Design of a Wireless Power Transfer System for Wireless Sensor Networks in Biomedical Applications

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***Abstract*—Analysis and design of a wireless power transfer system for application in a brain implant is presented. The design consists of three main stages: the power transfer stage, the power management stage, and the energy storage stage. RF energy harvesting and inductive charging are considered as viable alternatives for the power transfer stage. Quantitative analysis of each technique reveals that both solutions are viable, but energy harvesting sacrifices charging speed for mobility of the implantee during charge, and inductive charging does the opposite. The design for a power management system is shown, and two commercially available charge management chips available from Texas Instruments are compared. The surface mounted bq25100 chip is found to be the superior option.**

***Index Terms*— Energy harvesting, Energy management, In vivo, Inductive charging, Implantable biomedical devices, RF signals**

I. Introduction

Neural implants are a promising but nascent technology with many potential applications. They can detect and transmit signals produced by the brain or they can stimulate the brain by outputting electrical impulses. This allows researchers to study the brain in new ways. These neural implants require power to operate, but conventional wired power sources are not feasible for a number of reasons. The implantee would have wires coming out of their skull and they would be tethered to a power source whenever the implant needed to be recharged. Instead, researchers turn to a more elegant solution: wireless power.

Wireless power transfer (WPT) solves many of the aforementioned concerns regarding the neural implant. WPT systems are unobtrusive, and are able to constantly provide a small amount of power. This means that these systems are able to charge the implant continuously, so the implantee does not need to be conscious of setting time aside to recharge the implant. This is particularly useful for in-vivo experiments, because it allows the test subject to move freely while wearing a neural implant without worrying about the implant running out of power.

Researchers at the University of Pennsylvania desire a WPT solution for use in the Brain-Machine Interface project. One goal of this project is to stimulate the brain of a swimming rat to induce it to swim in a specific direction. This poses some unique design challenges to be considered in the design of a WPT system, such as size constraints and the need for waterproofing. This paper seeks to analyze several viable alternatives for wireless power transfer. Different systems will be compared quantitatively, and their strengths and weaknesses considered in the context of the Brain-Machine Interface.

II. Background

This section covers the major components of a WPT system. Figure 1 shows a block diagram to help visualize the system.

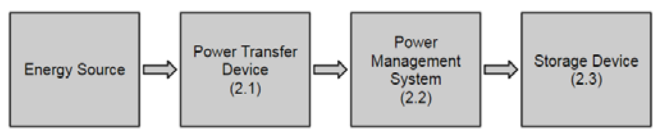

Figure 1: Block Diagram of Wireless Power Transfer System

2.1 Wireless Power Transfer Techniques

2.1.1 RF Energy Harvesting

Radio Frequency (RF) Energy Harvesting is accomplished by capturing RF radiation and converting it to DC power. RF signals are ubiquitous and plentiful in today's society [1]. Cell phones, WiFi routers, and radio stations are a few examples of RF sources. These sources emit RF signals in every direction, some of which are picked up by receivers and used to transmit information, and others which go unused, simply traveling and attenuating until they eventually disappear. RF energy harvesting seeks to capture these unused signals and harness their energy so it can be used to power devices.

An RF energy harvesting device consists of several components. In order to receive RF signals, an antenna must be used. Since these signals are sinusoidal in nature, they induce an alternating current. This alternating current is then passed through a rectifier, which converts it to direct current [1]. Additional circuit components may be included as well, such as a voltage monitor, an amplifier, and matching circuits (circuits used to smoothly transition the signal from one component to the next). Commercially available hardware exists that includes many of these components on one small chip. This paper considers the Powercast P1110, an energy harvesting device designed for the 908 – 928 MHz range [2].

2.1.2 Inductive Charging

Inductive charging is based on the concept of electromagnetic induction. A coil of wire with current flowing through it will produce a magnetic field. Similarly, if a coil of wire is placed in a changing magnetic field, a current will begin to flow in the coil. A WPT system can be created using this concept by connecting one coil to a constant power source (such as a wall outlet or a DC power supply) and placing the second coil a short distance away from the first. The magnetic field created by the current in the first coil will in turn induce a current in the second coil, effectively transferring the power wirelessly [4]. Figure 2 demonstrates this phenomenon.

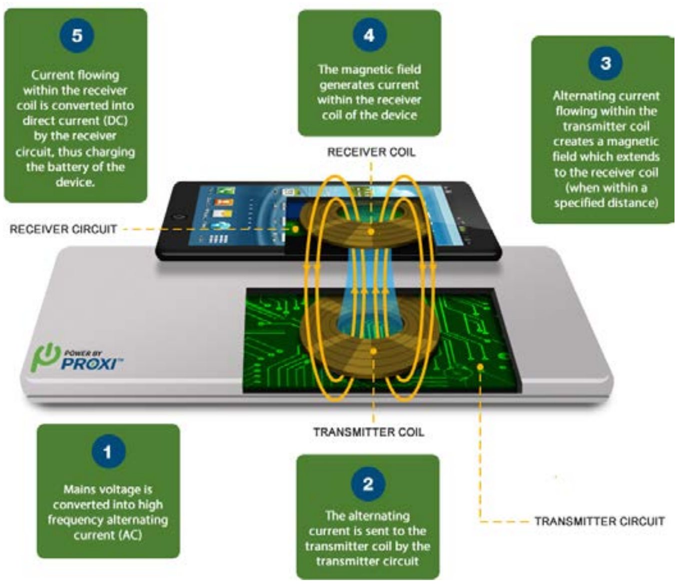

Figure 2: Diagram of an Inductive Charging System (adopted from [4])

As shown in figure 2, the current must be converted to alternating current (AC) before entering the coils. Once transferred to the second coil, the current must be rectified back to direct current (DC). Only a changing magnetic field can induce current in a coil; a static magnetic field is unable to do so [4]. Therefore, alternating current is used to induce a continuously changing magnetic field, which then creates an alternating current in the second coil, which must then be rectified before it can be used to power a device.

2.2 Power Management

A wireless power transfer system requires a power management stage to function properly. The purpose of power management is to automatically monitor and regulate the flow of power from the power transfer stage to the energy storage device. Without this stage in place, the power received by the power transfer stage would be directly and perpetually provided to the energy storage device. Since energy storage technologies are very sensitive and can be easily damaged if not charged optimally, a power management system is designed with certain threshold values for parameters such as voltage, current, temperature, etc. If any of the parameters are outside an acceptable range, as defined by these threshold values, the power management system immediately terminates charging in order to prevent damage to the energy storage device.

2.3 Energy Storage Solution

It is rarely the case that the power received from an energy source will be exactly equal to the power consumed by a device at any given moment. Because of this mismatch, power ends up going to waste [5]. If less power is received than is demanded by the load, all of the received power goes to waste. If the power received exceeds the power consumed, the excess power goes unused, typically becoming heat, sound or vibrational energy. In these cases, a storage device is desirable for the unused energy, such as a battery. The energy stored in the battery can be accessed later, when it is required.

III. Bench Test Setup

3.1 Powercast P1110 RF Energy Harvesting Chip

The P1110 chip was incorporated into a custom-designed Printable Circuit Board (PCB) with an SMA connector for RF input and six I/O pins for bench testing. Tests involving the P1110 were performed using a Fluke 6060A Synthesized RF Signal Generator. The signal generator was connected to the PCB via an 8" male to male SMA cable. This is solely for testing purposes. In the future, the signal generator will be replaced by an antenna, which will be incorporated into the final design.

3.2 Fluke 6060A Synthesized RF Signal Generator

This signal generator can be set to output at a given frequency and power. Output frequency can be set in the Hz, kHz or MHz ranges, with a maximum output frequency of 1050 MHz. The output power is measured in dBm and has a minimum step size of 0.1 dBm. The maximum power output is +13 dBm.

3.3 TDK WRM483245-15F5-5V-G Inductive Charging Coil

This is a commercially available inductive charging coil that includes a PCB that rectifies and conditions the output voltage. It accomplishes this through the use of a TI bq51013b wireless power receiver chip [6]. The output of the device is ~5V and 0.5 to 0.7A [7]. This is the receiver side coil of an inductive charging pair. A source coil is required to transmit the power. The source coil used in these experiments was a commercially available Qi compliant inductive charging mat. The charging mat was powered via USB connection.

3.4 TI Charge Management Chips

Two different Texas Instruments charge management devices were considered for the power management stage of the wireless power transfer system. The bq2954 is a DIP package (through hole) device, and can be easily used with a breadboard for bench testing. The bq25100 is a surface mounted device with a much smaller profile, which is preferable for a final design. Both devices perform many of the same functions, with minor differences.

3.5 Lithium-Ion Battery

A lithium-ion battery is used as an energy storage device. Two batteries were used in tests, both with a maximum internal voltage of 4.2V. One battery had a capacity of 150mAh while the other had a capacity of 1200mAh. Wires were soldered onto the terminals of the battery, which allowed for easy attachment to different devices for charging and discharging.

IV. Results and Deliverables

4.1 Energy Harvester vs. Inductive Charger

4.1.1 Charging Speed

Bench tests were performed with both the energy harvester as well as the inductive charging coils to see how long it took each of them to charge a lithium-ion battery. The energy harvester was given a 915 MHz signal at 10.0 dBm input power by a signal generator. The inductive charging coils were at minimum separation, with the receiver coil face down on the center of the power mat. A 1200mAh battery was used for both tests. The results of these tests are shown in Figure 3.

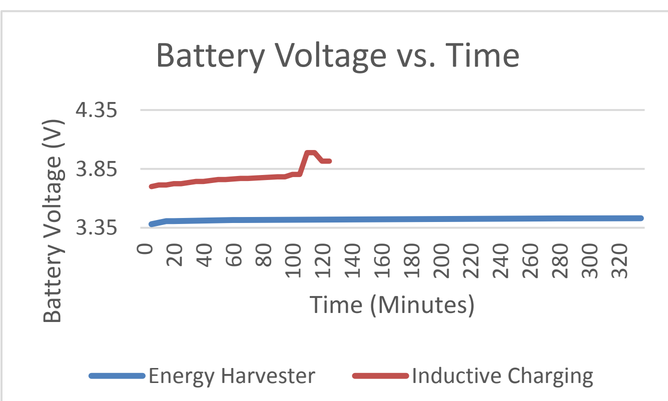

Figure 3: Charging Speed of Energy Harvesting vs. Inductive Charging

The inductive charging coils were found to charge the battery much faster than the energy harvester in this experiment. The inductive charger increased the voltage of the battery from 3.70 to 3.91V in 2 hours, a rate of about 0.105V/hr. The energy harvester increased the voltage of the battery from 3.38 to 3.43V in 5.58 hours, a rate of about 0.0089V/hr. These results are dependent on the charging current. The input power of the energy harvester is limited by the signal generator, so an antenna may be able to receive higher power signals that induce larger charging currents. Conversely, the inductive charging coils are operating at near-maximum performance due to their proximity. In practical applications, the coils may need to be farther apart, which would drastically reduce the amount of power they could transmit.

4.1.2 Mobility of Implantee

One of the most attractive aspects of wireless power transfer is the fact that it does not tether the implantee to a specific location during charging, which would restrict their movement and inhibit their daily activities. Not all wireless power transfer technologies have the same effective range, meaning that some will allow more freedom of movement for the implantee than others. Energy harvesting allows for nearly unlimited range of movement. An RF energy harvester can harness energy from tens of meters away [8]. One experiment tested the effective range of an RF energy harvester to be up to 1 mile away [9]. The only drawback to the energy harvester's range is that it is very sensitive to line-of-sight, meaning that it will not function well inside buildings, where there are many sharp angles and turns and few direct lines from one point to another.

In contrast to RF energy harvesting, inductive charging is very short-ranged. Power transfer drops off dramatically when the coils are separated by more than a few centimeters. This means that in terms of mobility, inductive charging offers almost no benefit over wires. This is especially problematic for testing of the brain implant, which is performed using animals like monkeys and rats. It will be very difficult to keep the animal stationary in a specific position in order to allow for effective charging using the inductive coils.

4.2 Power Management Stage

PCB designs were laid out in CadSoft Eagle PCB software.

4.2.1 bq2954 Circuit

Two designs were made; one included the TI bq2954 along with several through-hole components used for setting threshold values. The schematic is shown in Figure 4.

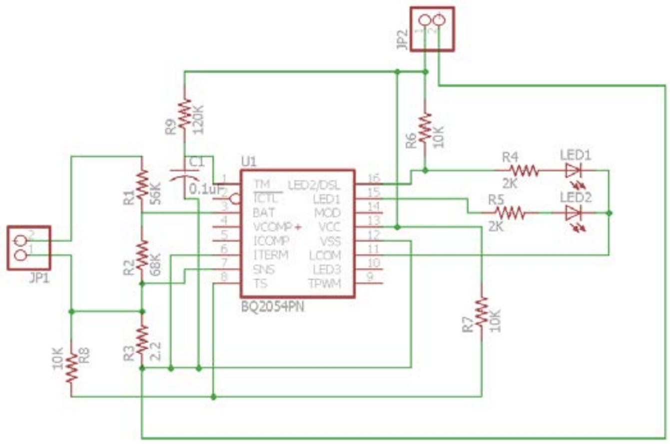

Figure 4: Power Management Stage Using Through-Hole Components

The bq2954 has an internal threshold value for maximum voltage set by the manufacturer. If this value is exceeded, the chip will terminate charging immediately. This internal threshold is set at 2.05V, but can be configured by the user to achieve a different threshold value. Resistors R1 and R2 form a voltage divider that can accomplish this. Equation 1 shows how values for R1 and R2 were obtained.

$$\frac{R1}{R2} = \frac{N * Vcell}{2.05} - 1 = \frac{1 * 3.7}{2.05} - 1 = 0.804 \approx \frac{4}{5}$$

$$R1 = \frac{4}{5} R2 \qquad (1)$$

Similarly, the bq2954 has a maximum current threshold value. The chip will output this current to the battery during charging. The user can configure this current threshold by changing the value of R3. A charging current of 0.8 times the capacity of the battery is considered safe. This means that for a 150mAh battery, a charging current of 120mA is desired. Equation 2 shows how to achieve this using R3.

$$R3 = \frac{0.25V}{Imax} \qquad (2)$$

R4, R5, R6, and the two LEDs form a charge indicator circuit, which indicates when the battery is charging, full, or disconnected. R7 and R8 are used to disable the temperature sensing function of the bq2954. R9 and C1 form a timeout circuit. This circuit sets an absolute maximum time for the charging cycle. This circuit results in a maximum timeout of 6 hours, as shown in equation 3.

$$t = 500 * R * C = 500 * (120K\Omega) * (0.1\mu F) \approx 6\ hours$$

4.2.2 bq25100 Circuit

The second PCB design incorporates the TI bq25100, which is roughly equivalent to the bq2954, but comes in a surface mounted package. This means that it is much smaller and more suitable for use in the BMI implant. The schematic for this design is shown in Figure 5. A custom library had to be created for the bq25100, since it was not included in the default Eagle libraries.

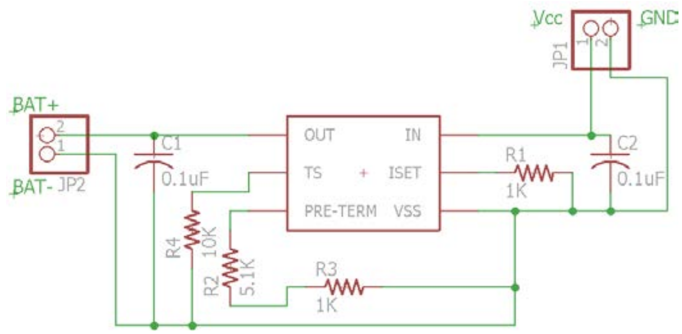

Figure 5: Power Management Stage Using Surface Mounted Components

R1 sets the charging current according to equation 4.

$$0.135V = R1 * I_{max}$$

Once the maximum voltage threshold (set to 4.2 in the bq25100) has been reached, the current will begin to drop. Once the current falls below a certain threshold, the battery is considered fully charged and current will terminate. R2 and R3 are used to set this termination current threshold. The expected range is 600Ω to 30kΩ. Values in this design were chosen based on availability of components in the lab.

R4 disables temperature sensing and C1 and C2 are bypass capacitors (also known as decoupling capacitors) used to isolate electrical noise and prevent it from affecting the operation of the rest of the circuit.

4.2.3 PCB Board Designs

The board layouts for the two designs are shown in Figures 6a and 6b.

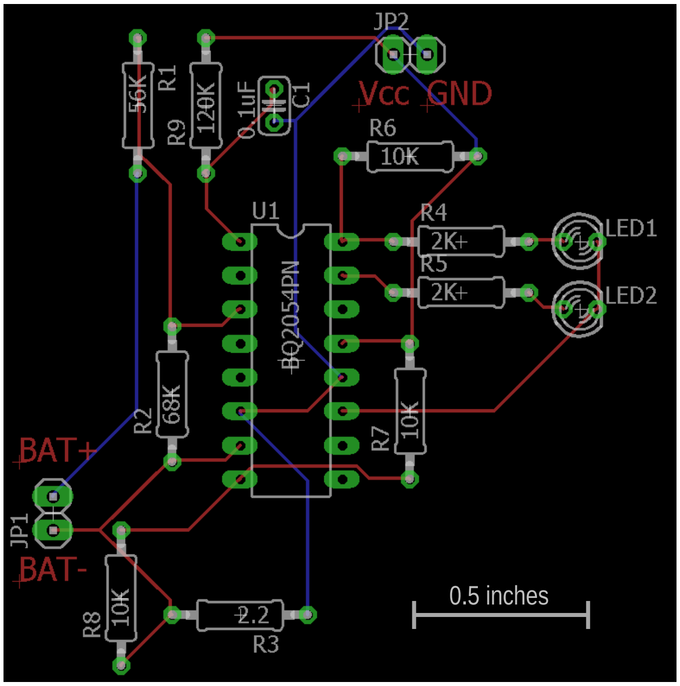

Figure 6a: Through-Hole Board Design

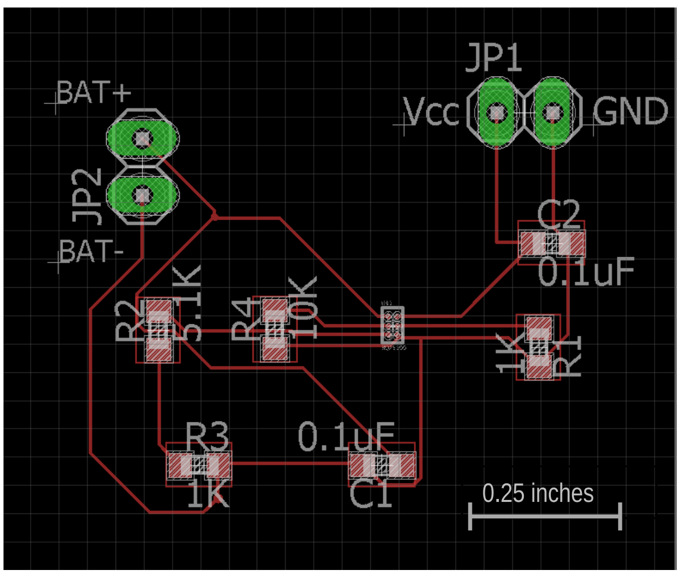

Figure 6b: Surface Mounted Board Design

V. Conclusion

RF Energy Harvesting and inductive charging both remain viable options for a wireless power transfer system. Energy harvesting does not require external hardware or time dedicated to charging, whereas inductive charging is dependent on proximity to an external coil. Both applications are very small and light, making them suitable for implant applications. In the experiment performed, the inductive coils charged the battery much more quickly than the energy harvester, but there are many factors that could affect this. Future testing should be performed under varying conditions to test the effectiveness of both methods.

The bq25100 is the most suitable solution for the power management stage of the WPT system. It is very small, making it easily implantable, and there are fewer I/O pins, making it more streamlined and simpler to work with as compared to the bq2954.

Acknowledgments

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