Wireless power system and method of operation

TECHNICAL FIELD

1. This invention relates generally to the wireless power field, and more specifically to a new and useful wireless power system and method of operation.

BRIEF DESCRIPTION OF THE FIGURES

1. FIGURE 1 is a schematic representation of an embodiment of a wireless power system.
2. FIGURE 2 is a schematic representation of an embodiment of a method of operation for a wireless power system.
3. FIGURE 3 is a schematic representation of an embodiment of the wireless power system integrated with a vehicle.
4. FIGURE 4A is a top view of a first specific example of the wireless power system integrated with an aerial vehicle.
5. FIGURES 4B–4C are an isometric view and an front view, respectively, of a second specific example of the wireless power system integrated with an aerial vehicle.
6. FIGURE 5 is a top view of a specific example of a dipole element of an example of the wireless power system.
7. FIGURE 6 is a schematic representation of an example of the wireless power system.
8. FIGURES 7A–7B are a top view and a bottom view, respectively, of a second specific example of the wireless power system.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

1. The following description of the preferred embodiments of the invention is not intended to limit the invention to these preferred embodiments, but rather to enable any person skilled in the art to make and use this invention.

1. Overview.

1. A wireless power system preferably includes one or more substrates and a wireless power receiver (e.g., as shown in FIGURE 1), wherein the wireless power receiver preferably includes one or more radio frequency (RF) absorption sheets. The system is preferably configured to be integrated with a device having one or more loads, more preferably wherein the system is configured to deliver electrical power to the one or more electrical loads. For example, the system can be integrated with a vehicle (e.g., as shown in FIGURE 3), preferably an aerial vehicle (e.g., rotary wing vehicle, such as a quadcopter), such as wherein the system is operable to provide electrical power to one or more electrical loads of (and/or attached to) the vehicle. However, the system can additionally or alternatively include any other suitable elements, have any other suitable functionality, and/or be integrated with any other suitable devices.
2. A method of operation for a wireless power system preferably includes receiving power wirelessly and/or delivering power to one or more electrical loads (e.g., as shown in FIGURE 2). The method can optionally include deploying the system, stowing the system, and/or configuring the system in any other suitable manner. The method is preferably performed using the wireless power system described herein, but can additionally or alternatively be performed using any other suitable system(s).

2. System.

2.1 Substrates.

1. Each substrate of the system preferably functions to support one or more RF absorption sheets, and can additionally or alternatively be configured to support any other suitable elements of the system. The substrate is preferably lightweight (e.g., employing a small amount of material, such as defining a structure with many voids and/or openings, rather than a continuous or substantially continuous sheet-like structure) and/or minimally occlusive (e.g., having significant open space such that the interference of the substrate with airflow, such as airflow driven by one or more rotary wings, is negligible, minimized, and/or below a threshold value), such as shown by way of example in FIGURES 4A–4C.
2. The substrate is preferably flexible. For example, the substrate can include (e.g., be made of) one or more flexible materials, such as flexible polymers (e.g., polyimide). However, the substrate can additionally or alternatively include any other suitable materials.
3. In some examples, the substrate includes one or more gridlines (e.g., flexible gridlines, such as made from or including one or more flexible polymers). For example, these gridlines can define a rectangular array (e.g., square array) with open space between the gridlines (e.g., as shown in FIGURES 4A and/or 4B).
4. The substrate can optionally include one or more frames (e.g., circumferential frames). In a first example, the substrate includes a rigid frame (e.g., which can function to retain the substrate in a particular configuration). In a second example, the substrate includes a flexible frame, such as a flexible frame configured to exert tensile forces on the interior material (e.g., on the flexible gridlines). In this example, the flexible frame can be operable to make the substrate tend toward an open arrangement (e.g., as opposed to a closed and/or stowed arrangement, such as a folded and/or rolled arrangement), such as a planar or substantially planar arrangement. However, the substrate can additionally or alternatively include any other suitable frames.
5. The substrate is preferably configured to attach mechanically to a device with which the system will be integrated, such as to a vehicle. As described above, the vehicle is preferably an aerial vehicle (e.g., rotary wing vehicle, such as a quadcopter), wherein the device is preferably configured to reduce interference with vehicle operation (e.g., minimize aerodynamic drag, minimize interference with rotary wing operations, such as minimizing occlusion of rotor downdraft, etc.). Further, the substrate is preferably configured to electrically connect to the device (e.g., vehicle) and/or the electrical equipment attached thereto (e.g., connecting an electrical output of the wireless power receiver to the device and/or electrical equipment attached thereto).
6. In some embodiments, the system (e.g., the substrate(s) thereof) can be operable to transition between a stowed configuration and a deployed configuration. In the stowed configuration, the system is preferably configured to reduce or minimize its effect on vehicle (e.g., aerial vehicle such as rotary wing vehicle) operation, such as reducing the system’s aerodynamic drag and/or interference with vehicle propulsion and/or control mechanisms (e.g., interference with airflow before and/or interaction with one or more wings and/or control surfaces, such as interference with airflow caused by rotation of one or more rotary wings). In examples, in the stowed configuration, the system (and/or elements thereof) can be folded, rolled, and/or otherwise stowed. In the deployed configuration, the system is preferably able to efficiently receive power wirelessly (e.g., while still ensuring that its effect on vehicle operation is sufficiently low), such as by being configured in a substantially flat or planar configuration and/or being configured in a substantially maximum area configuration (e.g., a configuration in which the footprint of the substrate and/or the impedance sheets have the maximum area possible, or close to the maximum area possible), having a frame in a substantially convex configuration, and/or the like. In examples, in the deployed configuration, the system (and/or elements thereof) can be unfolded, unrolled, and/or otherwise deployed. However, the system can additionally or alternatively be operable to transition between any other suitable configurations.
7. Further, the system can additionally or alternatively include any other suitable substrates having any suitable configurations and/or functionalities.

2.2 Wireless power receiver.

1. The wireless power receiver preferably functions to receive RF power transmitted wirelessly (e.g., transmitted via one or more propagating modes, preferably not via evanescent modes, but additionally or alternatively, via one or more evanescent modes). For example, the wireless power receiver can include one or more elements such as described in U.S. Patent Application 18,674,945, filed 27-MAY-2024 and titled “SYSTEM AND METHOD FOR WIRELESS POWER RECEPTION”, which is herein incorporated in its entirety by this reference (e.g., wherein the wireless power receiver includes the ‘system 100 for wireless power reception’ as described therein or any suitable elements thereof, such as wherein the wireless power receiver includes one or more ‘antennas 110’ and/or ‘RF–DC converters 130’ defined on the one or more substrates). In some examples, the wireless power receiver can be configured to operate such as described in U.S. Patent Application 18/891,137, filed 20-SEP-2024 and titled “METHOD AND SYSTEM FOR WIRELESS POWER DELIVERY”, which is herein incorporated in its entirety by this reference (e.g., wherein the wireless power receiver can be configured to operated such as described therein regarding the ‘receiver’).
2. The wireless power receiver preferably includes a plurality of RF impedance sheets, more preferably including exactly two such sheets. However, the wireless power receiver can alternatively include more than two impedance sheets, can include only a single impedance sheet, and/or can include any suitable number of impedance sheets.
3. Each impedance sheet is preferably attached to (e.g., defined on) a substrate of the system. In a first example, the receiver includes multiple impedance sheets defined on a single substrate (e.g., including two total sheets, each defined on an opposing side of a single substrate). In a second example, the receiver can include impedance sheets defined on different substrates (e.g., including one impedance sheet defined on each substrate, such as one sheet on each of two total substrates of the system). In a third example, the receiver can include both multiple sheets defined on a single substrate (e.g., defined on opposing sides of the substrate), and sheets defined on different substrates (e.g., wherein one or more additional substrates can each include a single impedance sheet, can each include two impedance sheets defined on opposing sides of the substrate, etc.). However, the sheets can additionally or alternatively be arranged on the substrate(s) in any other suitable manner.
4. The spacing defined between the impedance sheets (e.g., spacing between substantially parallel substantially planar sheets) is preferably small, as a reduced spacing between the sheets can function to achieve a high quality factor for the wireless power receiver (resulting in a correspondingly narrow bandwidth). For example, the spacing between the sheets can be defined by the thickness of a substrate on which two sheets are defined (e.g., on opposing sides of the substrate), such as being in a range of tens of microns (e.g., 10 µm, 20 µm, 50 µm, etc.). However, the impedance sheets can additionally or alternatively have any other suitable arrangement relative to each other.
5. Each impedance sheet preferably includes a plurality of RF elements, such as dipole elements (e.g., as shown in FIGURE 5), resonant elements (e.g., antenna elements), such as loop resonators, and the like. The RF elements are preferably arranged in a regular (or substantially regular) array, such as an array defined by the substrate (e.g., by the gridlines thereof), such as shown by way of example in FIGURES 7A–7B, which depict an RF impedance sheet including a two-by-two array of dipole elements. More generally, the RF elements preferably are arranged on (e.g., defined on) the substrate without occluding the open space defined by the substrate, and accordingly, the RF elements preferably are arranged substantially along any gridlines and/or other structures defined by the substrate (e.g., as shown in FIGURE 6). However, the RF elements can additionally or alternatively have any other suitable arrangement.
6. The RF elements (e.g., of a single impedance sheet or any suitable subset thereof) preferably define a connected array, wherein the different RF elements are electromagnetically coupled to each other. For example, an impedance sheet can include a plurality of dipole elements, each connected to neighboring dipoles at their ends (e.g., at the current nodes of the dipoles). The connected array preferably provides for DC coupling between the coupled elements, but more preferably does not provide for RF coupling between these elements (e.g., thereby preventing emergence of multi-mode functionality in the impedance sheet). To achieve such coupling, the connected array can include one or more additional structures (e.g., arranged at or near the current nodes at which the different elements are connected). In examples, these structures can include inductive structures (e.g., inductors configured to provide DC coupling, but not RF coupling), harmonic matching structures, such as structures configured to preserve odd harmonics, but destroy or substantially destroy even harmonics (e.g., one or more parasitic structures, such as notches, cuts, stubs, and the like), and/or any other suitable structures.
7. The RF elements of an impedance sheet can be connected (e.g., connected for DC, but preferably not for RF) in series and/or in parallel. For example, a plurality of RF elements can be connected in series to their neighbors along one direction of an array (e.g., wherein the array includes end-to-end connections between neighboring dipoles), wherein different sets of series-connected elements (e.g., different rows of series-connected dipoles) are connected in parallel. However, the impedance sheets can additionally or alternatively include any other suitable electrical couplings and/or connections.
8. The impedance sheets (and/or any suitable subset thereof, such as any two impedance sheets) are preferably configured to achieve substantially zero transmission and substantially unity absorption at a particular design wavelength (e.g., a specific RF wavelength). For example, the RF elements (of all sheets, of at least two sheets, any suitable subset of the RF elements of such sheets, etc.) are preferably tuned to achieve this impedance response. In one example, in which the wireless power receiver includes two impedance sheets, each including a connected array of dipoles, the dipole lengths of the first impedance sheet and the dipole lengths of the second impedance sheet can be treated as two separate parameters, and tuned to achieve the desired properties of substantially zero transmission and substantially unity absorption at the design wavelength (e.g., wherein the two impedance sheets can define a metamaterial, and the dipole length on the two sheets can be used as two degrees of freedom to achieve the appropriate permittivity and permeability for the desired response at the design wavelength). Note that for a receiver having a sufficiently high quality factor (e.g., achieved via a sufficiently small spacing between impedance sheets), the impedance sheets can be substantially transparent to RF frequencies away from the design wavelength, thereby preventing undesired interference of the wireless power receiver with RF transmissions sufficiently distinct from the design wavelength.
9. One or more of the impedance sheets can include one or more non-linear structures. These structures can function as one or more RF-to-DC converters (e.g., wherein the one or more non-linear structures define a class F converter in cooperation with one or more inductive and/or parasitic structures of the impedance sheets, such as structures defined in and/or between the RF elements). For example, the non-linear structures can include one or more diodes, transistors, and/or any other suitable structures. The non-linear structures preferably enable the wireless power receiver to deliver DC output power (e.g., to one or more connected electrical loads, such as a load of and/or attached to a device with which the wireless power receiver is integrated, such as to an aerial vehicle to which the wireless power receiver is attached).
10. However, the wireless power receiver can additionally or alternatively include any other suitable elements in any suitable arrangement.

3. Method.

1. As described above, the method of operation for a wireless power system preferably includes receiving power wirelessly and/or delivering power to one or more electrical loads, and can optionally include deploying the system, stowing the system, and/or configuring the system in any other suitable manner.
2. Receiving power wirelessly is preferably performed while the system is deployed (e.g., with the substrate(s) and/or impedance sheets in a substantially flat or planar configuration and/or in a substantially maximum area configuration, with the substrate frame in a substantially convex configuration, etc.). The power is preferably received via one or more propagating RF modes (but can additionally or alternatively be received via one or more evanescent RF modes and/or from any other suitable sources). For example, the power can be received from one or more transmitters configured to transmit power wirelessly (e.g., to the receiver) at the design wavelength (e.g., wherein receiving power wirelessly is preferably performed in response to the power being transmitted to the receiver). In some examples, receiving power wirelessly can be performed such as described in U.S. Patent Application 18,674,945, filed 27-MAY-2024 and titled “SYSTEM AND METHOD FOR WIRELESS POWER RECEPTION” and/or in U.S. Patent Application 18/891,137, filed 20-SEP-2024 and titled “METHOD AND SYSTEM FOR WIRELESS POWER DELIVERY”, each of which is herein incorporated in its entirety by this reference. However, the method can additionally or alternatively include receiving power wirelessly in any other suitable manner.
3. Delivering power to one or more electrical loads is preferably performed concurrently (or substantially concurrently) with receiving power wirelessly, more preferably wherein the power that is received wirelessly (or a significant fraction thereof, such as the majority thereof) is delivered to the one or more electrical loads. The power is preferably rectified (e.g., before or after being delivered, more preferably before); for example, the power can be received as RF power and can be rectified (e.g., at the system, such as within one or more of the impedance sheets) and then delivered to the one or more electrical loads as DC power (e.g., as described in U.S. Patent Application 18,674,945, filed 27-MAY-2024 and titled “SYSTEM AND METHOD FOR WIRELESS POWER RECEPTION”, which is herein incorporated in its entirety by this reference). The one or more electrical loads are preferably associated with (e.g., part of, integrated with, attached to, etc.) a vehicle (e.g., aerial vehicle, such as a quadcopter or other rotary wing vehicle) with which the system is integrated. For example, delivering power can include delivering the electrical power that was received wirelessly to an electrical system of an aerial vehicle with which the system is integrated (e.g., to a battery thereof). However, the method can additionally or alternatively include delivering power in any other suitable manner.
4. The method can optionally include deploying the system, such as by controlling the system (e.g., the substrate thereof) to switch to a deployed configuration. In examples, deploying the system can be performed in response to determining that a battery charge state is below a threshold value and/or will be reduced below a threshold value in less than a threshold amount of time, in response to determining that current and/or anticipated flight commands can be satisfied while the system is in the deployed configuration (e.g., determining that the deleterious effects of having the system in the deployed configuration, such as increased aerodynamic drag and/or interference with airflow from rotors, will not prevent satisfactory operation according to current and/or anticipated flight plans), in response to determining that a wireless power transmitter is available and/or within range (e.g., able to transmit power efficiently to the system), in response to receipt of a command to deploy and/or receive power (e.g., received from a controller, such as from a wireless power transmitter), and/or with any other suitable timing. However, the method can additionally or alternatively include deploying the system in any other suitable manner and/or with any other suitable timing.
5. The method can optionally include stowing the system, such as by controlling the system (e.g., the substrate thereof) to switch to a stowed configuration. In examples, stowing the system can be performed in response to determining that a battery charge state is above a threshold value, in response to determining that a wireless power reception event has ended (e.g., the system is no longer receiving power wirelessly, the amount of power being received wirelessly is less than a threshold amount, etc.), in response to determining that current and/or anticipated flight commands can not be satisfied or have a significant risk of not being able to be satisfied while the system is in the deployed configuration (e.g., determining that the deleterious effects of having the system in the deployed configuration, such as increased aerodynamic drag and/or interference with airflow from rotors, may prevent satisfactory operation according to current and/or anticipated flight plans), in response to determining that no wireless power transmitter is available and/or within range (e.g., able to transmit power efficiently to the system), in response to receipt of a command to stow and/or cease receiving power (e.g., received from a controller, such as from a wireless power transmitter), and/or with any other suitable timing. However, the method can additionally or alternatively include stowing the system in any other suitable manner and/or with any other suitable timing.
6. Further, the method can additionally or alternatively include any other suitable elements performed in any suitable manner.
7. Although omitted for conciseness, the preferred embodiments include every combination and permutation of the various system components and the various method processes. Furthermore, various processes of the preferred method can be embodied and/or implemented at least in part as a machine configured to receive a computer-readable medium storing computer-readable instructions. The instructions are preferably executed by computer-executable components preferably integrated with the system. The computer-readable medium can be stored on any suitable computer readable media such as RAMs, ROMs, flash memory, EEPROMs, optical devices (CD or DVD), hard drives, floppy drives, or any suitable device. The computer-executable component is preferably a general or application specific processing subsystem, but any suitable dedicated hardware device or hardware/firmware combination device can additionally or alternatively execute the instructions.
8. The FIGURES illustrate the architecture, functionality and operation of possible implementations of systems, methods and computer program products according to preferred embodiments, example configurations, and variations thereof. In this regard, each block in the flowchart or block diagrams may represent a module, segment, step, or portion of code, which comprises one or more executable instructions for implementing the specified logical function(s). It should also be noted that, in some alternative implementations, the functions noted in the block can occur out of the order noted in the FIGURES. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and computer instructions.
9. As a person skilled in the art will recognize from the previous detailed description and from the figures and claims, modifications and changes can be made to the preferred embodiments of the invention without departing from the scope of this invention defined in the following claims.

CLAIMS

We claim:

1. The invention as shown and/or described.