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WIRELESS CHARGING OF ELECTRIC VEHICLES: A REVIEW AND EXPERIMENTS

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ABSTRACT

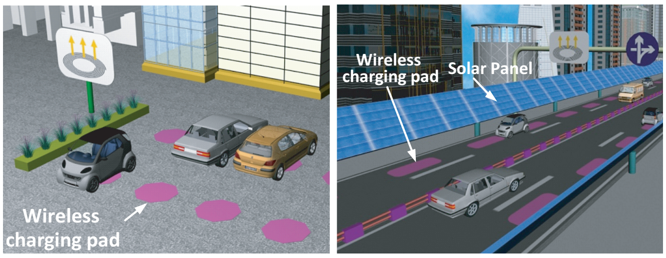
In this paper, the technologies for electric vehicle wireless charging are reviewed including the inductive coupling, magnetic resonance coupling and microwave. Among them, the magnetic resonance coupling is promising for vehicle charging mainly due to its high efficiency and relatively long transfer range. The design and configuration of the magnetic resonance coupling based wireless charging system are introduced. A basic experimental setup and a prototype electric vehicle wireless charging system are developed for experimental and research purposes. Especially the prototype system well demonstrates the idea of fast and frequent wireless charging of supercapacitor electric vehicles using magnetic resonance coupling. Though the idea of wireless energy transfer looks sophisticated, it is proved to be a handy technology from the work described in the paper. However, both component and system-level optimization are still very challenging. Intensive investigations and research are expected in this aspect.

1 Introduction

It has become a world consensus that vehicle electrification 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 (ICE). One of the key issues to commercialize electric vehicles is considered to largely rely on the development of long-term energy storage devices with competitive cost. However, the specific energy of gasoline (12000Wh/kg) is over or nearly hundreds of times that of a mass market rechargeable battery (20$\sim$200Wh/kg) [1]. It is known reliability, life cycle, weight and management of batteries are always problematic. Without a major breakthrough of battery technologies, electric vehicles are unlikely to become as convenient as conventional ICE vehicles, meaning they can travel 500 kilometers on a single charge and can recharge in minutes. Considering the urgent global scale environment and energy shortage problems, discussions are needed on alternative technological options other than batteries.

Compared to chemical and mechanical energy, electrical energy is convenient to transfer, transform and control. For a widespread use of electric vehicles, it is crucial to make the best use of novel possibilities brought by the electrification of vehicles. One of them is the wireless vehicle charging. The wireless transfer of electrical energy suggests the electrification could extend beyond delivering electrical energy and converting it into chemical energy through the on-board batteries of stationary vehicles. Especially, charging moving vehicles wirelessly on demand, i.e. dynamic charging, would lead to a paradigm shift of conventional transportation system, as illustrated in Fig. 1. With future ubiquitous wireless charging facilities, electric vehicles may only need to store a reasonable amount of energy for a relatively short period of time before next recharging. This will significantly alleviate the demand on on-board batteries or even enable the occurrence of battery-free vehicles.

From the requirements of fast and frequent wireless charging, alternative electricity storage devices, supercapacitors, could be more suitable than batteries for vehicle on-board usage. Supercapacitors have been used as auxiliary energy storage systems in hybrid and fuel-cell electric vehicles [10] [11]. 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. Supercapacitors could become ideal energy storage devices for future wirelessly charged electric vehicles.



(a) Stationary charging (b) Dynamic charging

Figure 1. Future electric vehicle wireless charging systems

The idea of wireless transfer of electrical energy has been known from a 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 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]- [9]. Among those mechanisms, inductive coupling, magnetic resonance coupling and microwave are considered to be suitable for the wireless charging of electric vehicles. The inductive coupling and magnetic resonance coupling are near-field technologies with no radiation; while microwave is a far-field method.

In this paper, the above three wireless vehicle charging methods are briefly reviewed; basic experiments and a prototype demo system are also reported using magnetic resonance coupling. The prototype system includes coils for wireless 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, and a model electric vehicle. All the major functional components for an electric vehicle's powertrain and charging system are included in the prototype system. Initial experimental results are promising; while further investigations, the optimized design of components and a system-level optimization are needed.

2 Wireless Vehicle Charging Methods

The focus of wireless energy transfer is different with the well-known wireless signal transfer, i.e. wireless telecommunications. Wireless telecommunications emphasizes the proportion of energy received to distinguish the signal, namely information carried, from the background noise. With wireless energy transfer, the main metric becomes the efficiency. A large part of energy sent out must be able to be picked up to make the system economical.

2.1 Inductive coupling

An electrical transformer is the simplest example for the wireless energy transfer using inductive coupling. As shown in fig. 2, its primary and secondary circuits are not directly connected. The electrical energy is transfered wirelessly through mutual induction between the primary and secondary coils. Currently the most of commercial vehicle wireless charging systems are using inductive coupling including Conductix-Wampfler's IPT (Inductive Power Transfer) vehicle charge system and the non-contacting charging system developed jointly by Showa Aircraft Industry and Nissan, as shown in Fig. 3(a) and (b), respectively. The inductive coupling now 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 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].

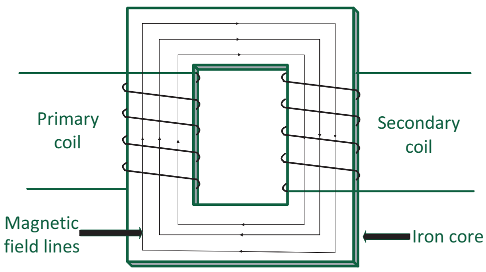


Figure 2. Electrical Transformer

2.2 Microwave

Energy transfer by means of microwave is directional, thus allows long distance power beaming. A rectenna can be used to

(a) IPT system developed by Conductix-Wampfler (b) Non-contacting charging system developed by Showa Aircraft Industry and Nissan

Figure 3. Wireless charging systems using inductive coupling

convert the microwave energy back into electricity. Power beaming using microwaves has been proposed for the transmission of energy from orbiting solar power satellites to Earth and the beaming of power to spacecraft leaving orbit has been considered [7]. A wireless vehicle charging system was developed by Mitsubishi Heavy Industry using 2.45GHz microwave as shown in Fig. 4 [8]. However, the relatively low transfer efficiency (usually less than 50 %) and potential microwave radiation exposure to human body make this method questionable.

Figure 4. Wireless vehicle charging system developed by Mitsubishi Heavy Industry using microwave

2.3 Magnetic Resonance coupling

The application of resonance improves the drawback of short range of the inductive coupling. Magnetic resonance coupling occurs when power sources and capture devices are specially designed magnetic resonators with approximately same natural frequencies. As same as mechanical resonance, the magnetic resonance makes the system be able to reach the highest energy absorption rate. As shown in Fig. 5, if the two coils, which are actually LC circuits, have same natural frequencies, significant power may be transmitted over a distance of up to a few times the size of the primary coil. The inductive coupling systems can also be tuned to resonance. However, the magnetic resonance coupling systems work at higher operating frequencies in MHz band. The technology of magnetic resonance coupling is promising for the wireless charging of electric vehicle with following advantages [5] [6]:

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

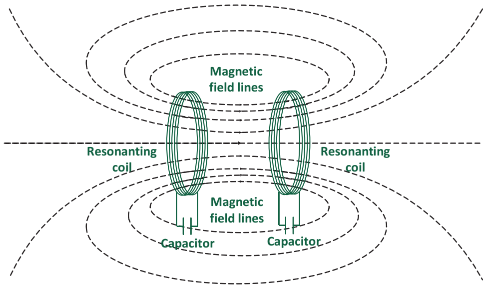


Figure 5. Magnetic Resonance

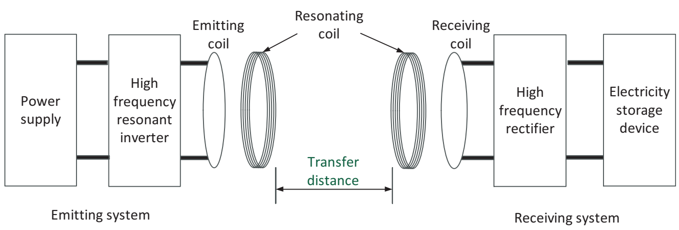


Figure 6. The whole wireless power transfer system

3 Wireless Charging System Configuration

One of typical configurations for a wireless charging system is shown in Fig. 6 using magnetic resonance coupling. There are three types of coils, one emitting coil, two resonating coils, and one receiving coil, respectively. The two resonating coils work as an isolated transformer to transfer the electromagnetic energy from the emitting coil to receiving coil through magnetic resonance coupling, which is intended to extend the transfer distance to a considerable level, such as over 10cm without using the ferrite cores. 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 quality factor of each resonating coil, thus the transfer efficiency. In order 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 the two resonating coils.

The resonating coils can be modeled as parallel LC resonant circuits. The resonance frequency f_r is determined by the inductance and capacitance using Equ. (1).

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

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. (2).

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

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. Therefore, the needed capacitance can be calculated using the coil inductance L and the targeted resonance frequency f_r, as shown in Equ. (1). The magnetic resonance coupling system can be modeled by two coupled RLC resonance circuits, in which the coupling coefficient is represented by the mutual inductance between the two coils [13].

In the emitting system, a high-frequency DC/AC inverter is used to supply the AC power at the resonance frequency of the two resonating coils. A full bridge voltage-fed topology can be applied to perform the high-frequency DC/AC inversion. The schematic of the voltage-fed resonant inverter are shown in Fig. 7, in which the MOSFET switches are driven by two MOSFET driver ICs, Texas Instruments UCC27201. The four gates are high-speed semiconductor MOSFET switches. 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.

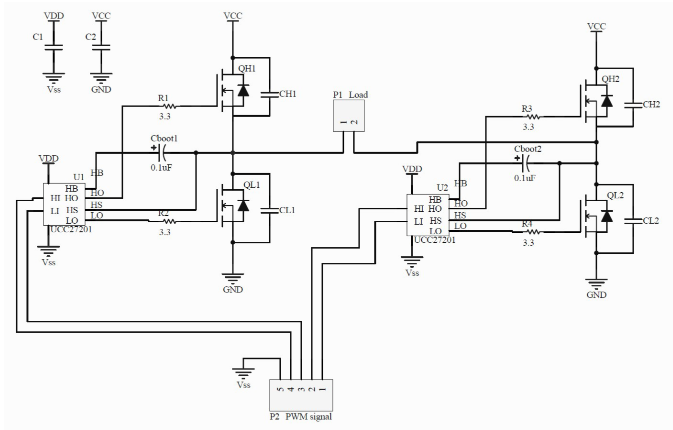


Figure 7. Schematic circuit diagram of a high-frequency voltage-fed resonant inverter

The receiving system consists of resonating coil, receiving coil, AC/DC rectifier and electricity storage device to receive and storage the electromagnetic energy being transferred wirelessly from the emitting system. The resonating coil is as same as the resonating coil adjacent to the emitting coil. The alternating electromagnetic energy is picked up by the resonating coil through magnetic resonance coupling; while then the energy is transferred to the receiving coil by inductive coupling. The two coils are concentric and lie in the same plane to maximize the power transfer efficiency. Schottky Barrier Diodes such as Zetex ZHCS2000 surface mount diodes can be chosen as the full bridge rectifier circuit diode, as shown in Fig. 8. This type of diode has very fast reverse recovery time and small typical reverse current, which is suitable for high frequency rectification. The DC output of the rectifier is connected to the electricity storage devices, such as batteries or supercapacitors.

The operational frequency for magnetic resonance coupling spans from kHz to GHz [14]. 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 and their gate driver circuits [15].

4 Basic Experiments

A basic experiment setup is shown in Fig. 9. The radius of the coils is 15cm. The line thickness is 2mm and the number of turns is 5. Network analyzer is used to figure out the frequency characteristics between the two resonating coils at 10mW power

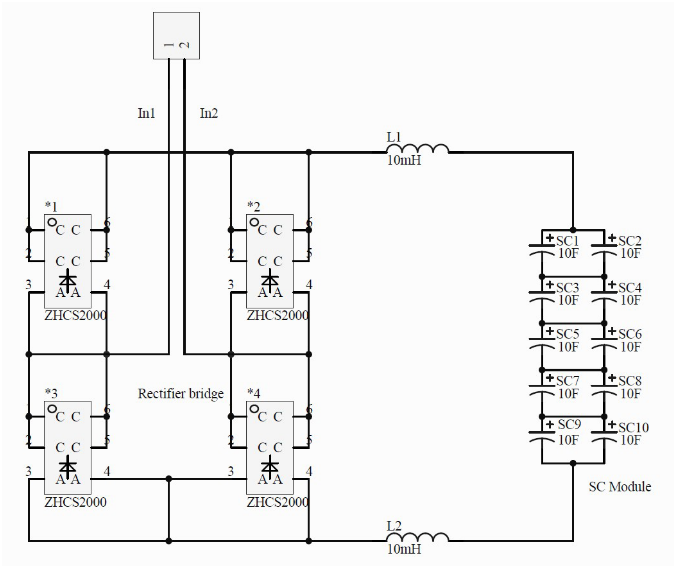


Figure 8. Schematic circuit diagram of high frequency rectifier

level. The network analyzer has two ports, one is for inputting high frequency signals and the other is used to read the corresponding transmitted signals. The relationship between the gap of the two coils and the wireless energy transfer efficiency is shown in Tbl. 1. It can be seen that using magnetic resonance coupling, the maximum efficiency of 93.69% is achieved with 14.8cm gap between the two coils, which is much larger than the range for the inductive coupling. F_m and F_e are the resonant frequencies of the system.

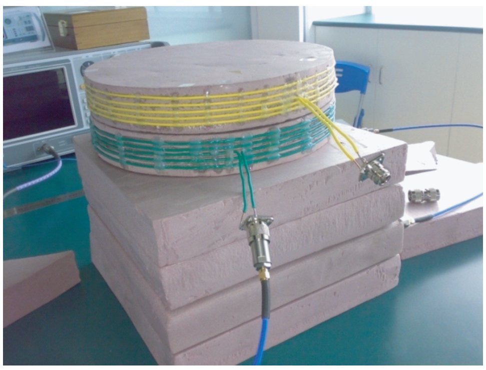


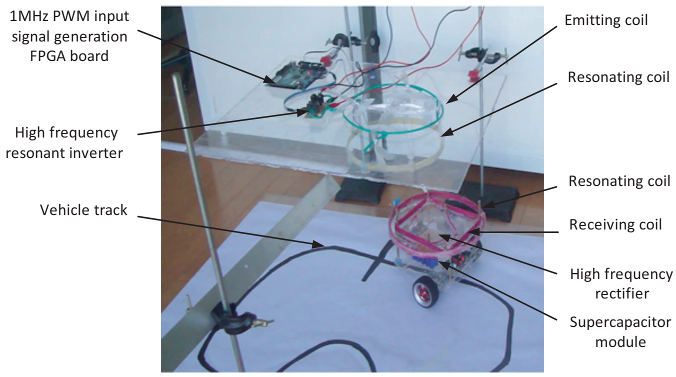
Figure 9. The basic experimental setup

A wireless charging system for an electric model vehicle is shown in Fig. 10. 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, FPGA PWM input signal generation FPGA board, high

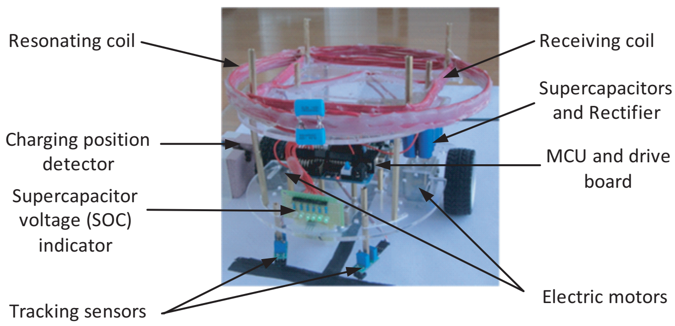
Table 1. Experimental Data for Gap Versus Efficiency

Gap (cm)	Efficiency (%)	F_m (MHz)	F_e (MHz)
5.6	88.84	13.59	19.87
10.1	93.32	14.74	17.85
14.8	93.69	15.27	16.51
24.1	88.07	16.11	16.11
28	70.04	16.08	16.08

frequency resonant inverter, receiving coil, high frequency rectifier, supercapacitors, motor control unit (MCU), motor driver and electric motors. Considering future ubiquitous wireless vehicle stationary and dynamic charging facilities, unlike in conventional vehicle wireless charging systems, the supercapacitors rather than batteries are used as the energy storage devices which are more suitable for fast and frequent wireless charging.



(a) Prototype demo system



(b) Model vehicle and sensors

Figure 10. The prototype demo system configuration

For validation purpose, the targeted frequency 1MHz is selected for the AC power generated by the DC/AC resonant inverter. 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 through inductively coupling; finally the 1MHz AC power is converted to DC power for the charging of supercapacitor module.

Special attention is also paid to the interaction among vehicle, wireless charging station and road conditions including the sensing of supercapacitor voltage (SOC) level, wireless charging area and vehicle track, as shown in Fig. 10(b). The model vehicle can automatically return to the charging area when the SOC (voltage) level of supercapacitor module is lower than a prescribed reference value. This prototype demo system can be used as a platform to investigate the potential of wireless charging of supercapacitor electric vehicles, the interactive relationship among various components from wireless energy transfer, storage to consumption, and the optimized configuration, design and control strategy, etc.

the 1MHz resonant frequency is confirmed by measuring the voltage and current in the emitting coil, as shown in Fig. 11. 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.

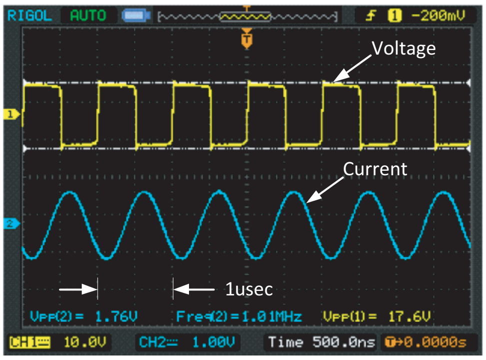


Figure 11. The voltage and current waves in the emitting coil

Again, network analyzer is used to find the frequency characteristics among the emitting coil, resonating coils and receiving coil. Fig. 12 is obtained using network analyzer with 10cm distance between the two resonating coils. The figure shows the maximum energy transfer efficiency occurs at frequency of 995kHz, which is in accordance with the targeted resonant frequency. 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 $(V_{out}/V_{in})^2 = 72.1\%$. Tbl. 2 shows the energy transfer efficiency with various resonant coil distance. The 50% efficiency occurs at the distance of about 22cm.

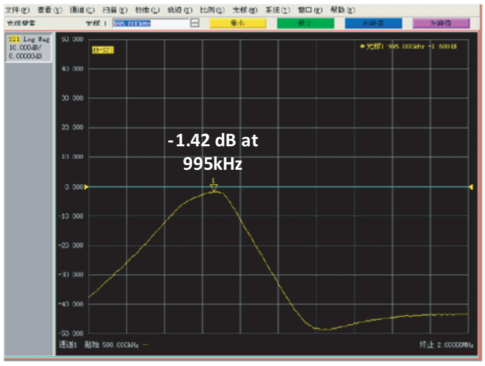


Figure 12. Transmission characterization of coils by network analyzer

Table 2. 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

5 Conclusions and Future Works

In this paper, the technologies for wireless electric vehicle charging are reviewed including the inductive coupling, magnetic resonance coupling and microwave. Among them, the magnetic resonance coupling is promising for vehicle charging mainly due to its high efficiency and relatively long transfer range. Then, the design and configuration of magnetic resonance coupling based wireless charging system are introduced. A basic experimental setup and a prototype electric vehicle wireless charging system are developed for experimental and research purposes. Especially the prototype system well demonstrates the idea of fast and frequent wireless charging of supercapacitor electric vehicles using magnetic resonance coupling. Though the idea of wireless energy transfer looks sophisticated, it is proved to be a handy technology from the work described above. Wireless power transfer in a small power region is reported in this paper. However, for a more practical range for vehicle charging in MHz band, such as the kW range, it is difficult to transfer high power with high switching frequencies over MHz using the state-of-art power electronic devices. And both component and system-level optimization are very challenging. Intensive investigations and research are expected in this aspect.

With this convenient testing platform, the costs of different power support systems can be evaluated, such as wirelessly charged supercapacitors and Li-ion batteries. And it is interesting to demonstrate the dynamic wireless charging of the supercapacitor model vehicle on the platform. The mini prototype system can be used to practice many novel ideas on the wireless charging of electric vehicles. At the same time, an one-seat full-size experimental vehicle is under development with both supercapacitors and batteries on board. A KW-level 13.56MHz Class D amplifier will be used as the high frequency power source in ISM band for the wireless charging, which uses special high power gate drivers and MOSFETs. Future results will be reported in following papers.

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