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WIRELESS CHARGING OF A SUPERCAPACITOR MODEL VEHICLE USING MAGNETIC RESONANCE COUPLING

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ABSTRACT

This paper discusses the basic considerations and development of a prototype demo system for the wireless charging of supercapacitor electric vehicles, which uses magnetic resonance coupling. Considering future ubiquitous wireless vehicle stationary and dynamic charging facilities, supercapacitor could be an ideal device to store a reasonable amount of electrical energy for a relatively short period of time. The prototype system includes all the major functional components for an electric vehicle's powertrain and wireless charging system including coils for energy emitting and receiving, a FPGA PWM input generation board, high frequency DC/AC inverter and AC/DC rectifier circuits, an on-board supercapacitor module, sensors for SOC level measurement and charging position detection, etc. All the components are integrated into a model electric vehicle. The prototype system well demonstrates the idea of the fast and frequent wireless charging of on-board supercapacitors. Promising results from initial experiments are explained; while further investigations, optimized design of components and a system-level optimization are needed.

1 Introduction

It has been world-widely recognized that electrifying vehicles can provide a solution to the emission and oil shortage problems brought by billions of conventional vehicles today, which are propelled by internal combustion engines. Consequently the most current research on electric vehicles (including the hybrid electric vehicles) are focusing on their environment and energy aspects. And one of the key issues for widespread use on electric vehicles is considered to largely rely on the development of long-term energy storage devices with competitive cost.

However, the specific energy of petrol (12000Wh/kg) is hundreds of times that of a mass-market battery (20$\sim$200Wh/kg) [1]. A high battery storage capacity and more efficient electric motor are not enough to entirely compensate for the huge mismatch in energy density. Depending on existing battery technology alone is unlikely to make electric vehicles competitive against conventional internal combustion engine vehicles. Innovative ideas are needed to take full advantage of the vehicle electrification. This will require a new generation of vehicles specifically designed and configured as electric vehicles, not the conventional vehicles converted to electric ones by simply replacing engine and tank with electric motor and battery pack.

Compared with chemical and mechanical energy, electrical energy is easier and more efficient to transform, transfer and control. It is said that the future of electric vehicles is relying on the breakthrough of the battery technology, which means the future vehicles will continue to depend on the chemical energy, but only move from oil-dependent to battery-dependent. However, the energy density, reliability, life cycle and management of batteries are always problematic. Considering the urgent global-scale challenges of environment and energy shortage problems, obviously besides waiting for a substantial progress in battery technology, other alternative technological options are also desired. And it is crucial to take full advantage of the revolutionary impacts brought by the electrification of vehicles.

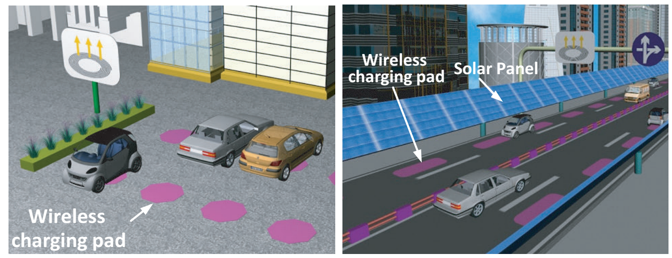
The idea of wireless transfer of electrical energy has been known from long time ago. Nikola Tesla proposed a “world system” for “the transmission of electrical energy without wires” that applies capacitive coupling in 1904 [2]. In recent years, there is a renewed interest in the research and applications of wireless energy transfer. Various methods have been applied such as inductive coupling, magnetic resonance coupling, microwave and laser radiation, etc [3]- [10]. Instead of near field in both inductive coupling and magnetic resonance coupling, microwave and laser radiation use far field to transfer electric power wirelessly. Efforts are needed to design a proper antenna array to shape the radiation beam correctly to ensure a high efficiency power transmission. A focused beam usually requires a large size antenna array. Besides, high power microwave/laser power sources are expensive.

The magnetic resonance coupling occurs when power sources and receiving devices are specially designed magnetic resonators with approximately same natural frequencies [6]. The inductive coupling systems can also be tuned to resonance [5] [11]. As another near-field method, inductive coupling is a mature technique that is widely used today for both low and high power applications. It can enable large power transfer in the order of tens of kW with a 10cm air gap between emitting coil and receiving coil at a low 90’s% overall system efficiency [12]. The power transfer distance for inductive coupling technique has been improved to 20 cm with the optimization of the magnetic structure [13]. The inductive coupling systems usually operate in kHz band because the state-of-art power electronic devices are available for both power generation and conditioning. On the other hand, this low frequency requires a large size coil and heavy ferrite materials, which may not be favored by vehicles in terms of payload efficiency. The weight of an on-board receiving coil with its ferrite core may be over 35kg for a 30kW commercial inductive coupling system [12]. The magnetic resonance coupling systems work at higher operating frequencies in MHz band. It is considered to be promising for the purpose of the wireless vehicle charging due to the following advantages:

1. High efficiency at moderate distance
2. Large transmission distance with moderate efficiency
3. Only interact with resonant body (lower electromagnetic exposure to non-resonant body)
4. Lighter weight (no need of iron or ferrite cores)
5. More compact in size

Wireless energy transfer suggests the electrification of vehicle could extend beyond delivering electrical energy and converting it into chemical energy through the on-board batteries of stationary vehicles. Especially, the wireless charging of moving vehicles on demand and in real-time (i.e. dynamic charging) would lead to a paradigm shift of conventional transportation system, as illustrated in Fig. 1.

The wireless charging of electric vehicles will significantly alleviate the demand on on-board batteries or even enable



(a) Stationary charging (b) Dynamic charging

Figure 1. Future electric vehicle wireless charging systems

battery-free vehicles. Considering the requirement of fast and frequent wireless charging, another type of electricity storage device, supercapacitors, could be more suitable than batteries due to their excellent characteristics for vehicle on-board usage:

1. Work electrostatically without reversible chemical reactions involved
2. Theoretically unlimited cycle life (can be cycled millions of time)
3. Fast and high efficient charge/discharge due to small internal resistance (97-98% efficiency is typical)
4. Precise voltage-based SOC (State Of Charge) measurement (energy stored in capacitors is proportional with the square of charge voltage)
5. A typical operating temperature range of -40 to +70°C and small leakage current
6. Environmentally friendly without using heavy metal for its structure material

Supercapacitors have been used as auxiliary energy storage systems in hybrid and fuel-cell electric vehicles [14] [15]. Compared with batteries, supercapacitors have a lower energy density but a higher power density, which make supercapacitors suitable for storing and releasing large amounts of electrical energy quickly; while batteries are desired for storing large amounts of energy over a long period of time. With future ubiquitous wireless stationary and dynamic charging facilities, electric vehicles may only need to store a reasonable amount of electrical energy for a relatively short period of time. Supercapacitors could be ideal on-board energy storage devices for the fast and frequent wireless charging. Especially, the fast wireless charging of supercapacitors is well suitable for public transportation systems, in which the vehicles have guaranteed stops and scheduled dwell time within a certain distance.

In this paper, a prototype demo system for the wireless charging of a supercapacitor model vehicle is reported, which uses magnetic resonance coupling. This is a demonstration of the concept of wireless charging to pure EVs powered by on-board supercapacitors alone, other than hybrid EVs in which supercapacitors serve as an auxiliary energy storage device [16] [17].

With the maturity of wireless charging technique, future EVs can be even powered by the electrical power wirelessly with a minimum loading of battery/supercapacitor. The prototype system includes coils for energy emitting and receiving, a FPGA (Field-Programmable Gate Array) PWM (Pulse Width Modulation) input generation board, high frequency DC/AC inverter and AC/DC rectifier circuits, an on-board supercapacitor module, sensors for SOC level measurement and charging position detection, and a model electric vehicle. Namely, all the major functional components for an electric vehicle's powertrain and charging system are included. Promising results from the initial experiments are also explained; while further investigations, optimized design of components and a system-level optimization are needed.

The operating frequency for the magnetic resonance coupling spans from kHz to GHz [18]. Higher frequency is usually desired for more compact and lighter resonators. However, there are restrictions on the usable frequency range under the regulation of ISM (industrial, scientific and medical) band and the performances of power switching devices [19]. For a validation purpose, in the prototype system the DC/AC resonant inverter is composed of four high speed MOSFETs with targeted frequency of 1MHz for the generated AC power.

2 Wireless Charging System Design
2.1 Coils

As shown in Fig. 2, there are three types of coils in the wireless charging system, namely one emitting coil, two resonating coils, and one receiving coil, respectively. The resonating coils work as an isolated transformer to transfer the electromagnetic energy from one winding to another using magnetic resonance coupling which is intended to extend the transfer distance to a considerable level, such as 10cm; while the conventional magnetic coupling without resonance can only reach a transfer distance less than 1cm without sacrificing the transfer efficiency. The emitting and receiving coils are non-resonating coils. They are inductively coupled to the resonating coils as the input/output terminal in order to minimize the effect of external loading to the resonating coils, which usually decreases the quality factor of each resonating coil, thus the transfer efficiency.

To achieve the maximum power transfer efficiency of this coil combination, the distance between the transmitting/receiving coil and its adjacent resonating coil need to be optimized as well as the distance between two resonating coils. At the same time, the receiving coil presents an inductance to the rectifier and charging circuit. This inductance makes the charging circuit behave as a current source that is actually required by the charging characteristics of supercapacitors.

The operating frequency of 1 MHz is selected as an initial target for the wireless charging system. At this frequency, the resonating coils can be modeled as a parallel LC resonant circuit.

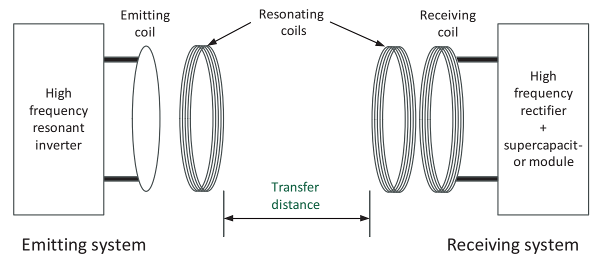


Figure 2. The configuration of the wireless energy transfer system

The resonance frequency is determined by the inductance and capacitance using Equ. (1),

$$f = \frac{1}{2\pi\sqrt{LC}} = 1MHz. \tag{1}$$

Namely,

$$LC = 2.533 \times 10^{-14} H \cdot F. \tag{2}$$

The circular shape coils are used to achieve the required inductance due to the simple structure and accurate theoretical inductance calculation. The inductance of a circular coils is calculated by Equ. (3),

$$L_{circle} = N^2 R \mu_0 \mu_r \left[ln\left(\frac{8R}{a}\right) - 2 \right]. \tag{3}$$

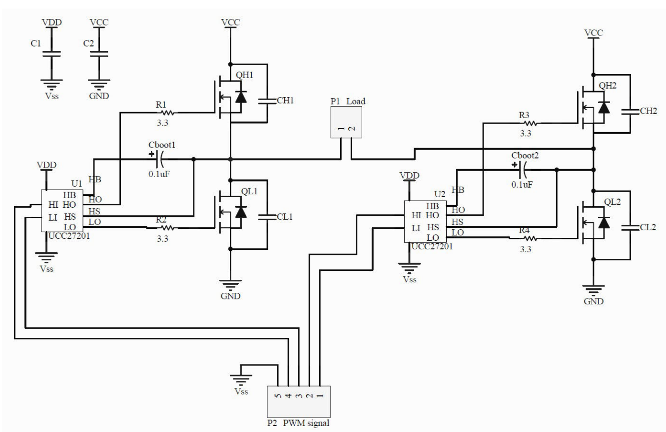
where N is the number of turns, R the radius of the circular coil, a wire radius, μ_0 absolute permeability ($4\pi \times 10^{-7} H/m$), and μ_r relative permeability of the medium (i.e. the ratio of the material's permeability to the permeability in air) which is 1 since magnetic resonance coupling does not need core. The radius of the selected wire is 0.7mm and the radius of the circular coil is approximately 10cm. The N is 5. Then the inductance is around 15.8μH and the capacitance is calculated to be 1.6nF.

2.2 High-frequency Resonant Inverter

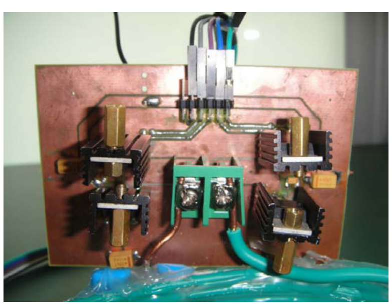
In the emitting system, a high-frequency DC/AC inverter is designed to supply the AC power at the resonance frequency of the two resonating coils. A full bridge voltage-fed topology is applied to perform the high-frequency DC/AC inversion. The schematic and photograph of the voltage-fed resonant inverter are shown in Fig. 3(a) and (b), respectively. The four gates are high-speed semiconductor MOSFET switches, Infineon IPD30N10S3L MOSFETs. The time characteristics of the MOSFET is shown in Tbl. 1. Parallel soft switching capacitors are employed to charge/discharge during the dead time; therefore, the switching losses can be essentially eliminated and also the stresses on the MOSFET switches are alleviated. As mentioned above, 1MHz is selected as the targeted frequency of the AC power converted by the full bridge resonant inverter.

Table 1. Time Characteristics of MOSFET

Turn-on delay time $t_{d(on)}$	6ns
Rise time t_r	4ns
Turn-off delay time $t_{d(off)}$	18ns
Fall time t_f	3ns



(a) Schematic circuit diagram



(b) Photograph

Figure 3. The high-frequency voltage-fed resonant inverter

The two half-bridges are driven by two MOSFET driver ICs, Texas Instruments UCC27201, respectively, which control the high side and low side MOSFET gates with PWM inputs. A FPGA board, Digilent Nexys2 built around a Xilinx Spartan-3E FPGA, is programmed by Verilog to generate a 1MHz square wave PWM input signals with MOSFET switching dead time considered.

2.3 Receiving system

The receiving system consists of resonating coil, receiving coil, AC/DC rectifier and supercapacitors to receive and storage the electromagnetic energy being wirelessly transferred from the emitting system. The resonating coil is as same as the resonating coil adjacent to the emitting coil. The 1MHz alternating electromagnetic energy is picked up by the resonating coil through magnetic resonance coupling; while the energy is then transferred to the receiving coil by inductive coupling. As shown in Fig. 4, the two coils are concentric and lie in the same plane to maximize the power transfer efficiency.

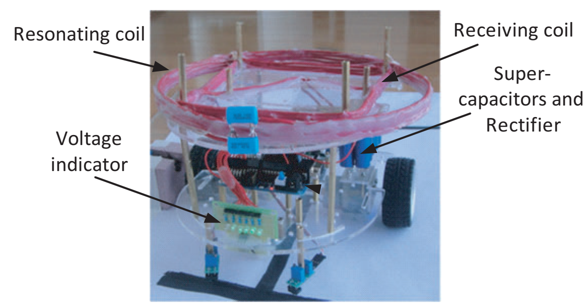


Figure 4. The wirelessly charged supercapacitor model vehicle

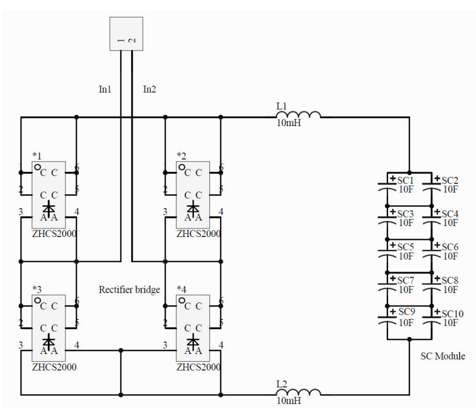
The whole receiving system is integrated with a rear two-wheel drive model electric vehicle. Especially, ten Falacap JLPA2R7106 supercapacitors instead of batteries are used as electricity storage devices for the fast and frequent wireless charging. Each supercapacitor has a rated 10F capacitance and 2.7V voltage, as shown in Tbl. 2. The supercapacitors are connected by 2P5S, i.e. 2 capacitors are in parallel and 5 in series; therefore the total rated capacitance and voltage are $10 \times 2/5 =$ 4F and $2.7 \times 5 = 13.5$V, respectively (see Fig. 5). A LED voltage indicator is introduced to visualize the SOC level of the supercapacitor module because the electrical energy stored in a capacitor is proportional with the square of its charge voltage.

Zetex ZHCS2000 surface mount Schottky Barrier Diode is chosen as the full bridge rectifier circuit diode, as shown in Fig. 5(b). The diode has very fast reverse recovery time t_{rr} of 5.5ns and small typical reverse current I_R of 160μA, which are suitable for high frequency rectification. The DC output of the rectifier is connected to the supercapacitor module. As shown in Fig. 6, the model vehicle has a similar configuration as real full-size electric vehicles. It can be used as a platform to investigate and verify the fast and frequency wireless charging of supercapacitor electric vehicles, the interactive relationship among various components from wireless energy transfer, storage to con-

Table 2. Specifications of supercapacitor

Rated capacitance	10F
Rated voltage	DC 2.7V
Internal resistance (AC)	$< 30\text{m}\Omega$
Internal resistance (DC)	$< 50\text{m}\Omega$
Maximum current	>9.00A
Size (D×L)	12mm(Φ) × 26mm(H)
Weight	3.0g
Power density	3.38Wh/kg / 4.30Wh/L

(a) Supercapacitor module



(b) Schematic circuit diagram of rectifier and supercapacitors

Figure 5. Supercapacitor module and high frequency rectifier

sumption, and the optimized configuration, design and control strategy, etc.

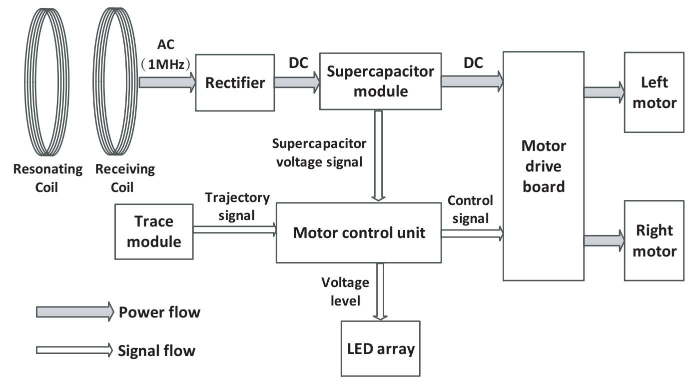
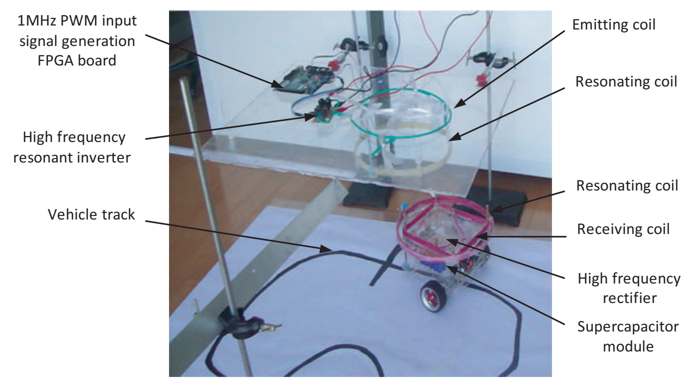
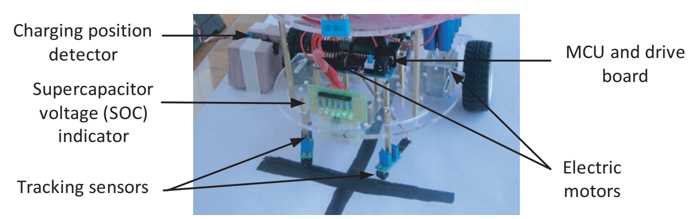


Figure 6. The configuration of the supercapacitor model vehicle

coil, high frequency rectifier, supercapacitor electricity storage device, motor control unit (MCU), motor driver and electric motors.



(a) Prototype demo system



(b) Model vehicle and sensors

Figure 7. The prototype demo system configuration

3 Prototype Demo System Configuration

The entire wireless charging system for the supercapacitor model vehicle is shown in Fig. 7. The prototype system includes all the major functional components for an electric vehicle's powertrain and wireless charging system including emitting coil, two resonating coils, 1MHz PWM input signal generation FPGA board, high frequency resonant inverter, receiving

As mentioned in the above section, the voltage-fed resonant inverter generates 1MHz PWM output voltage under the switching command from the FPGA board; one resonating coil next to the emitting coil picks up the alternating electromagnetic energy from emitting coil by inductive coupling; while another resonating coil receives the energy from resonating coil through magnetic resonance coupling and again the energy is transferred to receiving coil, which is inductively coupled with its adjacent resonating coil; then the 1MHz AC power is converted to DC power for the charging of supercapacitor module.

Special attention is also paid to the communication among vehicle, wireless charging station and road conditions including the sensing of SOC level of on-board electricity storage device, the position of wireless charging station and vehicle track, as shown in Fig. 7(b). The model vehicle tracks the black trajectory and automatically returns to the charging area when the SOC (voltage) level of the supercapacitor module is lower than a prescribed reference value. The charging system can communicate with the model vehicle and start the wireless charging when the model vehicle stops at the charging area due to the low SOC level.

4 Initial Experimental Results

Current initial experimental results of the wireless charging prototype system are reported as follows, while further detailed investigations are still needed. The simple experimental setup is shown in Fig. 8, in which the DC-link voltage for resonant inverter is 10V. Firstly the 1MHz resonant frequency is confirmed by measuring the voltage and current in the emitting coil, as shown in Fig. 9. It is observed that while the voltage in emitting coil is in square wave, a sine wave current is observed in the coil, which is expected from a voltage inverter in the design.

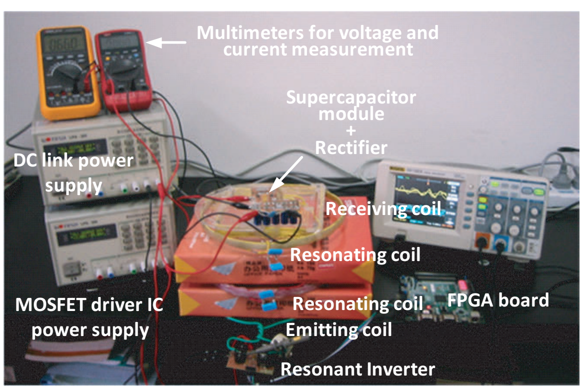


Figure 8. The experimental setup

Network analyzer is used to figure out the frequency characteristics among emitting coil, resonating coils and receiving coil. The network analyze has two ports, one is for inputting high frequency signals and the other is used to read the corresponding transmitted signals. Fig. 10 is obtained using network analyzer with 10cm distance between the two resonating coils. The figure clearly shows the maximum energy transfer efficiency occurs at frequency of 995kHz, which is in accordance

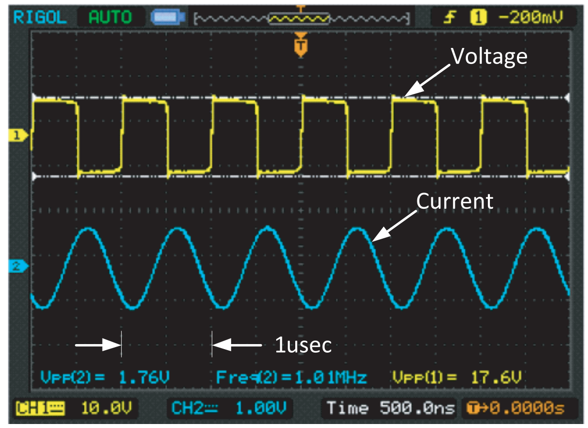


Figure 9. The voltage and current waves in the emitting coil

with the design target. The magnitude ratio is -1.42dB. Namely, $20log_{10}(V_{out}/V_{in}) = -1.42$, where V_{in} and V_{out} are the magnitudes of input and output voltages. Therefore, the energy transfer efficiency is $(V_{out}/V_{in})^2 = 72.1\%$. Fig. 11 and Tbl. 3 show the relationship between various resonant coil distance and corresponding energy transfer efficiency. Currently, the 50% efficiency occurs at the distance of about 22cm.

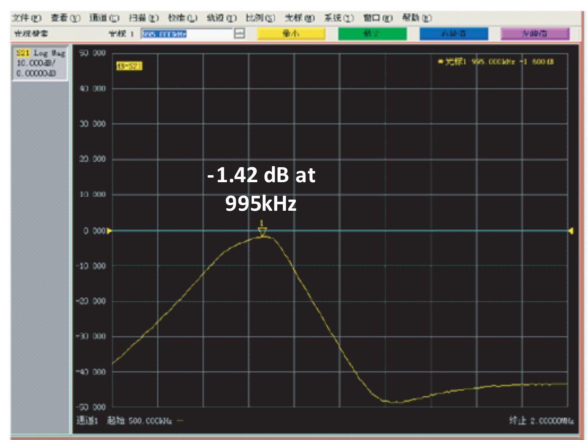


Figure 10. Transmission characterization of coils by network analyzer

Fig. 12(a)(b) show the voltage and current responses of the supercapacitor module and the DC power supply respectively during a complete wireless charging cycle, when the distance between the two resonating coils is 8cm. The total charging duration is approximately three minutes, which is much faster than that of Li-ion batteries as expected. The DC power supply maintains a constant voltage of 10V, while the current increases from 0.5 to 1A during the charging cycle. Therefore, the power provided by the DC supply power changes from 5 to 10W. For the

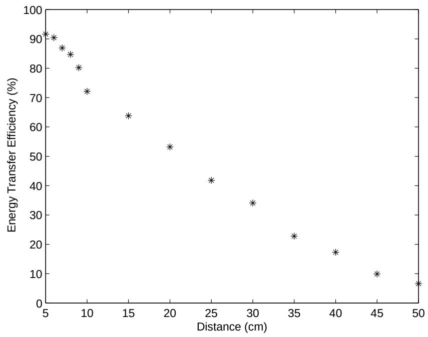
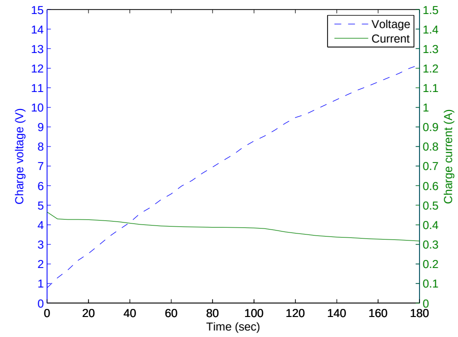


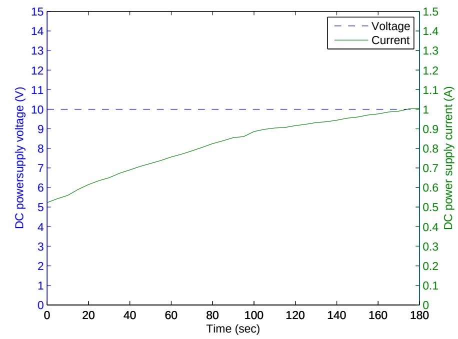
Figure 11. Resonant coil distance versus energy transfer efficiency

Table 3. Experimental Data for Distance Versus Efficiency

Distance (cm)	Magnitude Ratio (dB)	Efficiency (%)
5	-0.38	91.6
6	-0.44	90.4
7	-0.61	86.9
8	-0.72	84.7
9	-0.96	80.2
10	-1.42	72.1
15	-1.949	63.8
20	-2.737	53.2
25	-3.786	41.8
30	-4.671	34.1
35	-6.425	22.8
40	-7.618	17.3
45	-10.05	9.9
50	-11.809	6.6



(a) Supercapacitor modules



(b) DC power supply

Figure 12. Supercapacitor wireless charging characteristics

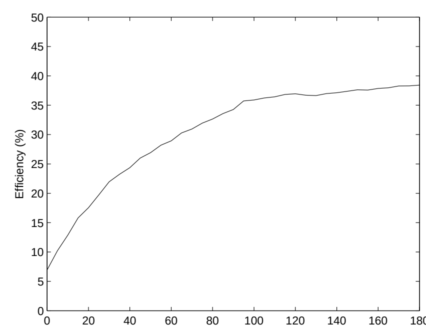


Figure 13. Total system efficiency

supercapacitor module, the current almost stays constant with a slight decrease over the charging cycle while the voltage increases monotonically from 0.78 to 12.37V. This observation is consistent with the constant current charging characteristic of supercapacitors. The power transfer to the supercapacitor modules varies from 0.36 to 3.87W. The total system efficiency is calculated and plotted in Fig. 13, in which the maximum system efficiency is approximately 38%.

5 Conclusions and Future Works

The design and configuration of a prototype vehicle wireless charging system are reviewed in detail including the winding and parameter tuning of coils, high frequency AC/DC and DC/AC conversion circuits, integration with the supercapacitor module, the model electric vehicle and sensors, etc. The prototype system well demonstrates the idea of the fast and frequent wireless charging of supercapacitor electric vehicles using magnetic resonance coupling. Though wireless energy transfer is considered to be complicated, it is proved to be a handy technology from the work described above. However, both component and system-level optimization are very challenging. Intensive investigations and research are expected in the future.

With this functional prototype system, several future works can be conducted. The costs of different power supply systems will be evaluated, such as wirelessly charged supercapacitors and Li-ion batteries. The corresponding control strategy will also be developed. It is interesting to demonstrate the dynamic wireless charging of the supercapacitor model vehicle. And the optimized design of circuits and coils are important for improving the efficiencies of energy transfer and transformation. Meanwhile, the system-level optimization of a wireless charging system need real-time feedback from the energy receiving/storage device, road and power sources through sophisticated sensors and wireless communication. A control strategy for such optimization will be an essential issue. The mini prototype system can work as a convenient testing platform to practice many novel ideas on the wireless charging of electric vehicles.

To prove feasibility of the proposed wireless charging technique on real EVs, a 1kW one-seat experimental vehicle is under development with both supercapacitors and batteries on board, as shown in Fig. 14. The power source for magnetic resonance coupling at MHz range is a high power RF power amplifiers using MOSFETs instead of conventional inverters at kHz for inductive coupling whose switching frequency can barely reach MHz. A kW-level 13.56MHz Class D amplifier is currently under development with a simulated efficiency of 80%. Future results will be reported in following papers.

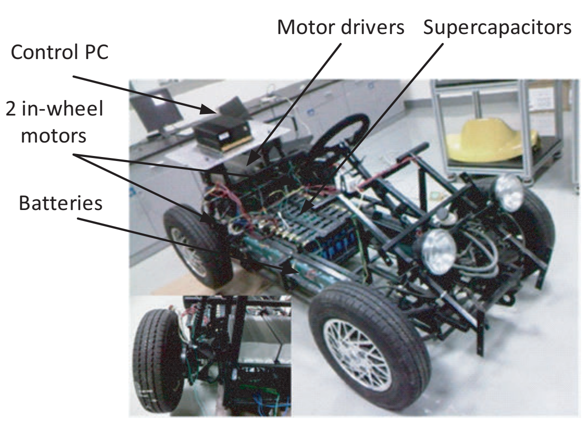


Figure 14. Experimental one-seat electric vehicle

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