Software-based Wireless Power Transfer Platform for Power Control Experimentation

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Abstract—**We present the design and evaluation of a software-based wireless power transfer platform that enables various open- and closed-loop power control functions to be prototyped and experimented. Our platform is based on a loosely-coupled planar wireless power transfer system using the class E power amplifier via inductive coupling. In conjunction with the system, flexible control functions are implemented using NI DAQ board and algorithms on MATLAB/Simulink software. For verifying our platform, we show two power control experimentations. The one is an output voltage regulation on different receiver position using a closed-loop power control, and the other is a no-load and metal detection using an open-loop power control. We show the good performance results for our two experimentations. We believe it is the first inexpensive platform that readily experiments the power control algorithm of a loosely-coupled planar wireless power transfer system.**

Keywords—wireless power; class-E amplifier; power control; inductive coupling; fault detection; voltage regulation

I. INTRODUCTION

In recent years, planar wireless power transfer systems have drawn a great deal of attention. Especially, the wide usage of mobile devices, such as smart phones, tablet computers, etc., have justified the necessity of planar wireless power transfer. International standards, such as Wireless Power Consortium (WPC), Alliance for Wireless Power (A4WP), Power Matters Alliance (PMA), etc., have been building de facto standards for commercialization of planar WPT system[1]. For example, WPC released Qi standard for smart phone wireless charging in 2011 [2].

A major issue involved in designing this type of planar wireless power transfer system is power fluctuation due to coupling and loading variations. If no adaptive power control is used, it is required to transmit excessive power to accommodate all the working conditions, which substantially reduces the power efficiency and imposes potential safety concerns. Therefore, in order to successfully commercialize planar wireless power transfer systems, it is necessary to have a robust open- and closed-loop power control between power source and charging devices[3]. First of all, stabilizing the received power over a wide range of coupling and loading variations using closed-loop control function is imperative. The transmitter should change its transmitted power in a way that the received power stays slightly above the minimum level that keeps receiver operation[4]. Also, wireless power transfer systems should ensure several safety issues using open loop control function. For example, wireless power transfer system should not heat up metal objects placed on or near the charging surface[5].

In this paper, we present the design and evaluation of a software-based wireless power transfer platform that gives users flexible open- and closed-loop power control functions. The platform is based on a loosely-coupled planar wireless power transfer system using the class E amplifier via inductive coupling. Its power control function is implemented using a NI DAQ and algorithms on MATLAB/Simulink software. Because all power control algorithms are implemented by MATLAB/Simulink software, it can be modified simply. Without a long and costly development process for developing a custom application-specific integrated circuit (ASIC), we are taking advantage of the flexible programming of a MATLAB/Simulink software. This is a novel approach for MATLAB/Simulink software to be part of a planar wireless power transfer system for power control experimentation.

II. PROPOSED SYSTEM

Figure 1 illustrates the overall block diagram of a software-based wireless power transfer platform for power control experimentation. Proposed platform is divided by 2 different blocks. Upper circuit part is a loosely-coupled planar wireless power transfer system using the class E power amplifier via inductive coupling. At first, the class E switching mode power amplifier is driven by a low-power clock with a gate driver, followed by a transmitter coil. The transmitter coil is in turn inductively coupled to the receiver coil. Finally, a full bridge rectifier using Schottky diodes is adopted to convert AC power to DC.

Lower control part consists of a PC, a NI DAQ-6008 board, a DC-DC buck converter, and software we have developed using MATLAB/Simulink. Proposed control system uses three sensors to monitor transmitter and receiver status. Using these sensing information, power control algorithm on MATLAB/Simulink software provides control voltage for a class E amplifier through a DC-DC converter via DAC of NI DAQ-6008 board.

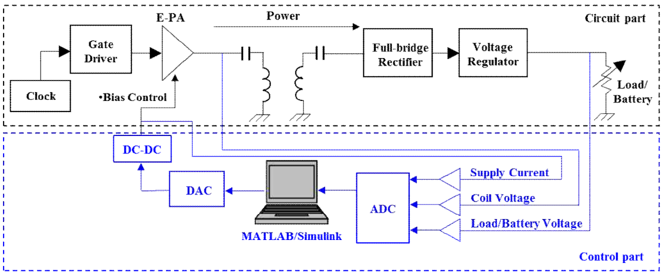


Figure 1. Overall block diagram of software-based wireless power transfer platform for power control experimentation.

A. Circuit part design

Figure 2 is a schematic of the fabricated wireless power transfer circuit. It mainly consists of a class E amplifier, transmitter and receiver coil pair, and a full bridge rectifier using Schottky diodes. The inverter is a class E amplifier using a cheap IRF510 power MOSFET driven by a low-power clock at 240 kHz. The class E amplifier drives the transmitter coil L_1. The induced voltage at L_2 is amplified by the resonant tank L_2-C_{rx}. Rectification is achieved via 4 diodes and a charging storage capacitor (C_L). Component values of L_{choke}, C_{shunt}, L_{out}, C_{out}, C_{tx}, and C_{rx} for optimum performance are selected based on the design rules similar to those presented in [6] and will not be discussed in this paper.

Although it would be ideal for coil pair to be the same size to ensure maximum coupling, our system uses a receiver coil significantly smaller than the transmitter coil. This allows user to freely place a device in any position and orientation. Therefore, the large transmitter coil, which has a dimension of 16 cm x 18 cm, is in turn inductively coupled to the small receiver coil, which has a dimension of 6 cm x 8 cm. Both coils were constructed of 100-strand #40 Litz wires. These coupling coils are designed by technique described in [7].

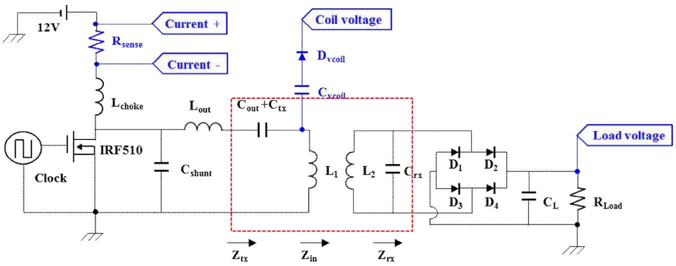
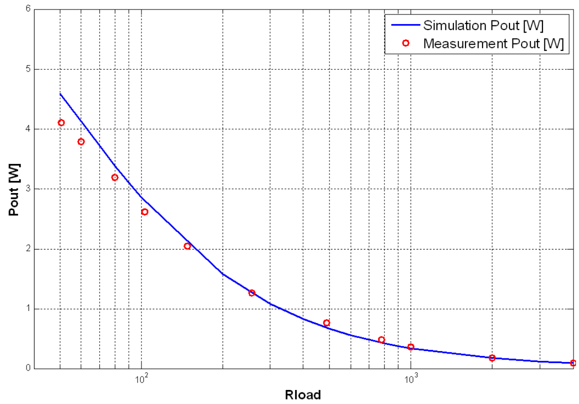
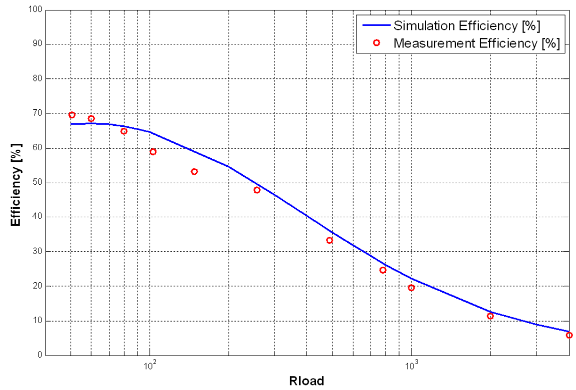


Figure 2. Schematic of fabricated wireless power transfer circuit.

Figure 3 shows measurement results of the received power and total efficiency versus load resistance, as well as the ADS simulated values. The system has power delivery of over 4 W and peak efficiency of over 70%. In addition, the fabricated system shows natural impedance response to achieve the desired power delivery profile across a wide range of load resistance while maintaining high efficiency to prevent any heating issues. For example, measured results show a high efficiency of at least 50% across the range of 50 Ω to 150 Ω, which matches the optimum range of power delivery above 2 W.



(a)



(b)

Figure 3. Measurement results as a function of R_{Load}. Circles are Measured values and Solid line is Simulated value of wireless power transfer circuit. (a) Received power (b) Efficiency

B. Control part design

As shown in Figure 2, proposed control system uses three sensors to monitor transmitter and receiver status, namely, the coil voltage, the supply current, and the load voltage. Coil voltage is extracted by rectifying the transmitter coil voltage via a high impedance path using a half wave rectifier. The voltage is then stepped down to workable voltage via a voltage divider. To mitigate loading effects and high frequency noise, a buffer of a operation amplifier is used before the NI DAQ-6008 board's ADC port. Next, supply current is extracted from the circuit via the current sense resistor R_{sense} in Figure 2. The R_{sense} resistor is located at the high side before L_{choke}. The voltage drop across the R_{sense} resistor is stepped up via a non-inverting operational amplifier. These two sensors can monitor transmitter status. Last, load voltage to monitor receiver status is extracted from R_{load} directly via a high impedance path.

Using these sensing information, power control algorithms on MATLAB/Simulink software provide control voltage for a class E amplifier through a DC-DC converter via DAC of NI DAQ-6008 board. Figure 4 is an example code on

MATLAB/Simulink for stabilizing receiver's output voltage. Using three sensing information (channel #0 for load voltage, channel #1 for coil voltage, and channel #2 for supply current), we can adjust class-E amplifier's bias voltage in order to maintain receiver power to 2 W constantly.

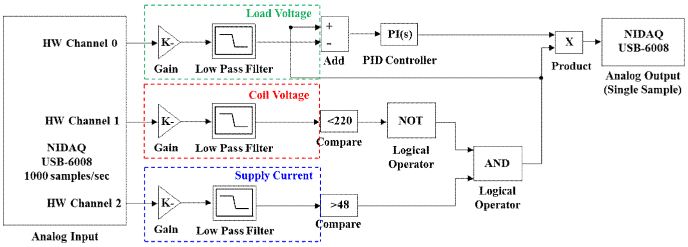


Figure 4. Example code on MATLAB/Simulink for stabilizing receiver's output voltage.

III. APPLICATION EXAMPLES

To verify our platform, we show two power control experimentations. The one is an output voltage regulation using a closed-loop power control, the other is no-load and metal detection using a open-loop power control.

A. *Output voltage Regulation– closed loop control*

As the position of receiver coil varies from center of transmitter coil, received power will change accordingly. Changes in the received power can cause large output voltage variations. Therefore, stabilizing the output voltage under coupling variation is imperative in a loosely-coupled planar wireless power transfer system design[8]. Our platform can change the transmitted power in a closed loop in a way that the received power stays slightly above the minimum level that keeps the receiver operational.

Our experimentation is as follows; Power transfer is started when receiver coil is located on transmitter coil. NI DAQ-6008 ADC board senses the status of transmitter and receiver. Using these sensing information, power control algorithms on MATLAB/Simulink software calculate appropriate control voltage for the class E amplifier through a DC-DC converter via DAC of NI DAQ-6008 board. Figure 5 shows the experimental setup of our software-based wireless power transfer platform. The sensing signals are processed in software on a PC with modest processing capabilities and all signal processing is done in MATLAB/Simulink environment.

Figure 6 shows the measured result of receiver's output voltage on different positions with power regulation using closed loop power control or not. We move receiver coil from side to side and measure R_{load} voltage. Without power regulation, default bias voltage of class E amplifier is fixed to 12 V, and the output voltages are changed due to a coupling variation on different receiver coil positions. On the other hand, our power control algorithm with power regulation can automatically adjust the input bias voltage of class E amplifier. Hence, we can look the constant output voltage of 2 W on every position. In detail, our power control algorithm generates control voltage from 1 V to 3 V. Using these control voltage, DC-DC buck converter generates output voltage from 9.4 V to 11.3 V to keep the receiver power to 2 W constantly.

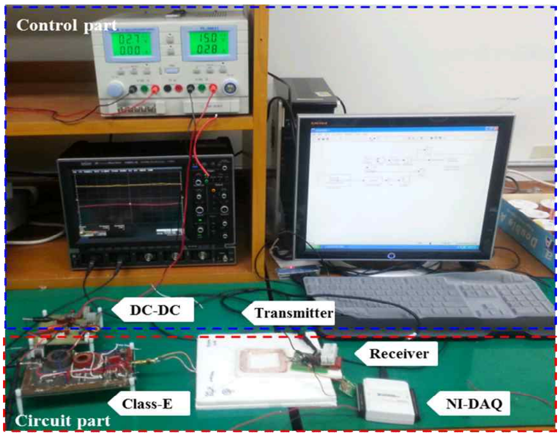


Figure 5. Experimention setup of our software-based wireless power transfer platform.

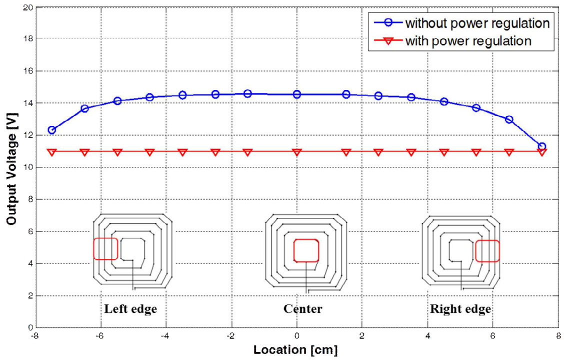


Figure 6. Measured result of output voltage on different receiver positions.

B. *Load and metal detection – open loop control*

Figure 7 shows the coil voltage and supply current space diagram which is used to detect no-load and metal object. When any receiver coil is located on the transmitted coil, values of transmitter coil voltage and supply current vary with load variations. For example, supply current goes downward when the load resistance changes from 50 Ω to 4 kΩ. This is because receiver pad don't need a lot of supply current at overcharged-state of 4 kΩ. But in case of detecting metal, it consumes excessive supply current and coil voltage. Also, our system shows the no-load condition when the operating condition is in the vicinity of the circle shape. Therefore, we can estimate what kinds of loads exist. For power saving and safety, the transmitter can be powered down when there is no valid receiver coil placed on the transmitter coil. In detail, if no-load or metal object is detected, power control algorithm on MATLAB/Simulink software can be powered down the DC-DC converter via DAC of NI DAQ-6008 board automatically.

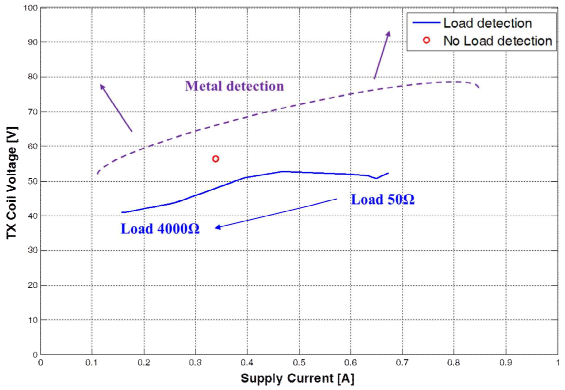


Figure 7. Measured result of different loading conditions on coil voltage vs. supply current

IV. CONCLUSIONS

In this paper, we suggest a software-based wireless power transfer platform using MATLAB/Simulink and NI DAQ board for open- and closed-loop power control experimentation, which has a merit of easy modification by re-writing user-level software. And we give two experimentations for the software-based wireless power transfer platform, which are output voltage regulation on different receiver positions and no-load and metal detection. We develop PC-based real system and show the good performance results for our two experimentations. We believe it is the first inexpensive tool that readily gives easy method to the power control algorithm of wireless power transfer system.

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