Low Switching Frequency AC-DC Boost Converter for Wireless Powered Miniature Implants

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Abstract

Providing wireless electrical power to an implantable medical device (IMD) is critical to an implant's efficacy. Wireless power transfer based on magnetic coupling is the primary approach to powering an IMD. Reducing the size and improving the efficiency are the two primary design goals for the power-harvesting component of an IMD. A pulse-width-modulated (PWM) boost converter converts a low-voltage AC power generated by a miniaturized receiving coil to a desired high-voltage DC power. However, in the traditional PWM boost converter, the switching frequency is much higher than the frequency of the input AC power.The high switching frequency not only dissipates more power on the switch, but also prevents the circuit from handling high-frequency input AC power. Consequently, a low switching frequency AC to DC boost converter is achieved by aligning the PWM signal with the input of the AC boost converter. The experimental verification of the optimal delay and duty cycle of the PWM control signal was made possible by a microcontroller based Printed Circuit Board (PCB) test platform that we re-designed using surface-mounts. This research attempts to prove that the converter significantly improves the conversion efficiency by reducing the dissipated power associated with the PWM switch.

1. Introduction

Every year, more than half a million people in the United States undergo surgery for biomedical implants [3]. Biomedical implants are highly desired in the medical field as they can save lives and also improve the quality of life of patients through methods shown in Fig. 1. Powering IMD wirelessly can extensively prolong the battery life of the implant. This can prevent the need of replacing the implant battery through surgical procedures. Conventional methods contain relatively large circuit parts that generate high input frequencies that may harm human tissue. It is important to create biomedical devices in small scale and to lower the switching frequency of the AC-DC boost converter to reduce power dissipation, keep the signals at a safe frequency, and increase the converter's efficiency.

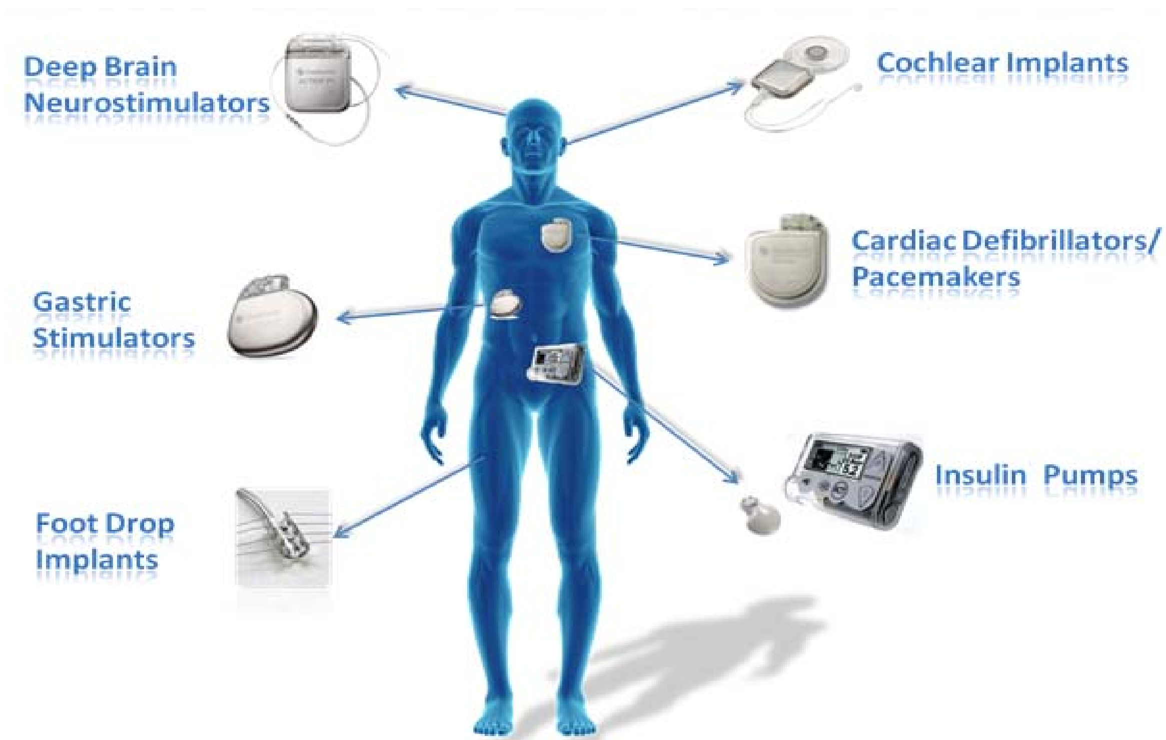

Figure 1: Examples of Implantable Medical Devices [4]

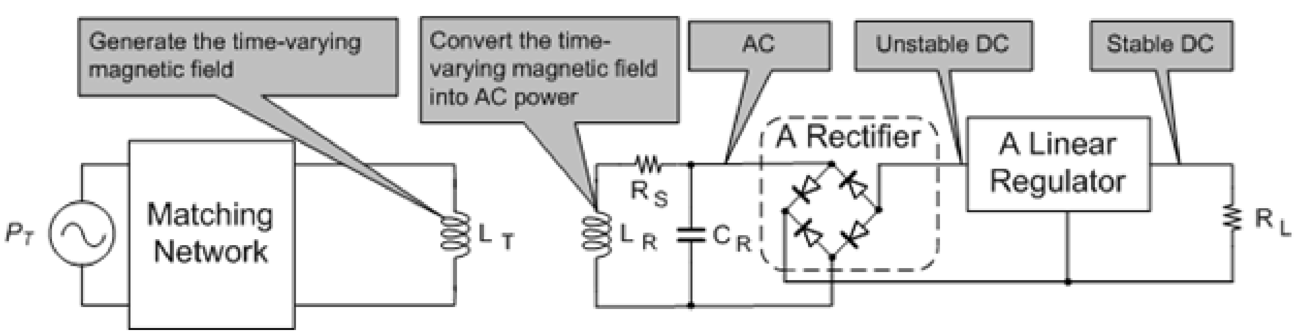

Figure 2: Schematic of Conventional Method [5]

The conventional approach to power an IMD uses an air core based transformer with two face-to-face inductive coils as seen from Fig. 2. These coils induce a voltage drop through magnetic coupling that is used as the power source for the device. The maximum output power from this method is 275 mW over a distance of one centimeter [5]. Since the coils generate a AC and the device needs DC to function, a passive diode bridge rectifier is used to convert AC into DC. A linear regulator is used to stabilize the DC. Then the voltage is increased by using a DC-DC booster.

A problem with the diode bridge rectifier approach is that the AC input voltage must be considerably higher that the V_{ON} of the rectifier. If the required voltage is not met, the efficiency of the power conversion quickly reduces to zero when V_{in} approaches 2 x V_{ON} [6]. Also, a comparatively large receiving coil is needed to overcome the required voltage of the rectifier. Because of the required size of the receiving coil, the size of the coil is around 3 cm in diameter.

The two inductive coils generate a high frequency input, which keeps the magnetic flux at a decent value with low radio frequencies (RF) through the coil. This high switching input frequency can range between 10 to 100 times greater than the AC input frequency. As a result, the high switching frequency dissipates power and deteriorates the converter efficiency. Most IMDs generally need several watts of power to function properly therefore a proposed approach is demonstrated.

2. Proposed Approach

The proposed approach uses a low switching frequency AC to DC boost converter. By aligning the input AC with the PWM signal, the AC-DC boost converter is able to convert a 500mV induced AC voltage into a 5V DC output. A motor rotates magnets and generates a magnetic field which produces the induced AC voltage in the coil.

These magnets are permanent and have magnetic field lines pointing from its north polarity to its south polarity. As a power source, rotating magnets are used to change the magnetic field lines hitting the coil. The coil compensates this magnetic field change by generating its own electromagnetic field. The energy stored in its electromagnetic field creates an induced current and a voltage drop in the coils that is used as the source of power in the circuit. The max output of the power source from this method is 10 watts over a distance of one centimeter, which is a great improvement from the 275mW generated in the previous method.

To maximize the input power generated, the positions of the magnets are oriented in opposite polarities to increase the magnetic flux change in the coil as seen in Fig. 3. A ferrite core may also be inserted inside the coil. The core's magnetic dipole moment vectors contain the property to align its magnetic vectors with the electromagnetic field of the inductor. This will greatly increase the electromagnetic field and induced voltage. In the old method, the addition of the ferrite core is impractical due to slow magnetization hysteresis during high frequency switching. The inductor and second auxiliary coil are wrapped around the same ferrite core to ensure that both voltages are in the same phase. A back plate may also be placed behind the coil as it magnetizes. If the magnets and coils are misaligned in the longitudinal direction, the losses in voltage are only in relatively small amounts [7]. The proposed approach is clearly the better method in wirelessly charging an IMD.

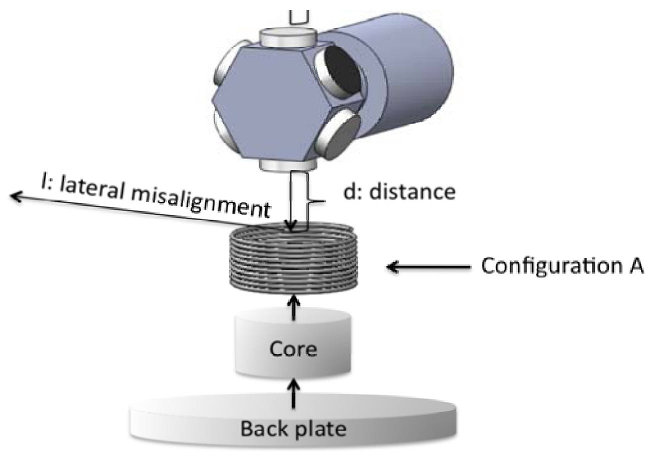

Figure 3: Magnets are aligned in opposite polarities on the hexagon steel rotor to maximize generated power [7]

2.1 The Operating Principles and the Advantages of the Switching Regulator

The voltage generated from the spinning magnets gives off AC signals. Instead of using a diode bridge rectifier to convert the AC input to DC output, the proposed method uses capacitors to adopt the AC and take in energy in both positive and negative half cycles as seen in the boost converter in Fig 4:

i. In Figure 4 (e), the switch edge lines up with the zero crossing of the input AC.
ii. In Figure 4 (a), the switch is on and the inductor stores energy in its electromagnetic field and voltage is induced.
iii. In Figure 4 (b), the switch is off and the current passes through the circuit as the inductor acts as the power source.
iv. In Figure 4 (c), during the positive half-cycle, the diode D_2 is off and C_{S1} charges. During the negative half cycle, the diode D_1 is off and the capacitor C_{S2} charges.

The three capacitors share energy through charge redistribution and can convert the input to DC. Unlike the previous method, the turn on voltage for the diode rectifier is no longer an issue. The boost converter is used to boost low voltage to high voltage and there is high efficiency due to minimal loss from not using the diode rectifier.

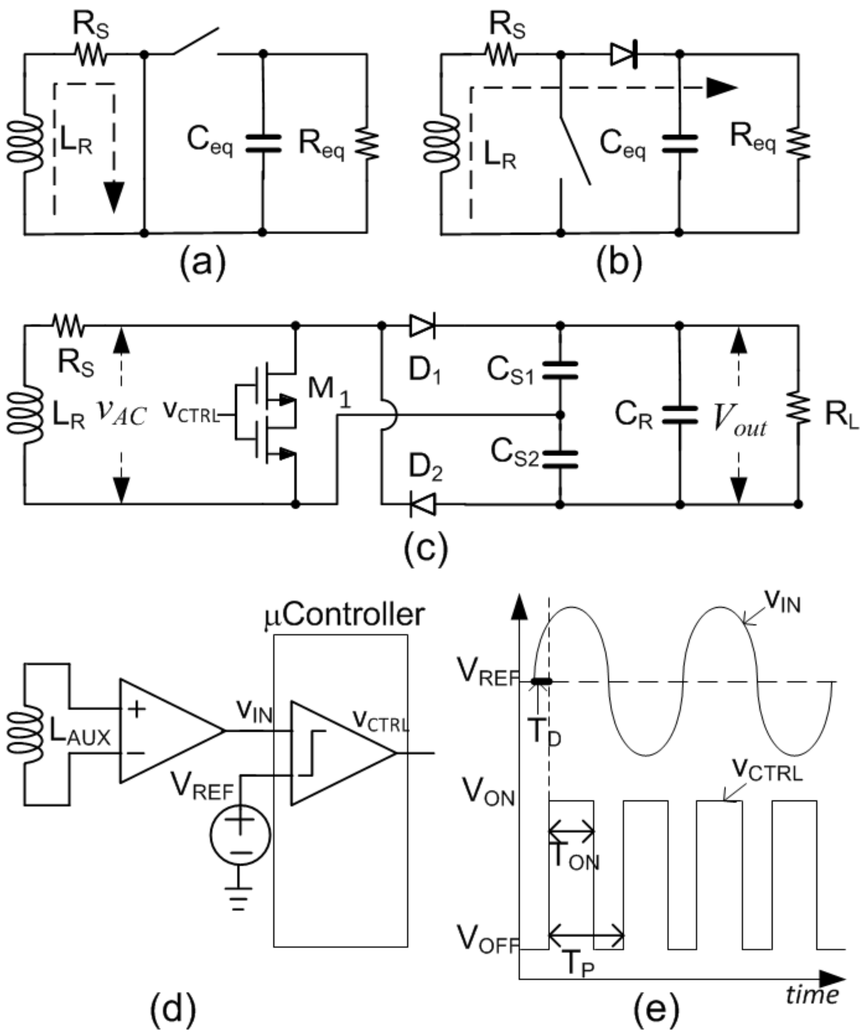

Figure 4: Simplified circuit diagram of the low switching frequency AC-DC boost converter and its operating principles.

2.2 Microcontroller

In order to get the maximum amount of voltage possible the AC voltage is aligned with a specific controlled signal. This is achieved by using a reference signal to distinguish the zero crossing of the AC input. The type of microcontroller that is used in this project is Atmel's AVR ATMEGA 328P. A microcontroller is a small computer that is able to execute a set of instructions. It has a CPU (Central Processor Unit) in addition to a fixed amount of Random

Access Memory (RAM), Read Only Memory (ROM), Input/Output (I/O) ports, and timer. The microcontroller can be programmed in C or Assembly Language by using software called Atmel Studio 6.0. All port registers of the microcontroller are bit accessible using hexadecimal (Base 16) or Binary (Base 2). Fig. 5 shows the schematic diagram of the microcontroller and all of the ports that it has, which are PORT B, C, and D. The microcontroller is used to constantly measure the waveform of the input AC to generate the controlling signal accordingly.

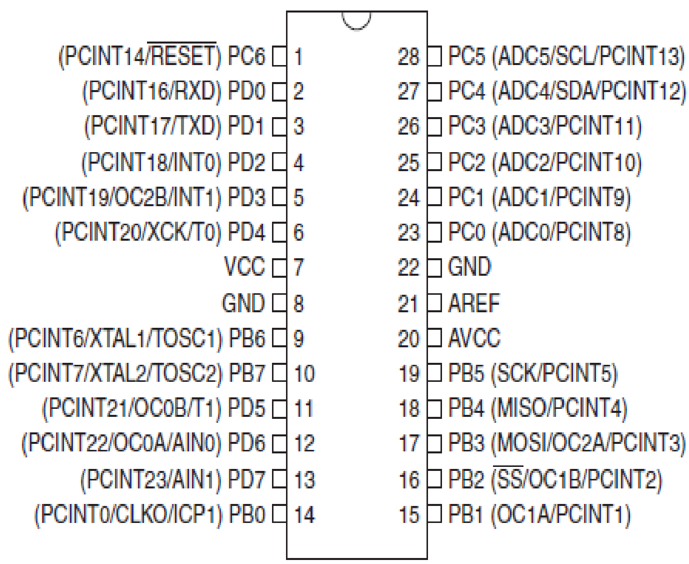

Figure 5: Schematic of the microcontroller[8]

3. Implementation

The program that is used for simulations is called LTSpice. The objective is to get the highest possible output voltage. The output voltage, V_{out} is the voltage across the load resistors as shown in Fig. 6. To obtain the highest output the timing of the switch and the pulse wave were modified. Other factors that were changed were the control voltage, V_{CTRL}, and the pulses that were regulated by the microcontroller. After attempting to fit from one to seven pulse in a half period of the AC voltage, it was finally determined that only one pulse, with a 57 percent duty cycle, yielded the maximum output voltage as shown in Fig. 7. The timing of the switches is modified to try and obtain a higher output when the switches are turned on.

The first step in making the PCB of the circuit was to make the schematic using a program called Eagle which is a diagram of the board. Then assigning footprints to each individual component in the circuit was necessary for the next step. Many footprints had to be made for the components that did not have one. The majority of the surface-mount footprints were already made on Eagle. The design uses standard through-hole components. The use of surface-mount components minimizes the size of the board and the parasitic resistances and capacitances. Figure 8 shows the difference in size between through-hole and surface-mount components.

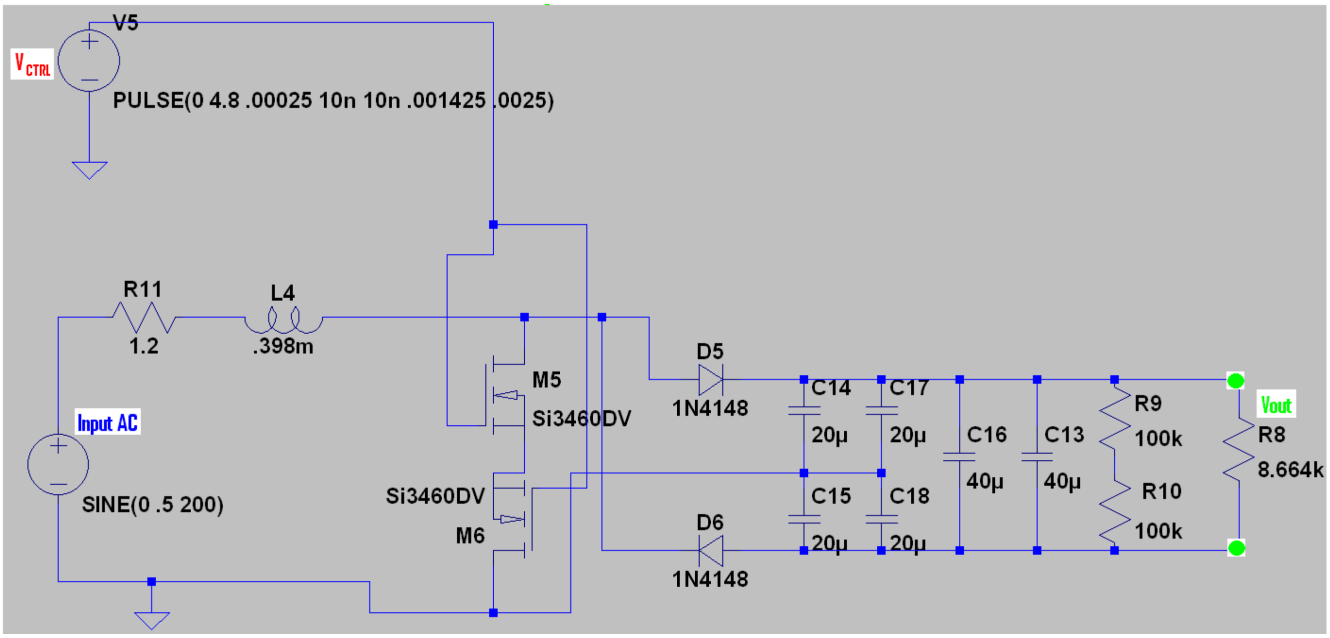

Figure 6: Schematic Diagram of the simulated AC-DC Boost Converter

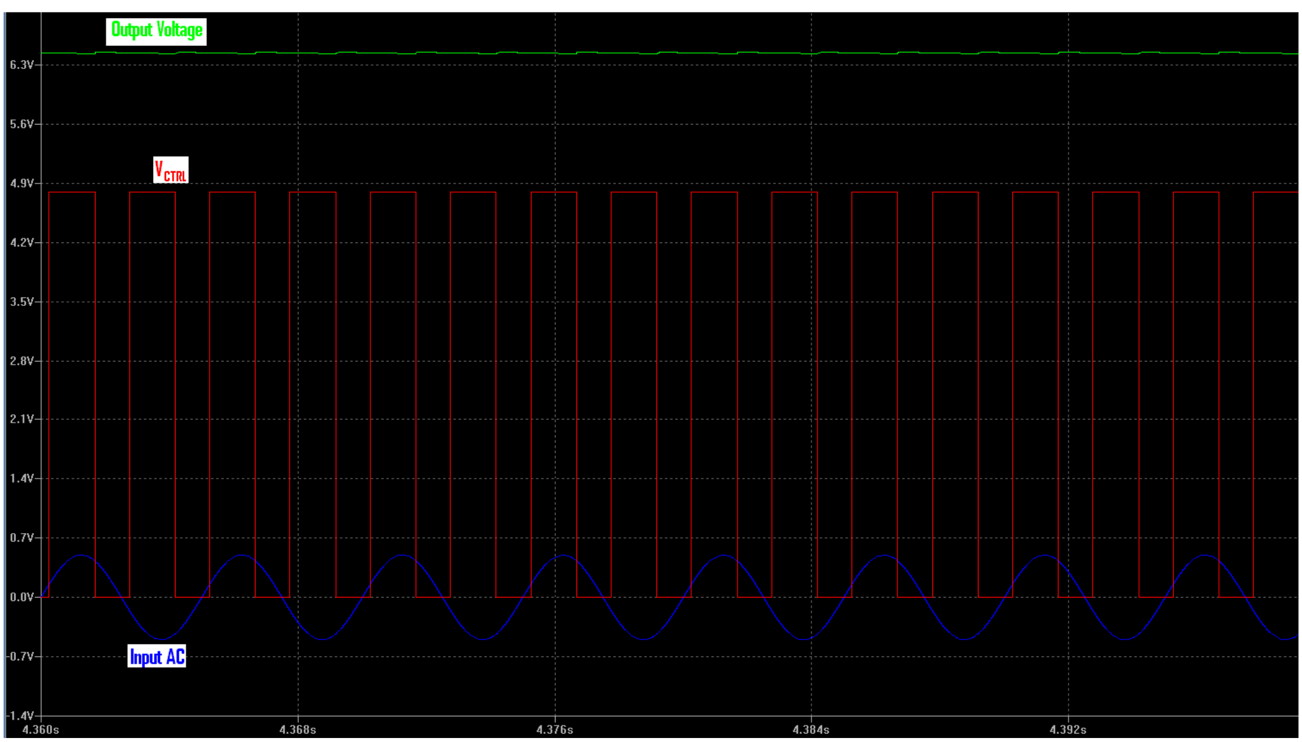

Figure 7: A graph showing the results of the simulated AC-DC Boost Converter at 57 % Duty Cycle

Once the schematic is finished and netlisted, the next step is to make the layout of the board. Also, where certain components were placed must be taken into consideration. Depending on how close or far they were to each other reflected on how poorly or well it functioned. One example is that the regulators had to be isolated from the microcontroller to reduce coupling and noise. Once all of the parts are placed, the Design Route Check (DRC) needs to be done. This step is to ensure that everything is ok on the board. For example, it checks if the board is routed correctly and if the wires are not too close together or too thick.

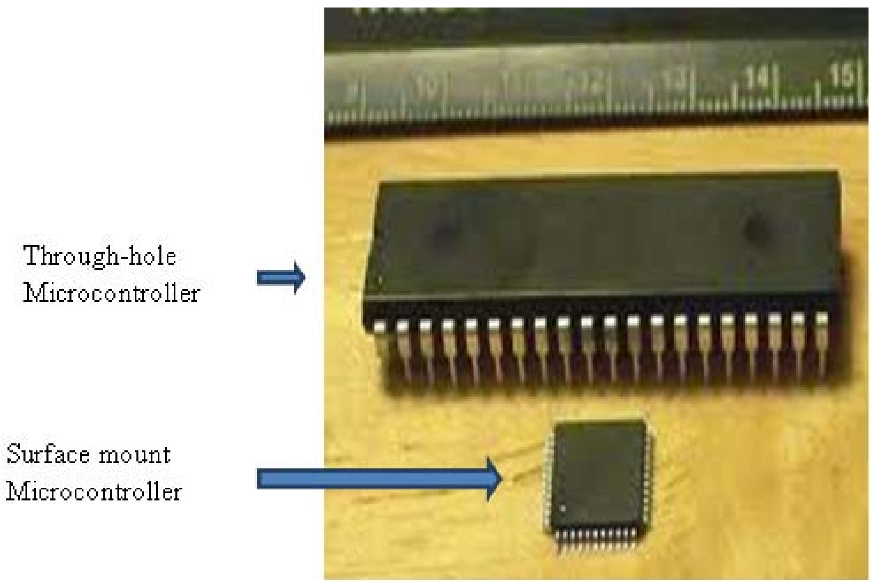

Figure 8: Photo of a surface mount element and a through-hole element [9]

4. Results & Analysis

From the circuit simulations, it is found that aligning the rising edge of the control voltage signal with the rising input AC signal maximizes the amount of energy charged. The most effective way of charging is by using one pulse per half cycle as shown in Fig. 9. The figure is a graph of Output DC Voltage versus Duty Cycle (T_{ON} divided by Pulse Period T_P).The DC output of coil B peaks at 5.83 V with a duty cycle of 62% and coil A peaks at 6.95 V when the duty cycle is 57%. The DC output peaks at the higher duty cycles for Coil B because it has a larger time constant (L_R/R_S).

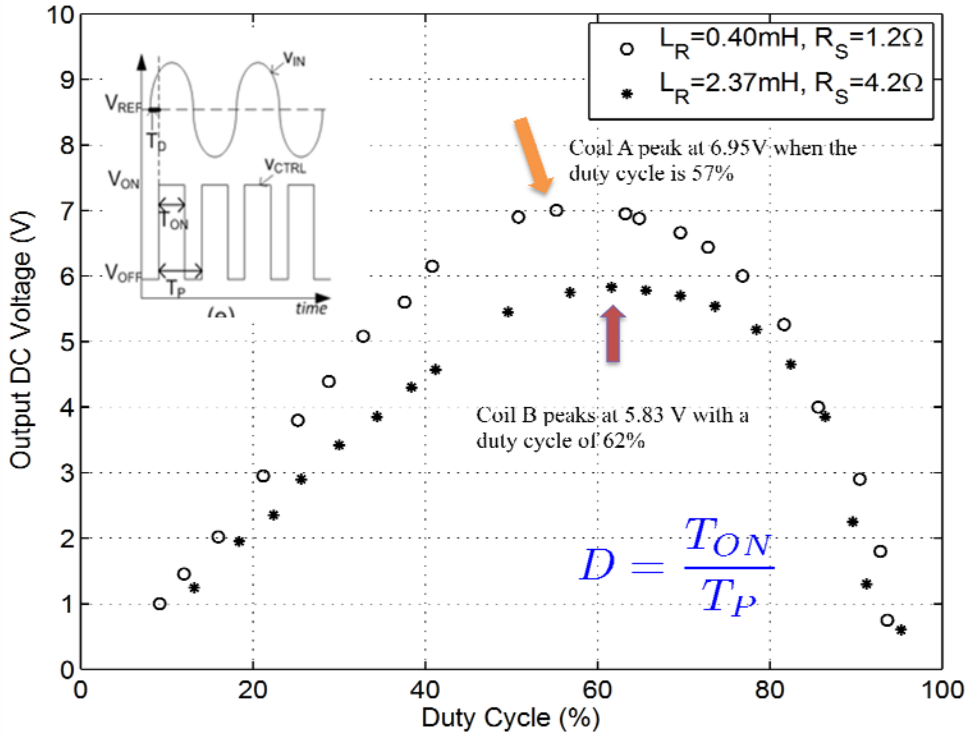

Figure 9: Graph of DC output versus the duty cycle

The timing between the input AC power and PWM pulse is crucial. Fig 10 shows the output DC voltage versus the normalized delay time, which is obtained by dividing T_{delay} by T_{period}. The graph shows that the DC output voltage drops 12%, from 6.95 V to 6.13 V, when the rising edge of the switching pulse is 5% behind the zero crossing of the input AC. The data points from the graph indicate that accurate timing between the switching pulse and input AC is important to the performance.

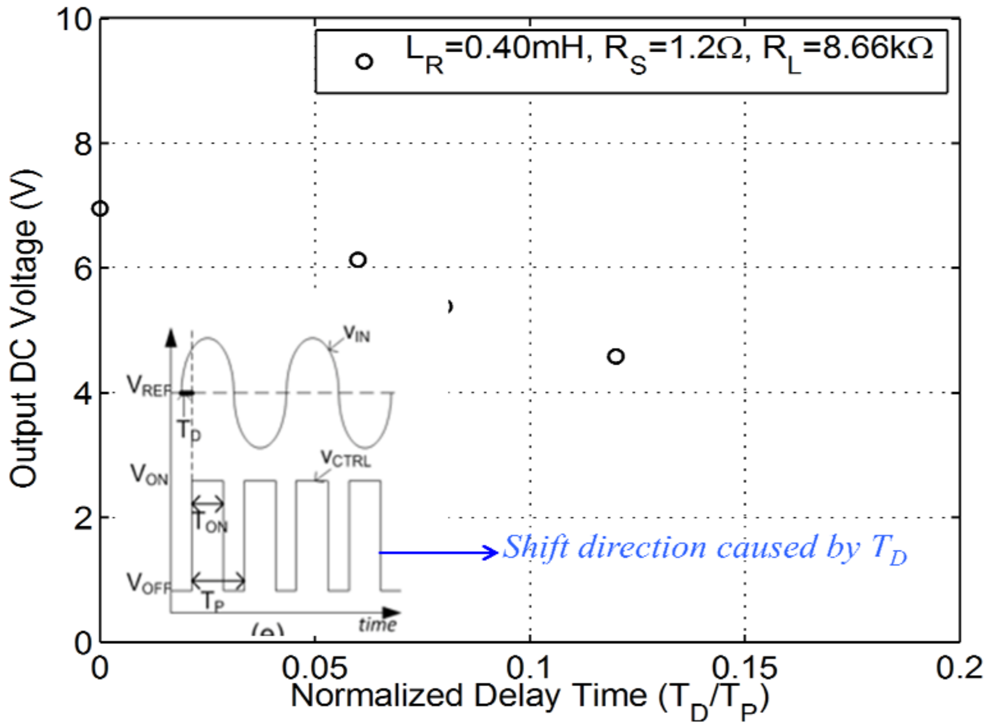

Figure 10: Graph of DC output versus the delay time that is inserted before the rising edge of the pulse wave.

5. Conclusion and Future Research

The proposed method uses spinning magnets and two inductors to produce 10 watts of power over one centimeter. There is also low power dissipation since the diode bridge rectifier approach is replaced with the multiple capacitor, microcontroller, and boost converter method. This allows the circuit to work with lower switching frequencies so that there is less damage to human tissue due to high radiation frequencies. The low power dissipation from the low switch frequencies will prevent the boost converter from deteriorating as quickly as the previous method. Using the proposed approach we can make the size of the coil much smaller unlike the conventional approach in which we need a large coil to overcome the diode turn on voltage. Using the proposed method we were able to convert a low AC voltage and boost it to a higher DC voltage by aligning the input AC with the PMW signal.

In the future this research may greatly benefit biomedical implants and the way they power wirelessly. More power is generated in this method and it eliminates the need of a comparatively large inductor. Also, not needing frequent battery replacements will save patients from undergoing surgery to replace batteries. In the future, research can be done to improve the proposed approach by using a closed loop control system. With a closed loop control system we can control the output voltage by tracking what the latest voltage is and either increase or decrease the voltage.

6. References

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7. Biographies

Jose Carrillo graduated from Cañada College with an Associate’s Degree in Engineering. He is majoring in electrical engineering and next fall he is attending Cal Poly San Luis Obispo as a junior. He wants to get a bachelor’s degree and possibly a Master’s degree. One of the most interesting things for Jose is the chance that he gets to work with a student and an advisor on a research topic that is associated with his major. Also, every day he is learning something new, whether it is soldering components to the PCB or learning how the circuit works as a whole.

Alam D. Salguero grew up in a little town in Guatemala where his parents pushed him to study hard because they knew that education was the window for success. He became interested in engineering by watching his father fixing the TV every time it broke down, so he started breaking things apart and trying to understand how they work. Eventually in high school, he had his first science course where he learned some principles of electricity. His curiosity increased with time which later pushed him to become an electrical engineer. After graduating from high school, he immigrated to the United States where he pursues his dream of becoming an engineer. A couple of months later, he enrolled in Cañada College where he got involved in science groups and community. Today, he is about to transfer to Cal Poly SLO and be one step closer from becoming an electrical engineer.

Ellaine J. Talle is an undergraduate student who is passionate in Electrical Engineering and the Environmental field. She was born in Manila, Philippines and came to the US when she was three. She was selected as a Morris K. Udall 2012 Scholar and was also appointed as the Skyline College President of the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS) and received her Associates Degree in Mathematics. Ellaine loves playing piano and solving puzzles and has been involved with engineering projects such as creating a windmill from scratch. She is transferring to the University of California, Irvine to get her Bachelor’s Degree in Electrical Engineering and a Master’s Degree in the Environmental field.

Enrique Raygoza attended Cañada College. He is majoring in Mechanical Engineering and transferring to the University of California, Irvine.

Xenia Leon was born in El Salvador and she came to the United States when she was 10 years old. Her parents have taught her that education is the key to success and that education is power. She received an Associate's Degree in Engineering from Cañada College. She is a first generation student who will be attending Cal Poly San Luis Obispo in the fall. She will be pursuing her bachelors in electrical engineering and a master in biomedical engineering.