

Supercapacitor Based Solar Wireless Charging Station

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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 power train 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.

KEYWORDS: Supercapacitor, Wireless Charging, Magnetic Coupling, Resonance,

I. INTRODUCTION

The energy transmission by the magnetic induction is an important technology, it contributes to making of various electric equipment cordless. It has been used for the wireless electric power transmission to IC card and the IC tag, etc., and it had tried to be used for the noncontact charger of the batteries of electric vehicles. Especially, this is thought to be one of the promising technologies as a security precaution to the leak accident at rain in the electric vehicle when it is charged in the outdoors. Our research group proposed the non-contact charge system using a self-oscillated Class C converter by magnetic coupling. We have done various reports since then about wireless power transmission, such as a noncontact charger of soft switching for which the inductor-commutation was used, and a noncontact charger for electric vehicles. Here, the electrochemical cell including the lithium-ion battery is a main current as the battery for the electric vehicle. However, this cell has the disadvantage in which it is weak in the rapid charge and discharge by large current. On the other hand, super capacitors (electric double layer capacitor) with an excellent rapid charge and discharge characteristics have been examined. The research of using this device as an energy storage element had started, and we also have reported the applied research about this device. The electrical bus that makes the super capacitor a power source has already been operated in Shanghai in China. However, the energy density of the super capacitor is lower than that of the electrochemical cell. Therefore when the voltage of the capacitor is decreased, the pantograph is raised and capacitors are charged in the bus stop (charge point) that the passenger gets on and off. Here it will be possible to charge rapidly with a super capacitor of the electric vehicle easily only by parking to the shop front or the garage if the wireless charge technology could be used. It will be opened from the trouble when the plug is connected by the hand by this technology. We have been researching the wireless power transmission that uses the resonance technology for the half bridge inverter and the noncontact transformer. However, when this system is applied to charge of a super capacitor, the fundamental characteristics, such as a relation of the resonance conditions, the composition of the noncontact transformer and the charging time of the super capacitor are not known well yet.

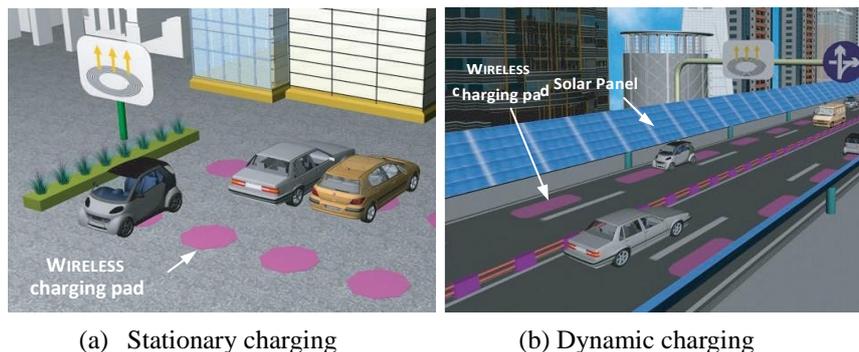
II. OBJECTIVES

- To develop a circuit using supercapacitor for wireless transmission of electric charge.
- To wirelessly charge an electric vehicle through resonance frequency.

III. DESCRIPTION

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.

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.



(a) Stationary charging

(b) Dynamic charging

Figure 1: Future charging systems for electrical vehicles

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

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 $+70^{\circ}\text{C}$ and small leakage current

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 wire- less 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 su- percapacitors 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 superca- pacitors serve as an auxiliary energy storage device 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 sys- tem includes coils for energy emitting and receiving, a FPGA (Field-Programmable Gate Array) PWM (Pulse Width Modu- lation) input generation board, high frequency DC/AC inverter and AC/DC rectifier circuits, an on-board supercapacitor mod- ule, 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, op- timized design of components and a system-level optimization are needed.

A. WIRELESS CHARGING SYSTEM DESIGN

Coils

As shown in Fig. 2, there are three types of coils in the wire- less 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 mag- netic coupling without resonance can only reach a transfer dis- tance 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 transmit- ting/receiving coil and its adjacent resonating coil need to be op- timized 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 charg- ing circuit behave as a current source that is actually required by the charging characteristics of supercapacitors.

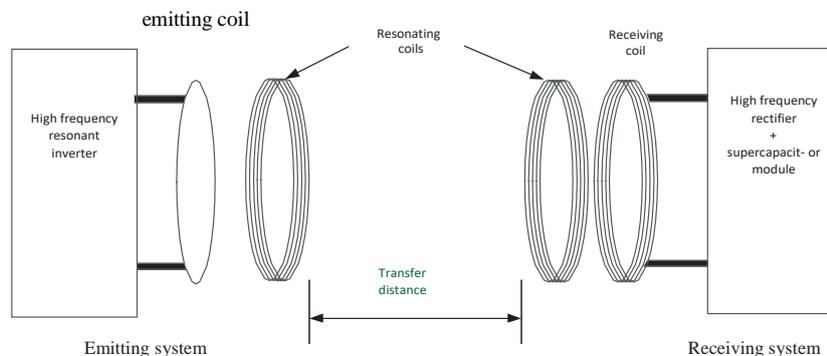


Figure 2: The configuration of the wireless energy transfer system

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

1

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

Namely,

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

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),

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

a

where *N* is the number of turns, *R* the radius of the circular coil, *a* wire radius, μ_0 absolute permeability ($4\pi \cdot 10^{-7} \text{H/m}$), and μ_r relative permeability of the medium (i.e. the ratio of the mate-

rial'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 $15.8\mu\text{H}$ and the capacitance is calculated to be 1.6nF.

B. 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.

C. WIRELESS RESONANT POWER TRANSMISSION CIRCUIT

The circuit for charging of a super capacitor that uses the wireless resonant power transmission is shown in Fig.

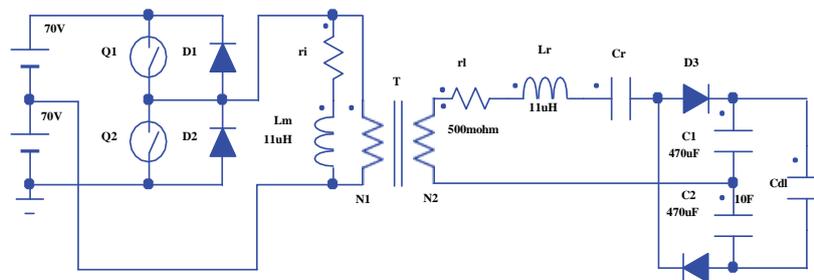


Figure 3

The half bridge inverter is on the primary side. The supercapacitor C_{dl} is charged with the voltage doubler circuit on the secondary side. The supercapacitor is charged with the voltage doubler circuit on the secondary side. The feature of this circuit is that the capacitor for the resonance and secondary winding of the transformer are connected with the series. The transformer T is expressed by the excitation inductance L_m , the leakage inductance L_r and the ideal transformer of winding N_1 and N_2 as shown in Fig. 1. T is the air-core transformer that is composed of the spiral windings as shown in Fig. 2, and the gap of the windings is g , and the distance from the center of the windings is d , respectively.

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.

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

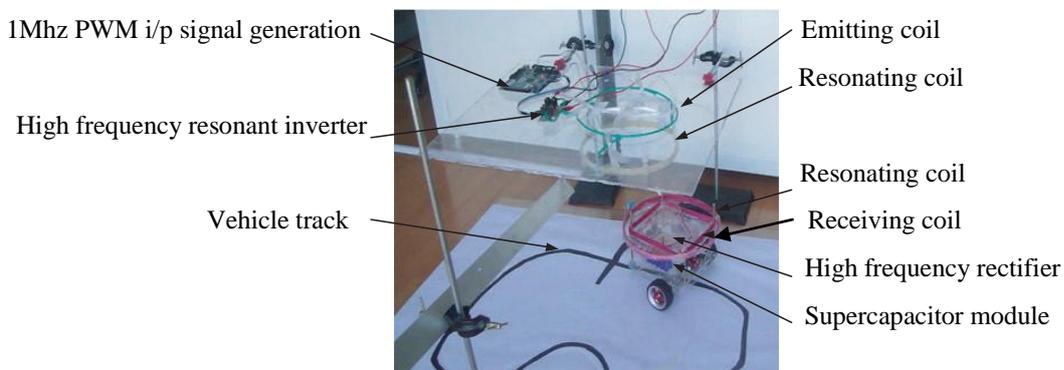


Figure 4(a) Prototype demo system

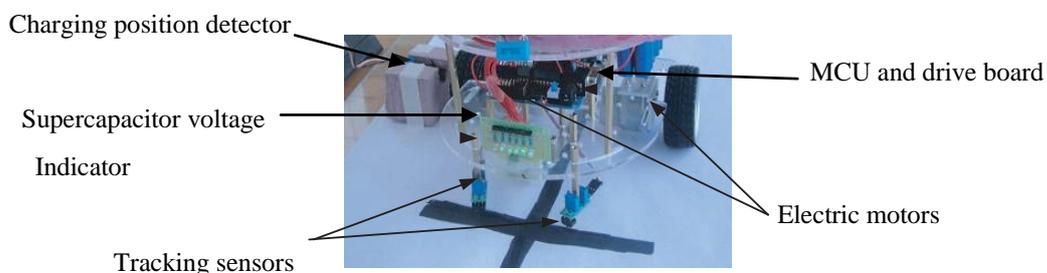


Figure 4(b) Model vehicle and sensors

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

Table 1: Specifications of Supercapacitor



Figure 5: Supercapacitor module

V. INITIAL EXPERIMENT 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 in-verter 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.

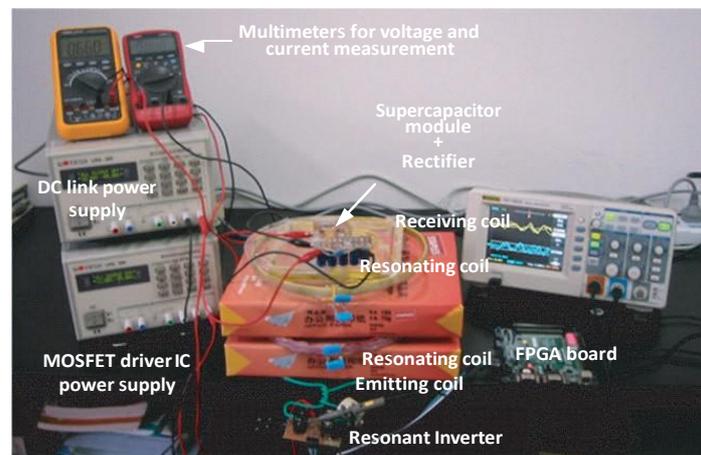


Figure 6: Experimental Setup

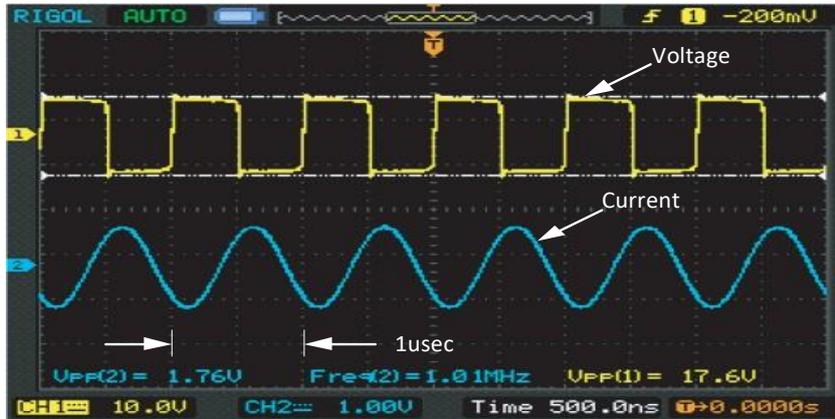


Figure 7: Current and voltage waves in emitting coil

The magnitude ratio is -1.42dB. Namely, $20\log_{10}(V_{out}/V_{in}) = -1.42$, 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.

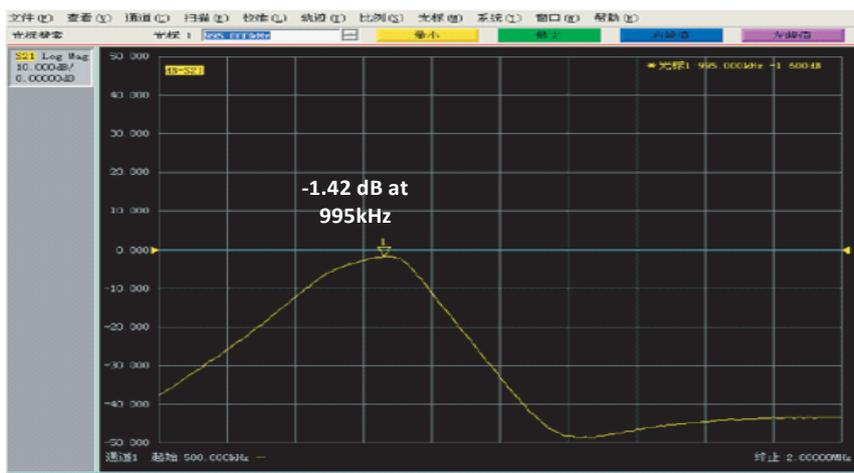


Figure 8: Transmission characteristics of coils

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%.

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

Table 2: Experimental data for distance vs efficiency

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VI. CONCLUSION 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.

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