 4 shows a simplified schematic of the exemplary embodiment of Figure 3;

Figure 5 shows the magnetic field contribution of the four-coil WPT system;

Figure 6 shows the magnetic field contribution of the exemplary embodiment of Figure 3;

Figure 7 shows a diagram to illustrate the power null phenomenon. This is the section view of WPT system with DD coils where the Rx is placed on the null power point. The magnetic flux lines are highlighted to describe that the net flux on Rx is zero at this point;

Figure 8 shows the mutual inductance against Δd_la of WPT systems using the DD type of coils;

Figure 9 shows a diagram of an exemplary embodiment;

Figure 10 shows the mutual inductances between resonator coils in the Tx and Rx against Δd_la of the exemplary embodiment of Figure 9;

Figure 11 shows (a) a diagram of an exemplary transmitter, particularly an extensible module; and (b) the magnetic field contribution on the surface of the module;

Figure 12 shows (a) a diagram of a 1×2 Tx array according to an exemplary embodiment; and (b) the magnetic field contribution on the surface of the 1×2 Tx array;

Figure 13 shows (a) a diagram of a 1×n Tx array according to an exemplary embodiment; and (b) the magnetic field contribution on the surface of a 1×6 Tx array;

Figure 14 shows photographs of (a) the top layer of the fabricated Tx module; (b) the bottom layer of the fabricated Tx module; (c) the top layer of the fabricated Rx; and (d) the bottom layer of the fabricated Rx;

Figure 15 shows the experimental setup of an exemplary embodiment, particularly a WPT system with a single Tx module;

Figure 16 shows measured results of (a) a conventional; and (b) an exemplary WPT system against lateral displacement;

Figure 17 shows WPT efficiencies of the system with an exemplary single-module Tx and a conventional Tx;

Figure 18 shows measurement results of (a) WPT efficiency as a function of the misalignment distance of an exemplary embodiment WPT system with a 1×2 array Tx; and (b) S21 against misalignment distance;

Figure 19 shows an experimental setup of to test the effect of a surrounding metal plate (a) a copper plate is placed 5 mm above the Rx of an exemplary WPT system; and (b) a copper plate is placed 5 mm above the Rx of a conventional WPT system; and

Figure 20 shows magnetic field distribution on the copper plate placed above the Rx of (a) an exemplary WPT system and (b) a conventional WPT system.

Detailed Description of the Drawings

Experimental Validation

Figure 15 shows a network 1 according to an exemplary embodiment for inductive charging of a device D, wherein the network 1 comprises a transmitter 10 and a receiver 20. The transmitter 10 comprises a set of coils 100, including a first coil 100A and optionally a second coil 100B, wherein the set of coils 100 comprises a first set of turns 110, including a first turn 110A, and a second set of turns 120, including a first turn 120A. The set of coils 100 of the transmitter 10 is arranged in a first plane P1. The first set of turns 110 and the second set of turns 120 are adjacent, defining a centre line CL therebetween. The first turn 110A of the first set of turns 110 has a first sense and wherein the first turn 120A of the second set of turns 120 has a second sense, opposed to the first sense. In use, current flows through the first turn 110A of the first set of turns 110 and the first turn 120A of the second set of turns 120 in mutually opposed senses, thereby providing a bipolar transmitter. The receiver 2 comprises a set of coils 200, including a first coil 200A, wherein the set of coils 200 comprises a first set of turns 210, including a first turn 210A. The set of coils 200 of the receiver 2 is arranged in a second plane P2, transverse to the first plane P1 substantially about the centre line CL.

An exemplary WPT system (i.e. a network according to the first aspect) with a single charging module was fabricated on an FR4 printed circuit board (PCB) with a double layer structure as shown in Figure 14. Inductive coils and feed/load loops were constructed by copper tracks on the PCB, whose thickness and width are denoted as h_c and w_c, respectively. The feed loop was fabricated on both layers of the PCB to form an “8” shape (i.e. figure of 8 shape), as shown in Figures 14 (a) and (b).

The load loop for the Rx was fabricated on the top layer as shown in Figure 14(c). All resonators in this exemplary WPT system had the same dimensions. They were fabricated on one side of the PCB connected with external capacitors soldered on the other side to form resonators. Parameters of the fabricated circuit (i.e. network according the first aspect) are listed in Table 1.

Parameters of the Fabricated Circuit		
Parameters	Value	Unit
Turns of resonator coil	5	NA
Copper Height h_c	0.035	mm
Track Width w_c	1	mm
Space Between Tracks l_s	1	mm
widths of the Tx l_{wT}	63	mm
widths of the Rx l_{wR}	63	mm
length of the Tx l_{lT}	131	mm
Capacitance of external capacitor (Ce)	60	pF
Self-inductance of resonator coil	3.32	µH
Self-inductance of feed loop	0.911	µH
Self-inductance of load loop	0.544	µH

Table 1: Parameters of fabricated circuit.

The experimental setup of the exemplary WPT system with a single Tx module is shown in Figure 15. The Rx was placed perpendicularly above the Tx module, so that they were aligned with each other. An Anritsu MS46322B vector network analyser (VNA) was used to measure the PTE of this WPT system. S-parameters were utilized as an indicator for transmission performance of the WPT system. The transfer efficiency can be expressed by Equation 9 as

$$\eta = \frac{|S_{21}|^2}{1 - |S_{11}|^2}$$

In the aligned condition as shown in Figure 15, the maximum efficiency can be achieved with a charging height of 5 mm, where S_{11} = -26.8 dB and S_{21} = -0.6 dB at the operating frequency of 13.56 MHz. The maximum efficiency is calculated to be 87.1%. The conventional four-coil WPT system was fabricated for comparison, whose Tx and Rx had the same design as the Rx in the exemplary WPT system. The maximum PTE achieved was 85%.

The robustness of the exemplary WPT system maintaining high efficiency against lateral displacement was measured. The misalignment was varied from 0 to 70 mm with a step of 10 mm. At each distance, the S-parameters were measured to calculate the efficiency. Figure 16 shows the measured efficiency as a function of the *Δd_la*. The efficiency declined slowly when the misalignment is from 0 to 20 mm. From 20 to 35 mm, there is still strong and consistent coupling existing between the Rx and Tx and the efficiency was still over 60%. After a misalignment distance of 35 mm, the efficiency dropped rapidly, because the overlapping area of the Rx and Tx was less than half of the maximum physical size of the Tx or Rx. Therefore, no strong coupling existed between the Rx and Tx after this point. The designed WPT system had over 70% efficiency when the misalignment distance varied from 0 to 30 mm which was 42.9% of the width of the Tx or Rx.

The performance of the exemplary WPT system was also compared with the conventional WPT system with a four-coil structure given in Figure 7. For fair comparison, the conventional WPT system was fabricated on a PCB with the same overall dimensions as the exemplary one.

The experimental setup for the exemplary extensible WPT system is shown in Figure 18(a). The Tx is extended to a 1×2 array with connections described in Section II.C. The two Tx modules with a separation distance of 1 mm were connected in series to form the Tx. The Rx remained unchanged and was placed above the Tx at the optimal distance. The power transmission efficiency versus the lateral misalignment distance *Δd_la* is shown in Figure 18(b). The performance of the extensible WPT system with a moving Rx is measured. The lateral misalignment distance was changed with an increment of 10 mm from the position where the Rx is perfectly aligned with Module 1 to the position where the Rx is aligned with Module 2. The efficiency decreases very slowly when the displacement of the Rx was less than the 40 mm. After a lateral displacement of 40 mm, the coupling between the Rx and Module 2 in the Tx became stronger. This leads to an increasing efficiency for the distance from 40 mm to 70 mm. The efficiency increases to the peak again, when the Rx is perfectly aligned with Module 2 in the Tx. This process would repeat when the Rx is moving further towards the next module.

Figure 18(b) shows the measured S_{21} of the 1×2 array system with respect to the lateral displacement. Compared with the results shown in Figure 16(a) and Figure 16(b), the S21 is much more stable so that the exemplary extensible WPT system has a much better performance against lateral displacement. The WPT system with a 1×2 Tx array can achieve 71.6% maximum efficiency when the Rx was aligned with Module 1 or Module 2. The minimum efficiency of the exemplary WPT systems is better than 57% at all positions. It validates that the exemplary WPT system can significantly reduce the output fluctuation and overcome the power null phenomenon. The simulated results and measured results are in good agreement.

Figure 19 demonstrates the effect of surrounding metal parts on the conventional and the exemplary WPT systems. A single-module Tx was used in this measurement. In this experiment, a 60 mm × 60 mm copper plate was placed 5 mm above the Rx of the two WPT systems respectively. Since the exemplary WPT system has a bipolar Tx, the magnetic flux line is confined in a small region. Only a small region of the copper plate has strong magnetic flux for the exemplary WPT system as shown in Figure 20(a). However, for the conventional WPT system with the unipolar Rx and Tx, the magnetic flux on the copper plate is much stronger as shown in Figure 20(b), which could induce excessive heat on the metal part.

The PTE of the conventional WPT system is significantly affected by surrounding metal parts. The transfer efficiency with and without the copper plate placed above the Rx are measured. Since the proposed WPT system has a perpendicular structure, the effect of the surrounding metal is very limited because most of the magnetic flux lines are around the Rx as shown in Figure 20(a). The exemplary WPT system achieved 87.1% maximum efficiency without the copper plate and 84.9% with a copper plate placed above the Rx. Conversely, most of the magnetic flux lines around the Rx of the conventional WPT system are significantly affected by the copper plate according to Figure 20(b). The PTE drops from 85.0% to almost zero when a copper plate was placed above the Rx.

The exemplary design is particularly useful for the charging of vehicles or trains on a track. The number of charging modules can be dynamically controlled. That is, the charging area can be enlarged or reduced by increasing or reducing the number of Tx modules. The charging modules can also be synchronized with a moving vehicle. Therefore, the exemplary extensible WPT system is suitable for many applications, especially wireless charging of EVs.

Summary

In conclusion, an extensible WPT system with a bipolar Tx and a perpendicular Rx-Tx structure has been described in this paper. An 8-shape feed loop was used to construct a bipolar Tx module. Meanwhile, the Tx module can be easily extended to a bipolar Tx array. This feature enables the exemplary WPT system to have an excellent extensibility. The output power fluctuation can be significantly reduced using this bipolar Tx array. This exemplary WPT system can overcome the power null phenomenon very effectively compared with the method of using DDQ coils. Since the unipolar Rx and bipolar Tx are placed perpendicularly with each other, the magnetic flux lines are mainly confined in the region of the WPT system. This will significantly minimize the effect of surrounding metal parts on the WPT system. As demonstrated by experiment, the exemplary extensible WPT system can achieve a smooth efficiency of 57% - 71.6% when an Rx moves along a two-module Tx. For a one-module system, the exemplary WPT system achieved 87.1% maximum efficiency. The efficiency only drops to 84.9% with a copper plate placed above the Rx, without any tuning needed. The exemplary system is particularly useful for DWC systems.

Although a preferred embodiment has been shown and described, it will be appreciated by those skilled in the art that various changes and modifications might be made without departing from the scope of the invention, as defined in the appended claims and as described above.

Attention is directed to all papers and documents which are filed concurrently with or previous to this specification in connection with this application and which are open to public inspection with this specification, and the contents of all such papers and documents are incorporated herein by reference.

All of the features disclosed in this specification (including any accompanying claims and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at most some of such features and/or steps are mutually exclusive.

Each feature disclosed in this specification (including any accompanying claims, and drawings) may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic series of equivalent or similar features.

The invention is not restricted to the details of the foregoing embodiment(s). The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims and drawings), or to any novel one, or any novel combination, of the steps of any method or process so disclosed.

CLAIMS

1. A network for inductive charging of a device, wherein the network comprises a transmitter and a receiver;

wherein the transmitter comprises:

a set of coils, including a first coil and optionally a second coil, wherein the set of coils comprises a first set of turns, including a first turn, and a second set of turns, including a first turn;

wherein the set of coils of the transmitter is arranged in a first plane;

wherein the first set of turns and the second set of turns are adjacent, defining a centre line therebetween;

wherein the first turn of the first set of turns has a first sense and wherein the first turn of the second set of turns has a second sense, opposed to the first sense; and

whereby, in use, current flows through the first turn of the first set of turns and the first turn of the second set of turns in mutually opposed senses, thereby providing a bipolar transmitter;

wherein the receiver comprises:

a set of coils, including a first coil, wherein the set of coils comprises a first set of turns, including a first turn; and

wherein the set of coils of the receiver is arranged in a second plane, transverse to the first plane substantially about the centre line.

2. The network according to any previous claim, wherein the first coil comprises the first set of turns and the second set of turns.

3. The network according to any previous claim, wherein the first set of turns includes N turns, including the first turn, wherein N is a natural number greater than or equal to 1 or a fractional number, optionally, wherein respective turns of the first set of turns have the first sense.

4. The network according to any previous claim, wherein the second plane is orthogonal to the first plane.

5. The network according to any previous claim, wherein the second plane includes the centre line.

6. The network according to any previous claim, comprising a conductor, for example a planar conductor, wherein the receiver is arranged between the transmitter and the conductor.

7. The network according to any previous claim, wherein the first turn of the first set of turns has substantially a shape selected from: an ellipse for example a circle, a polygon, preferably a

regular polygon, for example having P sides, where P is a natural number greater than or equal to 3.

8. The network according to any previous claim, wherein the receiver is configured to move relative to the transmitter along the centre line.

9. The network according to any previous claim, including an array, preferably a planar array, comprising a set of transmitters, including a first transmitter and a second transmitter.

10. The network according to claim 9, wherein the receiver is configured to move relative to the first transmitter and/or to the second transmitter along the centre line.

11. The network according to any of claims 9 to 10, wherein a mutual inductance between the receiver and the set of transmitters is substantially constant along the centre line.

12. The network according to any previous claim, comprising a way, for example a roadway or a railway, including the transmitter, and a land craft, for example a road vehicle or a train, comprising the receiver.

13. A way, for example a roadway or a railway, including the transmitter according to any of claims 1 to 11.

14. A land craft, for example a road vehicle for a roadway or a train for a railway, comprising the receiver according to any of claims 1 to 11.

15. A method of inductive charging of a device, for example a land craft according to claim 14, using a network according to any of claims 1 to 11 or a way according to claim 13.

ABSTRACT

Network for and method of wireless power transfer

A network 1 for inductive charging of a device D is described, wherein the network 1 comprises a transmitter 10 and a receiver 20. The transmitter 10 comprises a set of coils 100, including a first coil 100A and optionally a second coil 100B, wherein the set of coils 100 comprises a first set of turns 110, including a first turn 110A, and a second set of turns 120, including a first turn 120A. The set of coils 100 of the transmitter 10 is arranged in a first plane P1. The first set of turns 110 and the second set of turns 120 are adjacent, defining a centre line CL therebetween. The first turn 110A of the first set of turns 110 has a first sense and wherein the first turn 120A of the second set of turns 120 has a second sense, opposed to the first sense. In use, current flows through the first turn 110A of the first set of turns 110 and the first turn 120A of the second set of turns 120 in mutually opposed senses, thereby providing a bipolar transmitter. The receiver 2 comprises a set of coils 200, including a first coil 200A, wherein the set of coils 200 comprises a first set of turns 210, including a first turn 210A. The set of coils 200 of the receiver 2 is arranged in a second plane P2, transverse to the first plane P1 substantially about the centre line CL.

[Figure 15]