Position-insensitive long range inductive power transfer

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Abstract. This paper presents results of an improved inductive wireless power transfer system for reliable long range powering of sensors with milliwatt-level consumption. An ultra-low power flyback impedance emulator operating in open loop is used to present the optimal load to the receiver’s resonant tank. Transmitter power modulation is implemented in order to maintain constant receiver power and to prevent damage to the receiver electronics caused by excessive received voltage. Received power is steady up to 3 m at around 30 mW. The receiver electronics and feedback system consumes 3.1 mW and so with a transmitter input power of 163.3 W the receiver becomes power neutral at 4.75 m. Such an IPT system can provide a reliable alternative to energy harvesters for supplying power concurrently to multiple remote sensors.

1. Introduction
Far-field approaches to transferring power with electromagnetic fields over long distances (up to 10 m) suffer from many drawbacks that limit their potential to remotely power a network of sensors. Methods with dedicated transmitters that radiate power are generally quite inefficient. Employing antennas with narrow beam patterns can result in improvements in efficiency as the receivers are able to intercept a larger amount of the radiated energy. An example of these types of systems can be found in [1], where hundreds of µW could be transmitted over a distance of 1 m. However, the directivity of the antennas means that the freedom of movement of such receivers is severely restricted. Ambient RF energy harvesters are another candidate for far-field energy transfer; these do not require a separate transmitter as the energy is derived from mobile base stations, making them especially advantageous in urban environments. However, received power levels are limited to tens of µW as demonstrated in [2] with cm scale antennas.

Inductive power transfer (IPT) systems, which operate in the near field, are a particularly attractive alternative to existing far-field techniques. In a previous system [3], it was shown that more than 10 mW can be transferred to a load up to 6 m from the transmitter. An issue with this system, though, is that different levels of load current draw in the sensor node detuned the magnetic link, resulting in poor efficiency and a significant drop in received power. Also moving the receiver too close to the transmitter could cause damage to the receiver electronics due to excessive received voltage. This paper proposes an improved long-range IPT system for reliable long-range powering of sensors with milliwatt-level consumption. It overcomes the problems of the previous system by using an ultra-low power switch-mode impedance emulator to present a constant impedance, and wireless feedback to modulate the transmitter power.
2. Receiver impedance emulation

For IPT systems, the amount of power transferred is maximised when an optimal load is connected to the receiver’s resonant tank. In the case of a long-range system where coupling between the transmitter and the receiver is extremely weak, the optimal load $Z_{load}$ can be easily determined as it is simply the conjugate match of the receiver’s resonant tank at the operating frequency [3]. Thus,

$$Z_{load} = \left( \frac{1}{\frac{1}{r_{RX} + j\omega L_{RX}} + j\omega C} \right)^*$$

where $r_{RX}$ is the parasitic RX coil resistance, $L_{RX}$ is the RX coil inductance, $C$ is the RX tuning capacitance for the resonant tank, $\omega$ is the angular operating frequency of the system, and $(x)^*$ denotes the complex conjugate of $x$.

Different levels of sensor node activity, resulting in variations in load current draw, mean that the load impedance changes over time, detuning the magnetic link. This leads to poor efficiency and a collapse in power available to the load. Therefore, a method of impedance emulation is required so that a constant optimal impedance is always presented to the output of the bridge rectifier in the receiver. Switch-mode DC-to-DC converters can be controlled in such a way that the desired impedance is presented. An open-loop converter control scheme is preferred as the power consumption requirements can be minimised. Both the buck-boost converter (Figure 1a) and the flyback converter (Figure 1b) are candidates for an open-loop impedance emulation circuit [4], which is to be inserted between the bridge rectifier and the sensor node.

![Open-loop impedance emulator topologies](image)

Figure 1: Open-loop impedance emulator topologies

2.1. Buck-boost topology

A buck-boost converter operating in discontinuous conduction mode and with open-loop control (i.e. fixed duty cycle) can act as an impedance emulator. Buck-boost circuits were used in [5] as part of the power processing circuitry for MEMS energy harvester in order to present the correct electrical impedance to the generator. For the long-range IPT system, a Li-ion coin cell is placed across the output of the impedance emulator in order to fix the output voltage at $V_{batt} = 3.7$ V. Any excess power not consumed by the sensor node is stored in the cell, whilst the cell can also be used to power the sensor node and impedance emulator if the receiver is out of the transmit power range.

To determine the impedance seen at the input of a buck-boost converter in discontinuous conduction mode, the average current into the converter $I_{i,\text{average}}$ when a voltage $V_i$ is applied at the input is first calculated:

$$I_{i,\text{peak}} = \frac{V_i}{L} t_{on} = \frac{V_i}{L} \delta \implies I_{i,\text{average}} = \frac{1}{2} I_{i,\text{peak}} \frac{t_{on}}{T} = \frac{1}{2} I_{i,\text{peak}} \delta = \frac{V_i \delta^2}{2LT}$$
where $f = \frac{1}{T}$ is the switching frequency of the MOSFET, $L$ is the value of the inductor, $t_{on}$ is the time during which the MOSFET is switched on, and $\delta = \frac{t_{on}}{T}$ is the duty cycle of the switching signal.

Therefore, the input impedance of the buck-boost converter is:

$$R_{emulated} = \frac{V_i}{I_{average}} = \frac{2fL}{\delta^2}$$ \hspace{1cm} (2)

The buck-boost circuit remains in discontinuous conduction mode only if the current in the inductor can return to zero during the MOSFET off time. From this we obtain an upper bound for the operating duty cycle:

$$\frac{V_i}{L} t_{on} \leq \frac{V_o}{L} (T - t_{on}) \implies \delta \leq \frac{1}{1 + \frac{V_i}{V_o}}$$ \hspace{1cm} (3)

In this system, $V_o$ is fixed at 3.7 V by the battery, and the maximum expected $V_i$ is 55 V (higher voltages could damage the receiver electronics). From Equation 3, the maximum duty cycle for which the converter remains in discontinuous mode is $\delta = 0.0630$. This would mean that the MOSFET would have to switch at unrealistic speeds since the duty cycle is very short as a result of the large step-down ratio. Another issue with the buck-boost impedance emulator is that the output voltage is negative.

2.2. Flyback topology

To overcome these limitations of the buck-boost impedance emulator, a flyback impedance emulator was designed. Flyback circuits are used in [6] for emulating an impedance for low-power RF and wind energy harvesters, and in [7] as part of a high-power-factor rectifier. The expression for emulated resistance is the same as Equation 2, but with the buck-boost inductor $L$ replaced by the primary inductance of the flyback transformer, $L_1$:

$$R_{emulated} = \frac{2fL_1}{\delta^2}$$ \hspace{1cm} (4)

The flyback circuit remains in discontinuous conduction mode only if the current in the secondary winding of the transformer can return to zero during the MOSFET off time:

$$\frac{V_i}{L_1} t_{on} \leq \frac{V_o}{nL_2} (T - t_{on}) \implies \delta \leq \frac{1}{1 + \frac{nL_2V_o}{V_i}} = \frac{1}{1 + \frac{V_i}{nV_o}}$$ \hspace{1cm} (5)

where $L_2$ is the secondary inductance of the flyback transformer and $n = \sqrt{\frac{L_1}{L_2}}$ is the turns ratio.

With $V_o = 3.7$ V, $V_i = 55$ V and $n = 10$, the maximum duty cycle is $\delta = 0.402$, which means the MOSFET can be switched at more reasonable speeds. In addition, the output voltage of a flyback converter is positive. Like the buck-boost impedance emulator in Section 2.1, the flyback can be operated in discontinuous conduction mode and in open loop, keeping power consumption low.

The implemented flyback impedance emulator has the following parameters: $f = 19$ kHz, $L_1 = 140$ mH, $L_2 = 1.6$ mH, $\delta = 0.24$. This gives an emulated impedance of 92.3 kΩ, which is close to the optimal load presented to the rectifier. As $n = 9.35$ here, the maximum duty cycle is 0.386, which means that the flyback circuit will remain in discontinuous conduction mode.

Due to the extremely low magnetic coupling in this system, the optimal impedance presented to the rectifier is high (around 100 kΩ in this case), causing the received current to be very small (100s of µA). In reality the emulated impedance is not perfectly constant with variations
in input voltage due to parasitic oscillations in discontinuous conduction mode (Figure 2a) but nevertheless, the emulator performance was sufficient, restricting impedance changes to within +20/-50% of the optimal value. Figure 2b shows the efficiency of the impedance emulator with input voltage.

![Graph](image1)

(a) Emulated impedance with input voltage

![Graph](image2)

(b) Efficiency with input voltage

Figure 2: Performance of flyback impedance emulator

3. Transmitter power control
In order to maintain constant received power as the receiver position is changed and to prevent damage to the receiver electronics due to excessive received voltage, transmitter power modulation was implemented. At the receiver side, $V_{\text{RECT}}$ (shown in Figure 3), the voltage at the output of the rectifier and at the input of the flyback impedance emulator, is measured by a microcontroller in the sensor node. This voltage measurement is then sent to a microcontroller at the power transmitter side via a 433 MHz FSK wireless data link.

The microcontroller at the power transmitter side reads the measured $V_{\text{RECT}}$ value with an FSK data receiver, and this value is used to control the voltage of the DC power supply to the Class-E inverter, $V_{\text{CC}}$, in order to modulate the input power. The objective of the control algorithm is to keep $V_{\text{RECT}}$ close to 50 V. Any voltage above 60 V is deemed excessive and could potentially cause damage to the receiver electronics.

The method of $V_{\text{CC}}$ is as follows: if $V_{\text{RECT}}$ is greater than 55 V, then $V_{\text{CC}}$ is decreased by 10 V. If $V_{\text{RECT}}$ is less than 45 V, then $V_{\text{CC}}$ is increased by 2 V, but only if $V_{\text{CC}}$ is less than a certain value called $V_{\text{CC,MAX}}$. $V_{\text{CC,MAX}}$ is an upper limit on $V_{\text{CC}}$ that is set in order to keep $V_{\text{DS}}$ of the MOSFET in the Class-E inverter less than 1000 V, which is its breakdown voltage. A hysteresis band for $V_{\text{RECT}}$ (between 45 V and 55 V) is used to prevent frequency fluctuations in input power.

4. Results
Figure 3 shows a schematic diagram of the receiver coil and electronics, with the resonant tank on the left hand side, followed by the bridge rectifier, the impedance emulator and the sensor node with an RF data transmitter. Figure 4 shows post-emulator received power against distance between the receiver and the transmitter. Received power is constant at around 30 mW up to 3 m as the power is modulated, but beyond 3 m the transmit power saturates (limitations in the MOSFET voltage rating of the driver amplifier) and the received power decreases. The receiver electronics and feedback system consumes 3.1 mW and so with a transmitter input power of 163.3 W the receiver becomes power neutral at 4.75 m. At 5 m, received power falls to 2 mW.
5. Conclusion
With the use of an ultra-low power flyback impedance emulator to provide constant loading and wireless feedback to maintain constant transmitter power, it has been demonstrated that inductive power transfer can be used to reliably power a sensor node. IPT systems are therefore a viable alternative to existing far-field methods such as RF energy harvesters for supplying power concurrently to multiple remote sensors.

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