Evaluation of H-Bridge and Half-Bridge Resonant Converters in Capacitive-Coupled Wireless Charging

Abstract— This paper compares two main topologies used for capacitive-coupled consumer wireless charging which has several advantages over inductive coupling including lower cost and no shielding requirements. There has been minimal data in the literature on preferred transmitter topologies. Two types of transmission systems are compared in simulations and experiments. An experimental charging system was built and tested with the evaluation of efficiency of h-bridge and half bridge transmitters. Preliminary experimental results indicate that the h-bridge is economically more advantageous, but the H-bridge is better efficiency-wise. The overall results show that the capacitive-coupled transmission system is more effective than the inductively coupled transmission system to charge portable electronics. Immediate future work is implementation of closed-loop control for receiver-side voltage regulation.

I. INTRODUCTION

As of 2014, over 90 high-end mobile devices implement inductively-coupled wireless charging, which requires magnetic shielding that increases bulk and cost [1]. Recently, there has been increased interest in an alternative method - capacitive coupling [2], which uses two air capacitors formed by four metal plates located on the surface of the transmitter and receiver to couple the devices and transmit power which shows contactless power transfer [3]. Examples of inductively and capacitvely-coupled energy transmission systems are shown in Figures 1 and 2, respectively. By eliminating the large and expensive shielding of the inductively-coupled method, a capacitively-coupled system is able to decrease cost and manufacturing time [4]. This type of wireless energy transfer is especially suitable for mobile devices with large flat surface areas as their geometry naturally lends itself to the formation of large coupling capacitors [5]. While capacitive charging seems to be an attractive option for designers, it has had little to no adoption in consumer charging applications. This is mainly due the lack of previously published literature on practical design factors for such systems, with previous studies [2, 3] focusing on theoretical implementation and maximum efficiency, theoretical analysis [6, 7] or only focusing on specific system topologies [8]. Topologies have significant effects on the entire power transfer system [9], so this paper addresses one of the practical design factors by investigating suitable transmitter topologies for a standard wireless charging system.

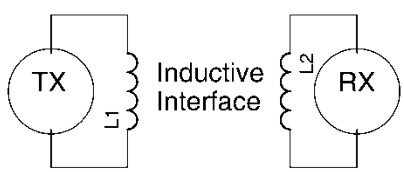


Figure 1 Inductively Coupled Transmission System

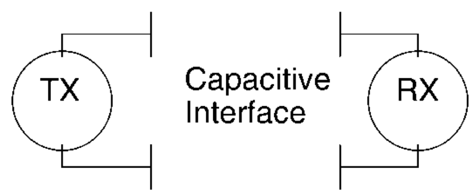


Figure 2 Capacitively Coupled Transmission System

This paper investigates the efficiency and material cost of the h-bridge and half bridge converters as transmitter drivers in a capacitively-coupled wireless energy transmission system for tablet applications. The h-bridge and the half bridge were chosen due to their popularity, widespread implementation in resonant power converters, simplicity, and low cost [10]. To be more specific, general operational specifications for the transmission system were chosen based on theoretical and practical considerations. Then, the system was designed at the component level using theoretical calculations. A simplified model of the system was then simulated in MATLAB and LTSPICE to confirm the validity of the theoretical calculations. After validation of the designs, both systems were constructed and their efficiency was measured using a power analyzer. The material cost of both systems was recorded and compared with a commercial wireless charging system. For this digest, a preliminary experimental open-loop platform was used, however for the final paper, closed-loop control will be implemented via FPGA controlled PLL. Finally, implications of the results and future work are discussed.

II. DESIGN

The system consists of five main parts which are H/Half-bridge, tank, rectifier, buck converter and load. As indicated before, open-loop control is used here by setting function generators to provide necessary PWM signals through gate driver circuit. The system parts and connection are shown in Figure 3. Figure 4 shows the topology of H-bridge and half bridge systems used in the paper.

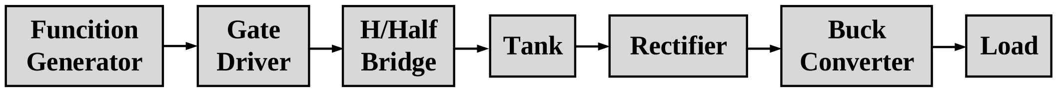
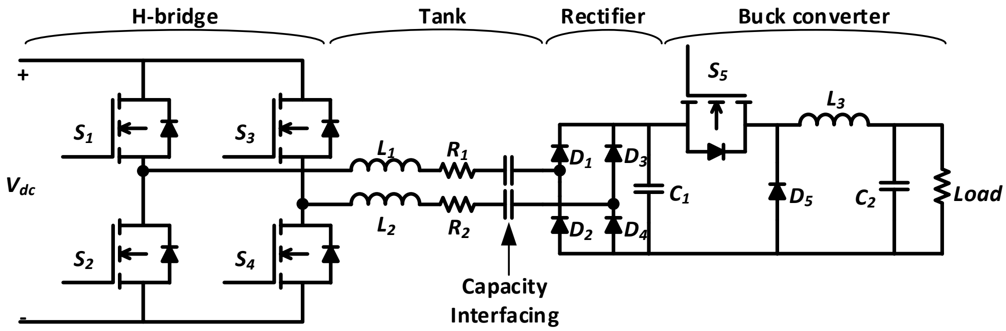
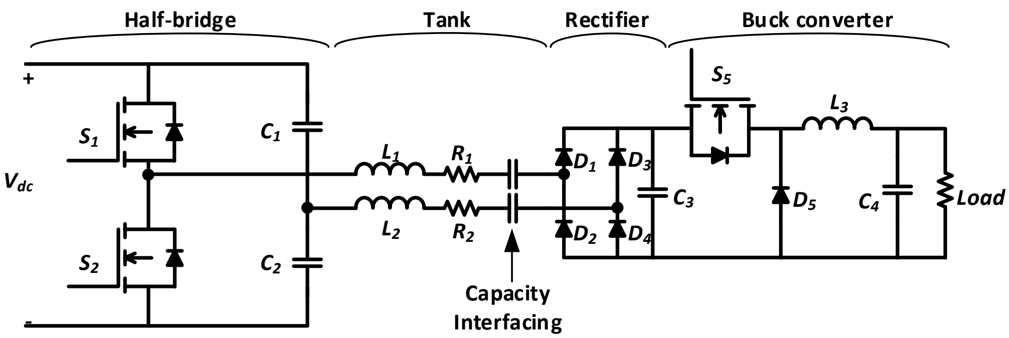


Figure. 3 Block Diagram of System



(a)



(b)

Fig. 4. System topology (a) H-bridge, (b) Half bridge

Table 1 System Operational Characteristics

Power Rating	10 W
Voltage Output	5.1 V
Maximum Current Draw	2.1 A

Table 2 System Design Characteristics

Output Power	10W
Output Voltage	5V
Output Current	2A
Input Voltage	60V

The voltage, current, and power outputs of the proposed converters were designed to match the original charger of a popular tablet, while the maximum V*I is a little higher than the rated power with allowed tolerance which are shown in Table 1. The cost of the system had to remain below commercially available wireless charging systems. The Launch Port, the most popular system, has the manufacturer's suggested retail price (MSRP) of $350. (2015) Therefore the target cost was to remain below $245, which at 70% of MSRP is a rough estimate of material cost for the product. Finally, the size of the capacitive interface was limited to the size of the tablet itself, which is 180*240mm. The system design characteristics are based on a real tablet's operational characteristics listed in Table 2.

III. SIMULATIONS

A simulation that models both converter topologies was built in Simulink using the SimPowerSystem toolbox to ensure that both topologies operated at resonance for the selected tank capacitance and inductance at a frequency of 144kHz. The simulation was later verified in experiments but a better simulation model is still in progress to ensure that current waveforms match in simulations and experiments. Figure 5 shows the waveforms of the H-bridge, while Figure 6 shows the waveforms of the half-bridge. From Figures 5 and 6 it can be seen that the tank current and tank voltage are in phase, indicating operation at resonance that correct operation was achieved and energy was transferred. The tank current was similar to a sine wave, indicating successful band-pass filtering of the square wave output.

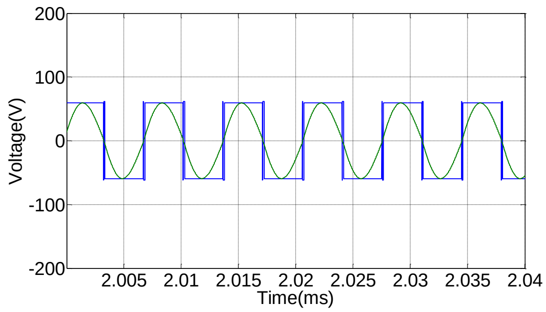


Fig. 5. Simulation Waveforms of H-bridge
Blue: H-bridge output voltage; Green: Tank voltage

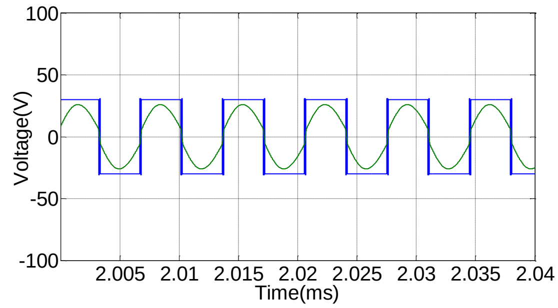


Fig. 6. Simulation waveforms of half-bridge
Blue: Half-bridge output voltage; Green: Tank voltage

IV. EXPERIMENTS

Both converters were experimentally tested without the output buck converter and with a 200Ω resistive load as shown Figure 7. Cost of the PCB and enclosure was not included, but the price of electronic components is very attractive. The part number and values of components in the circuit is shown in Table 3 which leads to a total cost of $21.90 per H-bridge system, and a total cost of $18.05 per half-bridge system. All the component used in both systems are the same except the DC-link capacitor which is not necessary in H-bridge. For preliminary testing and for this digest, open loop control via two adjustable function generators was used, and the operational frequency was hand adjusted to be 144kHz based on phase and power factor measurements.

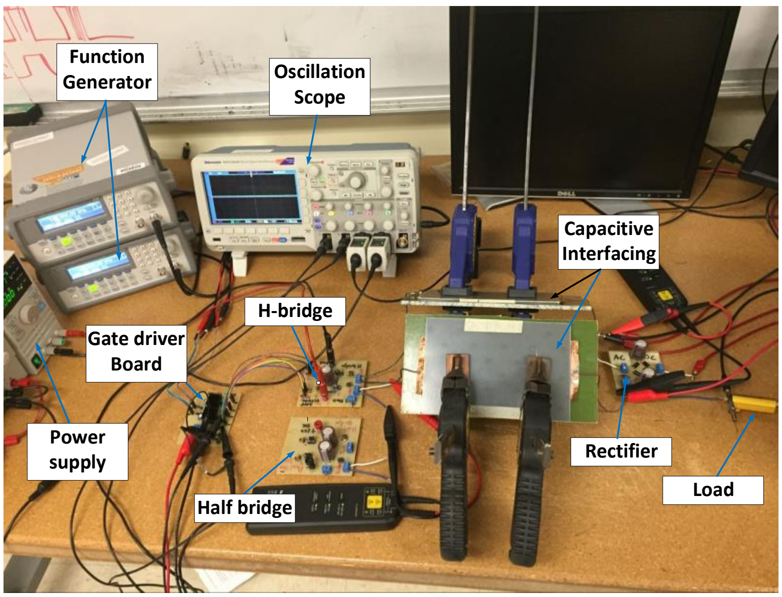


Fig. 7. Testing Platform

Table 3 Cost comparison

Component	Part Number	Value
MOSFET (H/Half)	AOI4286	N/A
Tank inductor (H/Half)	1812FS-334_LB	330uH
Zener diode (H/Half)	1N5230BTR	N/A
Gate driver (H/Half)	IR2113PBF	N/A
Aluminum capacitor (H/Half)	ESK226M016AC3AA	22uF
Diode (H/Half)	EGP10G	N/A
Gate resistor (H/Half)	CFR-12JB-52-20R	20Ω
Ceramic capacitor (H/Half)	490-5375-ND	1uF
Rectifier diode (H/Half)	STPS5L60	N/A
DC-link capacitor (Half)	EKZE101ELL471MM25S	470uF

V. PRELIMINARY RESULTS

From Table 4 and Figure 10, it can be seen that the preliminary results of the experiment showed that the h-bridge, which cost $21.9 per system, was more efficient than the half bridge in both simulation and experimental results, which cost $18.05 per system. A measured PF of 0.96 for the H-bridge and 0.97 for the half bridge shows that both devices acted to be close to a resonant load.

The preliminary experimental waveforms of H-bridge and half-bridge are shown in Figures 8 and 9 and they were similar to the simulation waveforms, which shows a good validation of simulation and experimental results. The tank current and voltage were in phase with the bridge voltage and current, indicating the operation is at resonance, just as was predicted by the MATLAB simulation. However, the sinusoidal tank voltage and current was more triangular, likely due to the extra inductance in the converters caused by the unideal construction. The final paper will utilize improved PCB based construction, which should improve waveform characteristics considerably.

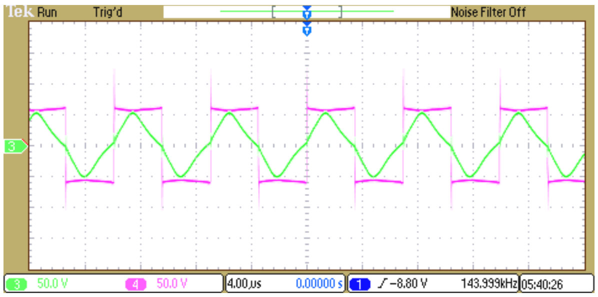


Fig. 8. H-bridge System
Magenta: H-bridge output voltage;
Green: Tank voltage

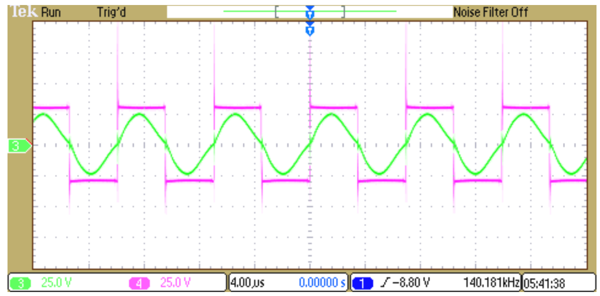


Fig. 9. Half-bridge System
Magenta: Half-bridge output voltage;
Green: Tank voltage

Table 4 Simulation vs. Experimental Results

	Simulation Efficiency	Experimental Efficiency
H-Bridge	79.56%	57.00%
Half Bridge	54.70%	50.90%

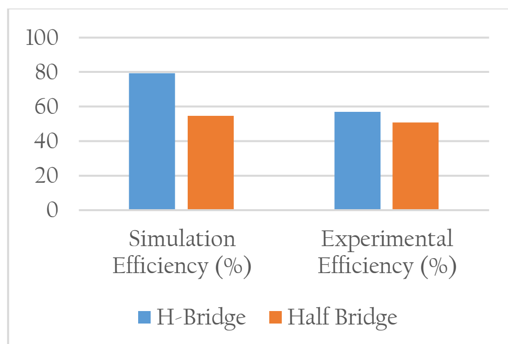


Fig. 10. Experimental Efficiency Results

Experimental results show lower efficiency than expectation, indicating that both models have unaccounted losses. One source of loss may be the proto-board construction, which adds stray capacitance and inductance. However, assuming that both devices encountered similar losses due to construction and material usage, the clear conclusion is that in efficiency perspective, the h-bridge is a more effective topology for consumer wireless charging by capacitive coupling applications. The half bridge is less efficient but more cost effective. The reason that the h-bridge was more expensive than the half bridge was due to it including double the number of gate driver circuits and MOSFETS compared to the half-bridge topology. The H-bridge is a cost effective topology when the cost of the two transistors the additional gate driver circuit are less than the cost of the half-bridge DC link capacitors. As this is a low voltage, low power application, the half bridge is a more cost effective topology. To combine the cost effectiveness and efficiency, an efficiency and cost ratio (ECR) should be considered. Based on the experimental results the ECR of per H-bridge system is 2.6%, and the ECR of per half bridge system is 2.8%, which indicates half-bridge is more suitable for capacitively-coupled wireless charging with the consideration of both efficiency and cost.

VI. CONCLUSION

This paper clearly shows that the h-bridge is more efficient and the half-bridge is more cost effective in capacitively-coupled charging applications, however, with the consideration of ECR, half-bridge has more superiority. The results set a clear precedent for future design engineers. Immediate future work that will be completed will focus on building the whole desired circuits on a PCB to eliminate losses due to construction, and conversion to closed loop control via a PLL controlled by a FPGA. A more accurate simulation model is desired to facilitate control design. Long term work will focus on replacing the silicon MOSFET with Gallium Nitride (GaN) since it's more efficient at high switching frequency and implementing ZVS and testing a class E amplifier for the same application.

VII. REFERENCES

[1]Mercier, P.P.; Chandrakasan, A.P., "Rapid Wireless Capacitor Charging Using a Multi-Tapped Inductively-Coupled Secondary Coil," *IEEE Transactions on Circuits and Systems I: Regular Papers, vol.60, no.9, pp.2263-2272, Sept. 2013*

[2] M. Kline, "Capacitive Power Transfer," M.S. thesis, Electrical Engineering and Computer Sciences, Univ. California, Berkeley, 2010

[3]Kline, M.; Izyumin, I.; Boser, B.; Sanders, S., "Capacitive power transfer for contactless charging," in *Proc. Applied Power Electronics Conference and Exposition (APEC), 2011, pp.1398-1404*

[4] Dai, J.; Ludois, D., "A Survey of Wireless Power Transfer and a Critical Comparison of Inductive and Capacitive Coupling for Small Gap Applications," *IEEE Transactions on Power Electronics, , vol.PP, no.99, pp.1,1*

[5] Liu, J.; Hu, A.; Nair, N., "Modelling and Analysis of a Capacitively Coupled Contactless Power Transfer System," *Transactions on IET Power Electronics, vol.4, no. 7, pp.808-815, Aug. 2011*

[6] Chao Liu; Hu, A.P., "Steady State Analysis of a Capacitively Coupled Contactless Power Transfer System," in *Proc. Energy Conversion Congress and Exposition, 2009, pp.3233–3238.*

[7] Liu, C.; Hu, A.P., "Power Flow Control of a Capacitively Coupled Contactless Power Transfer System," in *Proc. Industrial Electronics Conference of IEEE, 2009, pp. 743–747.*

[8] Theodoridis, M., "Effective Capacitive Power Transfer," *IEEE Transactions on Power Electronics, vol.27, no.12, pp.4906-4913*

[9] Qiang, H.; Huang, X.; Tan, L.; Huang, H., "Study on Topology Design of Wireless Power Transfer for Electric Vehicle Based on Magnetic Resonance Coupling," *Advanced Materials Research (AMR), ,vol.308-310, pp.1000,1003*

[10] Kazimierczuk, M.; Wang, S. "Frequency Domain Analysis of Series Resonant Converter for Continuous Conduction Mode," *IEEE Transactions on Power Electronics,vol.7, no.2, pp. 270,279*