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Wireless Power Transfer Coil with Insulated Conductive Wires

Abstract

A wireless charging system may include a wireless power receiving device that receives wireless power signals from a wireless power transmitting device. The wireless power receiving device and the wireless power transmitting device may each include a wireless power transfer coil that comprises windings of a wire bundle having multiple wire units, each wire unit having multiple wire subunits, and each wire subunit having multiple insulated conductive wires.

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Background/Summary

[0001] This application claims the benefit of U.S. provisional patent application No. 63/553,807, filed Feb. 15, 2024, which is hereby incorporated by reference herein in its entirety.

FIELD

[0002] This relates generally to power systems and, more particularly, to wireless power systems for charging electronic devices.

BACKGROUND

[0003] In a wireless charging system, a wireless power transmitting device transmits wireless power to a wireless power receiving device. The wireless power receiving device charges a battery and/or powers components using the wireless power. Each one of the wireless power receiving device and the wireless power transmitting device includes a wireless power transfer coil. Efficient coupling between the wireless power transfer coils in the wireless power transmitting device and the wireless power receiving device can beneficially promote charge performance, reducing charging time.

SUMMARY

[0004] A wireless power transmitting device may be configured to provide wireless power to a wireless power receiving device. The wireless power transmitting device may include a wireless power transfer coil and inverter circuitry coupled to the wireless power transfer coil. The wireless power transfer coil may include windings of a wire bundle, the wire bundle may include a plurality of wire units that twist along a length of the wire bundle, each wire unit of the plurality of wire units may include wire subunits that twist along a length of that wire unit, and each wire subunit of the plurality of wire subunits comprises a plurality of insulated conductive wires that twist along a length of that wire subunit.

[0005] A wireless power receiving device may be configured to receive wireless power from a wireless power transmitting device. The wireless power receiving device may include a wireless power transfer coil and rectifier circuitry coupled to the wireless power transfer coil. The wireless power transfer coil may include windings of a wire bundle, the wire bundle may include a plurality of wire units that twist along a length of the wire bundle, each wire unit of the plurality of wire units may include wire subunits that twist along a length of that wire unit, and each wire subunit of the plurality of wire subunits comprises a plurality of insulated conductive wires that twist along a length of that wire subunit.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. **1** is a schematic diagram of an illustrative wireless power system in accordance with some embodiments.

[0007] FIG. **2** is a circuit diagram of wireless power transmitting and receiving circuitry in accordance with some embodiments.

[0008] FIG. **3** is a cross-sectional side view of an illustrative wire bundle for a wireless power transfer coil in accordance with some embodiments.

[0009] FIG. **4** is a top view of an illustrative wireless power transfer coil with windings of the wire bundle of FIG. **3** arranged in a plurality of turns in accordance with some embodiments.

[0010] FIGS. **5**A-**5**C are cross-sectional side views of a single wire subunit showing the varying radial positions of an insulated conductive wire at different points along the wire bundle of FIGS. **3** and **4** in accordance with some embodiments.

[0011] FIGS. **6**A-**6**C are cross-sectional side views of a single wire unit showing the varying radial positions of a wire subunit at different points along the wire bundle of FIGS. **3** and **4** in accordance with some embodiments.

[0012] FIGS. **7**A-**7**C are cross-sectional side views of the wire bundle of FIGS. **3** and **4** showing the varying radial positions of a wire unit at different points along the wire bundle in accordance with some embodiments.

[0013] FIGS. **8**A-**8**C are cross-sectional side views of the wire bundle of FIGS. **3** and **4** showing the varying radial positions of an insulated conductive wire at different points along the wire bundle in accordance with some embodiments.

[0014] FIG. **9** is a cross-sectional side view of an illustrative wireless charging system with a power transmitting device and a power receiving device in accordance with some embodiments.

[0015] FIG. **10** is a top view of an illustrative ring-shaped ferrite core in accordance with some embodiments.

[0016] FIG. **11**A is a side view of an illustrative wireless power transfer coil with a ferrite core having only one lip in accordance with some embodiments.

[0017] FIG. **11**B is a side view of an illustrative wireless power transfer coil with a ferrite core having no lips in accordance with some embodiments.

DETAILED DESCRIPTION

[0018] An illustrative wireless power system (also sometimes called a wireless charging system) is shown in FIG. **1**. As shown in FIG. **1**, wireless power system **8** may include one or more wireless power transmitting devices such as wireless power transmitting device **12** and one or more wireless power receiving devices such as wireless power receiving device **24**. Wireless power system **8** may sometimes also be referred to herein as wireless power transfer (WPT) system **8** or wireless power system **8**. Wireless power transmitting device **12** may sometimes also be referred to herein as power transmitter (PTX) device **12** or simply as PTX **12**. Wireless power receiving device **24** may sometimes also be referred to herein as power receiver (PRX) device **24** or simply as PRX **24**.

[0019] PTX device **12** includes control circuitry **16**. Control circuitry **16** is mounted within housing **30**. PRX device **24** includes control circuitry **38** mounted within a corresponding housing **52** for PRX device **24**. Exemplary control circuitry **16** and control circuitry **38** are used in controlling the operation of WPT system **8**. This control circuitry may include processing circuitry that includes one or more processors such as microprocessors, power management units, baseband processors, digital signal processors, microcontrollers, graphics processing units (GPUs), central processing units (CPUs), application processors (APs), application-specific integrated circuits with processing circuits, and/or other processing circuits. The processing circuitry implements desired control and communications features in PTX device **12** and PRX device **24**. For example, the processing circuitry may be used in controlling power to one or more coils, determining and/or setting power transmission levels, generating and/or processing sensor data (e.g., to detect foreign objects and/or external electromagnetic signals or fields), processing user input, handling negotiations between PTX device **12** and PRX device **24**, sending and receiving in-band and out-of-band data, making measurements, and/or otherwise controlling the operation of WPT system **8**.

[0020] Control circuitry in WPT system **8** (e.g., control circuitry **16** and/or **38**) is configured to perform operations in WPT system **8** using hardware (e.g., dedicated hardware or circuitry), firmware and/or software. Software code for performing operations in WPT system **8** is stored on non-transitory computer readable storage media (e.g., tangible computer readable storage media) in the control circuitry of WPT system **8**. The software code may sometimes be referred to as software, data, program instructions, instructions, or code. The non-transitory computer readable storage media may include non-volatile memory such as non-volatile random-access memory (NVRAM), one or more hard drives (e.g., magnetic drives or solid state drives), one or more removable flash drives or other removable media, or the like. Software stored on the non-transitory computer readable storage media may be executed on the processing circuitry of control circuitry **16** and/or **38**.

[0021] PTX device **12** may be a stand-alone power adapter (e.g., a wireless charging mat or charging puck that includes power adapter circuitry), may be a wireless charging mat or puck that is connected to a power adapter or other equipment by a cable, may be an electronic device (e.g., a laptop computer, a desktop computer, a computer monitor containing an embedded computer, a tablet computer, a cellular telephone, a media player, or other handheld or portable electronic device, a smaller device such as a wristwatch device, a pendant device, a headphone or earpiece device, a device embedded in eyeglasses, goggles, or other equipment worn on a user's head, or other wearable or miniature device, a television, a computer display that does not contain an embedded computer, a gaming device, a navigation device, a wireless internet-connected voice-controlled speaker, a home entertainment device, a remote control device, a gaming controller, a peripheral user input device, a wireless base station or access point, equipment that implements the functionality of two or more of these devices, or other electronic equipment), may be equipment that has been incorporated into furniture, a vehicle, or other system, may be a removable battery case, or may be other wireless power transfer equipment.
[0022] PRX device **24** may be an electronic device such as a laptop computer, a desktop computer, a computer monitor containing an embedded computer, a tablet computer, a cellular telephone, a media player, or other handheld or portable electronic device, a smaller device such as a wristwatch device, a pendant device, a headphone or earpiece device, a device embedded in eyeglasses, goggles, or other equipment worn on a user's head, or other wearable or miniature device, a wireless tracking tag, a television, a computer display that does not contain an embedded computer, a gaming device, a navigation device, a wireless internet-connected voice-controlled speaker, a home entertainment device, a remote control device, a gaming controller, a peripheral user input device, a wireless base station or access point, equipment that implements the functionality of two or more of these devices, or other electronic equipment.
[0023] PTX device **12** may be connected to a wall outlet (e.g., an alternating current power source), may be coupled to a wall outlet via an external power adapter, may have a battery for supplying power, and/or may have another source of power. In implementations where PTX device **12** is coupled to a wall outlet via an external power adapter, the adapter may have an alternating-current (AC) to direct-current (DC) power converter that converts AC power from a wall outlet or other power source into DC power. If desired, PTX device **12** may include a DC-DC power converter for converting the DC power between different DC voltages. Additionally or alternatively, PTX device **12** may include an AC-DC power converter that generates the DC power from the AC power provided by the wall outlet (e.g., in implementations where PTX device **12** is connected to the wall outlet without an external power adapter). DC power may be used to power control circuitry **16**. During operation, a controller in control circuitry **16** uses power transmitting circuitry **22** to transmit wireless power to power receiving circuitry **46** of PRX device **24**.
[0024] Power transmitting circuitry **22** may have switching circuitry, such as inverter circuitry **26** formed from transistors, that are turned on and off based on control signals provided by control circuitry **16** to create AC current signals through one or more wireless power transmitting coils such as wireless power transmitting coil(s) **32**. These coil drive signals cause coil(s) **32** to transmit wireless power. In implementations where coil(s) **32** include multiple coils, the coils may be disposed on a ferromagnetic structure, arranged in a planar coil array, or may be arranged to form a cluster of coils (e.g., two or more coils, 5-10 coils, at least 10 coils, 10-30 coils, fewer than 35 coils, fewer than 25 coils, or other suitable number of coils). In some implementations, PTX device **12** includes only a single coil **32**.
[0025] As the AC currents pass through one or more coils **32**, alternating-current electromagnetic (e.g., magnetic) fields (wireless power signals **44**) are produced that are received by one or more corresponding receiver coils such as coil(s) **48** in PRX device **24**. In other words, one or more of coils **32** is inductively coupled to one or more of coils **48**. PRX device **24** may have a single coil **48**, at least two coils **48**, at least three coils **48**, at least four coils **48**, or another suitable number of

coils **48**. When the alternating-current electromagnetic fields are received by coil(s) **48**, corresponding alternating-current currents are induced in coil(s) **48**. The AC signals that are used in transmitting wireless power may have any desired frequency (e.g., 100-400 kHz, 1-100 MHz, between 1.7 MHz and 1.8 MHz, less than 2 MHz, between 100 kHz and 2 MHz, etc.). Rectifier circuitry such as rectifier circuitry **50**, which contains rectifying components such as synchronous rectification transistors arranged in a bridge network, converts received AC signals (received alternating-current signals associated with wireless power signals **44**) from one or more coils **48** into DC voltage signals for powering PRX device **24**. Wireless power signals **44** are sometimes referred to herein as wireless power **44** or wireless charging signals **44**. Coils **32** are sometimes referred to herein as wireless power transfer coils **32**, wireless charging coils **32**, or wireless power transmitting coils **32**. Coils **48** are sometimes referred to herein as wireless power transfer coils **48**, wireless charging coils **48**, or wireless power receiving coils **48**.

[0026] The DC voltage produced by rectifier circuitry **50** (sometime referred to as rectifier output voltage Vrect) may be used in charging a battery such as battery **34** and may be used in powering other components in PRX device **24** such as control circuitry **38**, input-output (I/O) devices **54**, etc. PTX device **12** may also include input-output devices such as input-output devices **28**. Input-output devices **54** and/or input-output devices **28** may include input devices for gathering user input and/or making environmental measurements and may include output devices for providing a user with output.

[0027] As examples, input-output devices **28** and/or input-output devices **54** may include a display (screen) for creating visual output, a speaker for presenting output as audio signals, light-emitting diode status indicator lights and other light-emitting components for emitting light that provides a user with status information and/or other information, haptic devices for generating vibrations and other haptic output, and/or other output devices. Input-output devices **28** and/or input-output devices **54** may also include sensors for gathering input from a user and/or for making measurements of the surroundings of WPT system **8**.

[0028] The example in FIG. **1** of PRX device **24** including battery **34** is illustrative. More generally, an electronic device may include a power storage device **34**. Power storage device **34** may be a battery, or may be, for example, a supercapacitor that stores charge.

[0029] PTX device **12** and PRX device **24** may communicate wirelessly using in-band or out-of-band communications. Implementations using in-band communication may utilize, for example, frequency-shift keying (FSK) and/or amplitude-shift keying (ASK) techniques to communicate in-band data between PTX device **12** and PRX device **24**. Wireless power and in-band data transmissions may be conveyed using coils **32** and **48** concurrently. When PTX **12** sends in-band data to PRX **24**, wireless transceiver (TX/RX) circuitry **20** may modulate wireless charging signal **44** to impart FSK or ASK communications, and wireless transceiver circuitry **40** may demodulate the wireless charging signal **44** to obtain the data that is being communicated. When PRX **24** sends in-band data to PTX **12**, wireless transceiver (TX/RX) circuitry **40** may modulate wireless charging signal **44** to impart FSK or ASK communications, and wireless transceiver circuitry **20** may demodulate the wireless charging signal **44** to obtain the data that is being communicated.

[0030] Implementations using out-of-band communication may utilize, for example, hardware antenna structures and communication protocols such as Bluetooth or NFC to communicate out-of-band data between PTX device **12** and PRX device **24**. Power may be conveyed wirelessly between coils **32** and **48** concurrently with the out-of-band data transmissions. Wireless transceiver circuitry **20** may wirelessly transmit and/or receive out-of-band signals to and/or from PRX device **24** using an antenna such as antenna **56**. Wireless transceiver circuitry **40** may wirelessly transmit and/or receive out-of-band signals to and/or from PTX device **12** using an antenna such as antenna **58**.

[0031] Each one of housing **30** and housing **52** may be formed from plastic, metal, fiber-composite materials such as carbon-fiber materials, wood and other natural materials, glass, other materials, and/or combinations of two or more of these materials.

[0032] The example in FIG. **1** of PTX **12** transmitting wireless power and PRX **24** receiving wireless power is merely illustrative. PTX **12** may optionally be capable of receiving wireless power signals using coil(s) **32** and PRX **24** may optionally be capable of transmitting wireless power signals using coil(s) **48**. When a device is capable of both transmitting and receiving wireless power signals, the device may include both an inverter and a rectifier.
[0033] FIG. **2** is a circuit diagram of illustrative wireless charging circuitry for system **8**. As shown in FIG. **2**, circuitry **22** may include inverter circuitry such as one or more inverters **26** or other drive circuitry that produces wireless power signals that are transmitted through an output circuit that includes one or more coils **32** and capacitors such as capacitor **70**. In some embodiments, device **12** may include multiple individually controlled inverters **26**, each of which supplies drive signals to a respective coil **32**. In other embodiments, an inverter **26** is shared between multiple coils **32** using switching circuitry.
[0034] During operation, control signals for inverter(s) **26** are provided by control circuitry **16** at control input **74**. A single inverter **26** and single coil **32** is shown in the example of FIG. **2**, but multiple inverters **26** and multiple coils **32** may be used, if desired. In a multiple coil configuration, switching circuitry (e.g., multiplexer circuitry) may be used to couple a single inverter **26** to multiple coils **32** and/or each coil **32** may be coupled to a respective inverter **26**. During wireless power transmission operations, transistors in one or more selected inverters **26** are driven by AC control signals from control circuitry **16**. The relative phase between the inverters may be adjusted dynamically (e.g., a pair of inverters **26** may produce output signals in phase or out of phase).
[0035] The application of drive signals using inverter(s) **26** (e.g., transistors or other switches in circuitry **22**) causes the output circuits formed from selected coils **32** and capacitors **70** to produce alternating-current electromagnetic fields (signals **44**) that are received by wireless power receiving circuitry **46** using a wireless power receiving circuit formed from one or more coils **48** and one or more capacitors **72** in device **24**.
[0036] Rectifier circuitry **50** is coupled to one or more coils **48** and converts received power from AC to DC and supplies a corresponding direct current output voltage Vrect across rectifier output terminals **76** for powering load circuitry in device **24** (e.g., for charging battery **34**, for powering a display and/or other input-output devices **54**, and/or for powering other components).
[0037] Quality factor is a dimensionless unit that represents ohmic losses of a wireless power transfer coil. To improve efficiency of wireless power transfer, it may be desirable for wireless power transfer coils in system **8** to have as high a quality factor (Q) as possible. A high quality factor for the coil means lower losses, and therefore improved efficiency during wireless power transfer operations. Lowering the resistance associated with a coil increases the quality factor for that coil.
[0038] To reduce the resistance and increase the quality factor associated with the wireless power transfer coils in system **8**, the wireless power transfer coils may be formed using a wire bundle that comprises a plurality of insulated conductive wires. For simplicity, a coil **32** in PTX **12** will be described in detail below. However, it should be understood that the descriptions for coil **32** also apply to coil **48** in PRX **24**. Using a plurality of insulated conductive wires in a wire bundle for coil **32** may help mitigate both the skin effect and proximity effect.
[0039] Skin effect causes alternating current to concentrate near the surface of a conductor, reducing its effective cross-sectional area and increasing resistance. Using multiple individually insulated wires grouped together disperses the current across the strands and reduces the skin effect. This reduces power loss and enhances the efficiency of the wireless power transfer system. Proximity effect is a phenomenon that occurs in conductors carrying alternating current (AC) when they are placed close to each other. In particular, the magnetic field generated by the current induces eddy currents in nearby conductors. The proximity effect can lead to increased resistance and power loss.
[0040] To mitigate increased resistance caused by the skin effect and the proximity effect, the wire

bundle for coil **32** may have the arrangement shown in FIGS. **3-11**. As shown in FIG. **3**, coil **32** may be formed from a wire bundle **102** that includes a plurality of wire units **104**, a plurality of wire subunits **106**, and a plurality of insulated conductive wires **108**. In the illustrated example, a plurality of insulated conductive wires **108** may be grouped together to form a single respective wire subunit **106**. A plurality of wire subunits **106** may be grouped together to form a single respective wire unit **104**. A plurality of wire units **104** may be grouped together to form wire bundle **102**. In the example of FIG. **3**, there are seven insulated conductive wires **108** in each wire subunit **106**, there are five wire subunits **106** in each wire unit **104**, and there are four wire units **104** in wire bundle **102**.

[0041] For simplicity of the drawing, the individual wire subunits **106** are only explicitly depicted for a single wire unit **104**. However, it should be understood that each wire unit includes a plurality of wire subunits **106**. Similarly, for simplicity of the drawing, the individual wires **108** are only explicitly depicted for a single wire subunit **106**. However, it should be understood that each wire subunit includes a plurality of wires **108**.

[0042] To mitigate resistance increases caused by the skin effect, each wire subunit may have less than eight insulated conductive wires **108**. Including seven wires or less of equal size in each wire subunit results in, at most, one wire in the subunit that is not at an outermost periphery of the wire subunit. In the example of FIG. **3**, wire subunit **106** has a single central wire that is surrounded by six wires at the outermost periphery of the wire subunit.

[0043] FIG. **4** shows a top view of wireless power transfer coil **32** with windings of wire bundle **102** arranged in a plurality of turns **110**. Each turn **110** refers to a loop of wire bundle **102** around the circumference of coil **32**. There may be a single layer of turns or multiple layers of turns. The number of layers of turns may be consistent between the inner diameter (ID) of coil **32** and the outer diameter (OD) of coil **32**. In one possible arrangement, coil **32** may include one layer of ten turns (e.g., **10** turns total arranged in a single layer). In another possible arrangement, shown in FIG. **4**) coil **32** may include two layers of five turns (e.g., **10** turns total arranged in two layers).

[0044] Coil **32** may have first and second leads **112** at the inner diameter and/or outer diameter of the coil. Coil **32** may have a geometric center C. FIG. **4** shows an example where leads **112-1** and **112-2** (on opposing ends of the windings of wire bundle **102**) are formed at the outer diameter of coil **32**. In this example, there are consistently two layers of turns between the inner diameter and the outer diameter of the coil. The first lead **112-1** may be electrically connected to a first end of wire bundle **102** which is part of a first layer of turns (not explicitly shown in FIG. **4**) and second lead **112-2** may be electrically connected to a second end of wire bundle **102** which is part of a second layer of turns. Both the first and second ends of wire bundle **102** are at the OD.

[0045] In the example of FIG. **4**, coil **32** has a circular perimeter for both the inner diameter and outer diameter. This example is merely illustrative. If desired, the inner diameter and/or outer diameter of the coil may have an elliptical perimeter and/or perimeter of another desired shape. The coil may surround a central opening.

[0046] Each wire subunit **106**, wire unit **104**, and wire bundle **102** may be twisted during the formation of wire bundle **102**.

[0047] After grouping insulated conductive wires together to form a wire subunit **106**, the wire subunit may be twisted (e.g., one end of the wire subunit is rotated while the other end of the wire subunit is fixed or rotated the opposite direction). Twisting the wire subunit causes the plurality of insulated conductive wires **108** that comprise the wire subunit **106** to twist along a length of wire subunit **106**.

[0048] After grouping wire subunits **106** together to form a wire unit **104**, the wire unit may be twisted (e.g., one end of the wire unit is rotated while the other end of the wire unit is fixed or rotated the opposite direction). Twisting the wire unit causes the plurality of wire subunits **106** that comprise the wire unit **104** to twist along a length of wire unit **104**.

[0049] After grouping wire units **104** together to form a wire bundle **102**, the wire bundle may be twisted (e.g., one end of the wire bundle is rotated while the other end of the wire bundle is fixed or rotated the opposite direction). Twisting the wire bundle causes the plurality of wire units **104** that comprise the wire bundle **102** to twist along a length of wire bundle **102**.

[0050] Twisting each wire subunit along a length of the wire subunit causes the radial position of the six wires **108** at the outermost periphery of each wire subunit to change as a function of length along that wire subunit. This is demonstrated in FIGS. **5**A-**5**C. FIG. **5**A is a cross-sectional side view of a single wire subunit **106** at a first point P.sub.1 along the wire bundle. FIG. **5**B is a cross-sectional side view of a single wire subunit **106** at a second point P.sub.2 along the wire bundle. FIG. **5**C is a cross-sectional side view of a single wire subunit **106** at a third point P.sub.3 along the wire bundle. As shown in FIGS. **5**A-**5**C, the radial position of a given wire **108′** within wire subunit **106** is different at the different points.

[0051] FIG. **5**A further shows how each wire **108** may have a respective diameter **130**. Diameter **30** may be between 20 microns and 100 microns, between 25 microns and 35 microns, between 45 microns and 55 microns, less than 100 microns, less than 70 microns, greater than 20 microns, etc. FIG. **5**A further shows how each wire **108** may have a conductive portion **108-**C and an insulating portion **108-**I that extends around the circumference of the conductive portion **108**-C. The conductive portion **108-**C of each wire may be formed from copper or any other desired conductive material. The insulating portion **108-**I of each wire may be a coating and may be formed from any desired insulating material.

[0052] For each wire unit, twisting that wire unit along a length of the wire unit causes the radial position of the five wire subunits **106** to change as a function of length along the wire unit. This is demonstrated in FIGS. **6**A-**6**C. FIG. **6**A is a cross-sectional side view of a single wire unit **104** at a first point P.sub.1 along the wire bundle. FIG. **6**B is a cross-sectional side view of a single wire unit **104** at a second point P.sub.2 along the wire bundle. FIG. **6**C is a cross-sectional side view of a single wire unit **104** at a third point P.sub.3 along the wire bundle. As shown in FIGS. **5**A-**5**C, the radial position of a given wire **106′** within wire unit **104** is different at the different points.

[0053] Twisting the wire bundle along a length of the wire bundle causes the radial position of the four wire units **104** to change as a function of length along the wire bundle. This is demonstrated in FIGS. **7**A-**7**C. FIG. **7**A is a cross-sectional side view of wire bundle **102** at a first point P.sub.1 along the wire bundle. FIG. **7**B is a cross-sectional side view of wire bundle **102** at a second point P.sub.2 along the wire bundle. FIG. **7**C is a cross-sectional side view of wire bundle **102** at a third point P.sub.3 along the wire bundle. As shown in FIGS. **7**A-**7**C, the radial position of a given wire unit **104′** within wire bundle **102** is different at the different points.

[0054] Forming the wire bundle using insulated conductive wires that are twisted to form wire subunits, which are twisted to form wire units, which are twisted to form a wire bundle may be a cost effective way to increase the variance in the position of each insulated conductive wire along the length of the wire bundle. Increasing the variance in the position of each insulated conductive wire along the length of the wire bundle may mitigate the proximity effect and accordingly decrease the resistance of coil **32** and increase the quality factor of coil **32**.

[0055] In one example, the wire subunit **106** from FIGS. **5**A-**5**C is the wire subunit **106′** in FIGS. **6**A-**6**C and the wire unit **104** from FIGS. **6**A-**6**C is the wire unit **104′** in FIGS. **7**A-**7**C. FIGS. **8**A-**8**C show the variance in position of insulated conductive wire **108′** from FIGS. **5**A-**5**C in this example. FIG. **8**A is a cross-sectional side view of wire bundle **102** at a first point P.sub.1 along the wire bundle. FIG. **8**B is a cross-sectional side view of wire bundle **102** at a second point P.sub.2 along the wire bundle. FIG. **8**C is a cross-sectional side view of wire bundle **102** at a third point P.sub.3 along the wire bundle. As shown, the position of wire **108′** within the cross-section of wire bundle **102** may vary as a function of length of the wire bundle. Because each wire subunit, each wire unit, and the wire bundle are all twisted, each given insulated conductive wire may be at any given position within the cross-section of the wire bundle at any given point along a length of the wire bundle.

[0056] In the example of FIG. **3**, wire bundle **102** has four wire units **104**, each wire unit **104** has five wire subunits **106**, and each wire subunit **106** has seven wires **108** (e.g., a 4×5×7 arrangement). This example is merely illustrative. In another possible arrangement, wire bundle **102** has five wire units **104**, each wire unit **104** has five wire subunits **106**, and each wire subunit **106** has seven wires **108** (e.g., a 5×5×7 arrangement). In another possible arrangement, wire bundle **102** has four wire units **104**, each wire unit **104** has six wire subunits **106**, and each wire subunit **106** has seven wires **108** (e.g., a 4×6×7 arrangement). Other possible arrangements include a 6×6×6 arrangement, a 6×6×7 arrangement, a 6×7×6 arrangement, a 6×7×7 arrangement, etc.

[0057] The windings of coil **32** may include any desired number of turns of wire bundle **102** (e.g., three or more turns, eight or more turns, ten or more turns, eleven or more turns, twelve or more turns, twenty or more turns, fifty or more turns, etc.). Wire bundle **102** may include any desired number of wire units (e.g., two or more wire units, three or more wire units, four or more wire units, five or more wire units, six or more wire units, seven or more wire units, less than ten wire unites, less than eight wire units, etc.). Each wire unit **104** may include any desired number of wire subunits (e.g., two or more wire subunits, three or more wire subunits, four or more wire subunits, five or more wire subunits, six or more wire subunits, seven or more wire subunits, less than ten wire subunits, less than eight wire subunits, etc.). Each wire subunit **106** may include any desired number of wires **108** (e.g., two or more wires, three or more wires, four or more wires, five or more wires, six or more wires, seven wires or less, six wires or less, five wires or less, etc.).

[0058] FIG. **9** is a cross-sectional side view of an illustrative wireless charging system with PTX **12** and PRX **24**. In the example of FIG. **9**, PRX **24** includes a single coil **48** and PTX **12** includes a single coil **32**. Coils **32** and **48** may each be formed from wire bundles having the arrangement of FIG. **3**.

[0059] As shown in FIG. **9**, coil **32** may be positioned within a housing **30**. Housing **30** may include one or more housing structures (e.g., formed from plastic, metal, glass, sapphire, and/or other desired materials). Similarly, coil **48** may be positioned within a housing **52**. Housing **52** may include one or more housing structures (e.g., formed from plastic, metal, glass, sapphire, and/or other desired materials). Housing **30** may have a surface **30**-C with concave curvature (sometimes referred to as concave surface **30**-C) whereas housing **52** may have a surface **52**-C with convex curvature (sometimes referred to as convex surface **52**-C). Surface **30**-C may have curvature that conforms to the curvature of surface **52**-C.

[0060] As shown in FIG. **9**, coil **48** may be positioned on magnetic core **114** and coil **32** may be positioned on magnetic core **116**. The magnetic cores **114** and **116** may be formed from a soft magnetic material such as ferrite. The magnetic cores may have a high magnetic permeability, allowing them to guide the magnetic fields in the system. The example of using ferrite cores is merely illustrative. Other ferromagnetic and/or ferrimagnetic materials such as iron, mild steel, mu-metal (a nickel-iron alloy), a nanocrystalline magnetic material, rare earth metals, or other magnetic materials having a sufficiently high magnetic permeability to guide magnetic fields in the system may be used for one or more of the cores if desired. The magnetic cores may sometimes be referred to as ferrimagnetic cores. Each one of magnetic cores **114** and **116** may be a single piece or made from separate pieces. The cores may be molded, sintered, formed from laminations, formed from particles (e.g., ceramic particles) distributed in a polymer, or manufactured by other processes.

[0061] PTX **12** may include a magnetic alignment structure **120** and PRX **24** may include a magnetic alignment structure **118**. FIG. **9** shows an example where additional input-output devices **54** are interposed between magnetic alignment structure **118** and surface **52**-C. Magnetic alignment structures **118** and **120** may be permanent magnets (e.g., formed from hard magnetic materials that retain their magnetism over time) or other magnetic structures. During operation of wireless charging system, magnetic alignment structures **118** and **120** may attract one another (e.g., magnetically couple). When magnetic alignment structure **120** is magnetically coupled to magnetic alignment structure **118**, concave surface **30**-C may conform to and be in direct contact with the convex surface **52**-C.

[0062] Core **114** may include a sloped surface that approximately matches the slope and/or curvature of surface **52**-C (e.g., at a point at surface **52**-C that overlaps coil **48** in the Z-direction). As shown in FIG. **9**, PRX **24** may include one or more planar components **122**. The planar components may include, as examples, a printed circuit board, a display panel configured to emit light in the positive Z-direction, a metal plate (e.g., to provide mechanical strength), etc. The planar components **122** are parallel to the XY-plane in FIG. **9**. Core **114** may have a first surface **114**-P that is parallel to planar components **122** and the XY-plane. Core **114** also includes a second surface **114**-S that is at a non-parallel, non-orthogonal angle relative to planar components **122** and the XY-plane. Coil **48** is positioned on surface **114**-S of core **114**. Surface **114**-S may sometimes be referred to as a sloped surface. The sloped surface may approximately match the slope and/or curvature of the portion of surface **52**-C that overlaps surface **114**-S in the Z-direction.

[0063] Core **116** may include a sloped surface that approximately matches the slope and/or curvature of surface **30**-C (e.g., at a point at surface **30**-C that overlaps coil **32** in the Z-direction). Housing **30** of PTX **12** may have a rear surface **30**-R that is parallel to the XY-plane and planar components **122** when PTX **12** is attached to PRX **24**. Core **116** may have a first surface **116**-P that is parallel to rear surface **30**-R and the XY-plane. Core **116** also includes a second surface **116**-S that is at a non-parallel, non-orthogonal angle relative to rear surface **30**-R and the XY-plane. Coil **32** is positioned on surface **116**-S of core **114**. Surface **116**-S may sometimes be referred to as a sloped surface. The sloped surface may approximately match the slope and/or curvature of the portion of surface **30**-C that overlaps surface **116**-S in the Z-direction.

[0064] The angle between sloped surface **114**-S and the XY-plane may be greater than 3 degrees, greater than 5 degrees, greater than 10 degrees, greater than 15 degrees, etc. The angle between sloped surface **116**-S and the XY-plane may be greater than 3 degrees, greater than 5 degrees, greater than 10 degrees, greater than 15 degrees, etc. Surfaces **114**-S and **116**-S may be parallel or approximately parallel (e.g., within 10 degrees of parallel, within 5 degrees of parallel, within 3 degrees of parallel, etc.) when magnetic alignment structure **120** is magnetically coupled to magnetic alignment structure **118**.

[0065] FIG. **9** shows how the number of layers of turns is wound in a consistent manner between the inner diameter of coils **32**/**48** and the outer diameter of coils **32**/**48**. In the example of FIG. **9**, there are consistently two layers of turns between the inner diameter of coils **32**/**48** and the outer diameter of coils **32**/**48**. Maintaining a consistent number of layers of turns between the inner diameter and outer diameter mitigates parasitic capacitance that otherwise increases the resistance of the coils. The example of two layers of turns in FIG. **9** is merely illustrative. There may instead by exactly one layer of turns between the inner diameter of coils **32**/**48** and the outer diameter of coils **32**/**48**, exactly three layers of turns between the inner diameter of coils **32**/**48** and the outer diameter of coils **32**/**48**, or any other desired consistent number of layers of turns between the inner diameter of coils **32**/**48** and the outer diameter of coils **32**/**48**.

[0066] Each one of ferrite cores **114** and **116** may be ring-shaped, as shown in FIG. **10**. The ring-shaped ferrite cores have a central opening that is aligned with a respective magnetic alignment structure. Magnetic alignment structure **118** is formed in the central opening of ferrite core **114** (and the central opening of coil **48**). Magnetic alignment structure **120** is formed in the central opening of ferrite core **116** (and the central opening of coil **32**).

[0067] In the example of FIG. **9**, each one of cores **114** and **116** includes an inner lip and an outer lip. FIG. **9** shows how core **116** includes an inner lip **132**-I and an outer lip **132**-O. Each lip extends past surface **116**-S in the positive Z-direction (e.g., in the direction of coil **32** and in the direction of the interface between the PTX and the PRX when the devices are attached). Coil **32** is therefore interposed between lips **132**-I and **132-0**. The coils may not extend past the upper surfaces of lips **132** in the positive Z-direction (e.g., in the direction of the interface between the PTX and the PRX when the devices are attached).

[0068] FIG. **9** shows how core **114** includes an inner lip **134-**I and an outer lip **134-**O. Each lip extends past surface **114-**S in the negative Z-direction (e.g., in the direction of coil **48** and in the direction of the interface between the PTX and the PRX when the devices are attached). Coil **48** is therefore interposed between lips **134-**I and **134-0**. The coils may not extend past the upper surfaces of lips **134** in the negative Z-direction (e.g., in the direction of the interface between the PTX and the PRX when the devices are attached).
[0069] If desired, one or both of lips **132-**I and **132-**O may be omitted from core **116**. FIG. **11**A shows an example where inner lip **132-**I is omitted and only outer lip **132-**O is included in core **116**. Lip **132-**O extends past surface **116-**S in the positive Z-direction (e.g., in the direction of coil **32** and in the direction of the interface between the PTX and the PRX when the devices are attached). On the inner side of the core, no portion of the core extends past surface **116-**S in the positive Z-direction (e.g., in the direction of coil **32** and in the direction of the interface between the PTX and the PRX when the devices are attached).
[0070] FIG. **11**B shows an example where both inner and outer lips **132-**I and **132-**O are omitted. In this example, no portion of the core (on either the inner diameter side or outer diameter side) extends past surface **116-**S in the positive Z-direction (e.g., in the direction of coil **32** and in the direction of the interface between the PTX and the PRX when the devices are attached). Similar to as described in connection with core **116**, one or both of lips **134-**I and **134-**O may be omitted from core **114**.
[0071] The foregoing is merely illustrative and various modifications can be made to the described embodiments. The foregoing embodiments may be implemented individually or in any combination.

Claims

1. A wireless power transmitting device configured to provide wireless power to a wireless power receiving device, the wireless power transmitting device comprising: a wireless power transfer coil; and inverter circuitry coupled to the wireless power transfer coil, wherein: the wireless power transfer coil comprises windings of a wire bundle; the wire bundle comprises a plurality of wire units that twist along a length of the wire bundle; each wire unit of the plurality of wire units comprises wire subunits that twist along a length of that wire unit; and each wire subunit of the plurality of wire subunits comprises a plurality of insulated conductive wires that twist along a length of that wire subunit.
2. The wireless power transmitting device of claim 1, wherein the wire bundle has three or more wire units.
3. The wireless power transmitting device of claim 2, wherein each wire unit has three or more wire subunits.
4. The wireless power transmitting device of claim 3, wherein each wire subunit has three or more insulated conductive wires.
5. The wireless power transmitting device of claim 4, wherein the wire bundle has less than eight wire units, wherein each wire unit has less than eight wire subunits, and wherein each wire subunit has less than eight insulated conductive wires.
6. The wireless power transmitting device of claim 1, wherein the wireless power transfer coil has a plurality of turns between an inner diameter of the wireless power transfer coil and an outer diameter of the wireless power transfer coil and wherein the wireless power transfer coil has first and second leads at the outer diameter.
7. The wireless power transmitting device of claim 1, wherein each insulated conductive wire has a diameter that is between 20 microns and 100 microns.
8. The wireless power transmitting device of claim 1, wherein each insulated conductive wire has a diameter that is between 25 microns and 35 microns.

9. The wireless power transmitting device of claim 1, wherein each insulated conductive wire has a diameter that is between 45 microns and 55 microns.
10. The wireless power transmitting device of claim 1, wherein the wireless power transfer coil has one or more layers of turns of the wire bundle between an inner diameter of the wireless power transfer coil and an outer diameter of the wireless power transfer coil, and wherein a total number of layers of the wire bundle is consistent between the inner diameter and the outer diameter.
11. The wireless power transmitting device of claim 10, wherein the total number of layers of turns of the wire bundle is greater than or equal to two.
12. The wireless power transmitting device of claim 1, further comprising: a ferrite core, wherein the wireless power transfer coil is a positioned on a surface of the ferrite core.
13. The wireless power transmitting device of claim 12, wherein the surface is a sloped surface.
14. The wireless power transmitting device of claim 12, wherein the surface is a first surface, wherein the ferrite core has a second, opposing surface, and wherein the first surface is at a non-parallel, non-orthogonal angle relative to the second surface.
15. The wireless power transmitting device of claim 12, wherein the ferrite core is ring-shaped.
16. The wireless power transmitting device of claim 12, wherein no portion of the ferrite core extends past the surface of the ferrite core in the direction of the wireless power transfer coil.
17. The wireless power transmitting device of claim 12, wherein the ferrite core has a first lip that extends past the surface of the ferrite core in the direction of the wireless power transfer coil, wherein the ferrite core has a second lip that extends past the surface of the ferrite core in the direction of the wireless power transfer coil, wherein the wireless power transfer coil is interposed between the first and second lips.
18. The wireless power transmitting device of claim 12, wherein the ferrite core has a central opening and wherein the wireless power transmitting device further comprises a permanent magnet in the central opening.
19. The wireless power transmitting device of claim 18, wherein the wireless power transfer coil is configured to provide the wireless power to an additional wireless power transfer coil in the wireless power receiving device during wireless charging operations, wherein the permanent magnet is configured to magnetically attract the wireless power receiving device, and wherein the surface of the ferrite core is parallel to an additional surface of an additional ferrite core associated with the additional wireless power transfer coil when the permanent magnet magnetically attracts the wireless power receiving device.
20. A wireless power receiving device configured to receive wireless power from a wireless power transmitting device, the wireless power receiving device comprising: a wireless power transfer coil; and rectifier circuitry coupled to the wireless power transfer coil, wherein: the wireless power transfer coil comprises windings of a wire bundle; the wire bundle comprises a plurality of wire units that twist along a length of the wire bundle; each wire unit of the plurality of wire units comprises wire subunits that twist along a length of that wire unit; and each wire subunit of the plurality of wire subunits comprises a plurality of insulated conductive wires that twist along a length of that wire subunit.