Power Delivery Optimization for a Mobile Power Transfer System based on Resonator Arrays

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Abstract

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Power Delivery Optimization for a Mobile Power Transfer System based on Resonator Arrays

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Abstract

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1. Introduction

Wireless power transfer (WPT) is promising with a wide range of power levels, from implantable medical devices to electric vehicles (scale of milliwatts to kilowatts). Although each application has specific requirements such as transfer distance, size, and power, most of them rely on either simple inductive coupling or resonant coupling. Inductive coupling uses the magnetic coupling between transmitting and receiving coils to transfer power. It has a working range of a few centimeters [1, 2]. Resonant coupling tunes the transmitting and receiving coils to a same resonant frequency, and the effective transfer distance can be greatly extended [3, 4]. Metamaterials have been shown to further improve the power transfer efficiency and range of a WPT system [6, 8, 9].

Recently, WPT systems using an array of resonators have been proposed. Example applications include the wireless charging for electric vehicles on the road, for elevators, and for mobile industrial robots. Theoretical and numerical studies of the technology have been reported [10, 11]. In this paper, we present recent experimental results on mobile power transfer with an array of coupled resonators to continuously moving devices.

2. Mobile WPT Array of Resonators Experimental Configuration

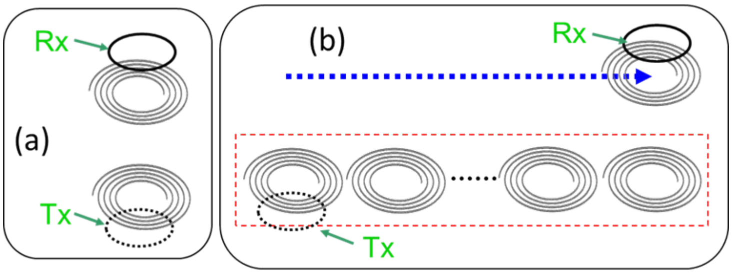

Figure 1: (a) WPT system with one resonant coil as transmitter and one resonant coil as receiver. (b) WPT system with an array of resonant coils as transmitter and one resonant coil as receiver.

As shown in Fig. 1(a), in a resonant coupling based WPT system, power is transferred between two resonant coils by the coupling of evanescent field. For devices that travel distances larger than the physical size of the resonator, this is not sufficient to provide wireless power continuously. Fig. 1(b) shows a simple example of a linear resonator array. The resonator design and the shape of the array can take different forms [10]. Power can be distributed by the array by inductively coupling power from a loop antenna into any resonator in the array; the power is distributed through the array via self-resonant coupling, thus no electrical connections between resonators is required. The receiver can now be anywhere along the array, which can be much larger than the physical size of one resonator. It is also possible to allow multiple receivers to be powered from the array at the same time.

We have built a mobile WPT test system. RF power is produced by a modified Kenwood TS-480HX transmitter, and coupled with a square single-loop antenna into an array of resonators. A toy train set was modified by attaching a resonator and non-resonating loop antenna about 5 cm above the tracks, supplying the RF power to a 40 watt lamp (dummy load) and a switching power supply to convert the rectified RF to +5VDC, to charge a 1 farad supercapacitor in the locomotive; the train motor is driven from the supercap. The train set runs on an oval-shaped track with dimensions 183 cm by 140 cm, and total length about 5.25 m. A planar array of resonators is placed beneath the track to transfer the energy from the fixed Kenwood loop antenna to the mobile train loop antenna.

Two types of resonators are designed for the straight and curved tracks respectively. Both types are planar 5-turn spirals printed on 0.5 mm Rogers 4350 circuit board, with copper thickness 35 μm, copper strip width 2 mm, spacing between neighboring copper strips 1 mm. The square-shaped resonator has an outer dimension of 15 cm by 15 cm; the trapezoid-shaped resonator has a height of 12.9 cm and side lengths of 15.4 cm and 18.8 cm. A total of 6 square-shaped resonators and 24 trapezoid-shaped resonators are used to fill up the oval-shaped track.

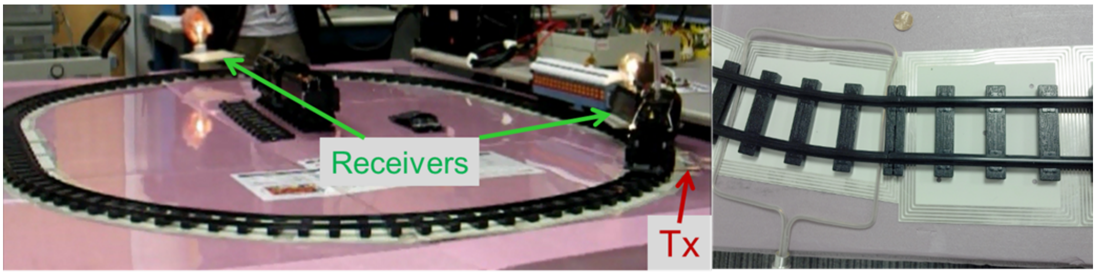

Figure 2: The mobile WPT experiment overall, and detail of the array of trapezoidal and square resonators and the transmitter loop antenna. A US 1-cent coin shows scale.

The train set is able to run continuously along the oval track powered via WPT. Both the light bulb on the train and a second test receiver are lit via with wireless power. While the train is traveling along the track, the lamp brightness varies as changing coupling and SWR foldback vary the power.

Despite the energy storage on the locomotive (approximately 12 joules) not all frequencies in the band of 23 to 25 MHz (the useful resonance band of our test system) will allow the train to complete the full oval due to presence of resonant nulls. Small motions of the track (~1 cm) versus the resonator structure or inter-resonator movement of ~ 2mm can shift the frequencies where the train can complete the full circuit by 100 KHz or more. We observed that at many frequencies, the system does not maintain sufficient voltage to operate the locomotive motor at all points in the loop. Manually changing the frequency shifts the resonant nodes and anti-nodes and allows adequate power delivery in the previous resonant null zones. Our hypothesis is that this frequency change can be automated, and yield an improved overall energy delivery.

We implemented a telemetry system on the train that measured the actual RF->HVDC voltage (post-dummy-load) at approximately 10 Hz and relayed the value in real time to a host Linux laptop via Bluetooth. We then operated the train-set at 100 watts maximum transmitter power from 23MHz to 25 MHz and logged the instantaneous power delivered. The experimental protocol was to test several different automatic frequency tuning strategies and compare them versus fixed frequency systems. Our tuning strategies operated within the same 23 to 25 MHz band as the fixed frequency standards, and changed frequencies in steps of either 50 or 100KHz, either automatically or with feedback via the telemetry system, and optionally pausing and/or reversing the stepping when the telemetry WPT voltage V++ exceeded a threshold Vt at ~ 45 volts (45 volts due to our HVDC -> +5VDC switching converter oscillator turn-on voltage).

3. Results and Discussion

Example results are seen in figure 3. The total power transferred with automatic tuning is slightly less, yet automatic tuning eliminates all "no power" resonant null stalling regions, greatly increasing actual usability of wireless power in the mobile context. The transmitter uses SWR foldback protection, so input power varies from 5 watts to 100 watts.

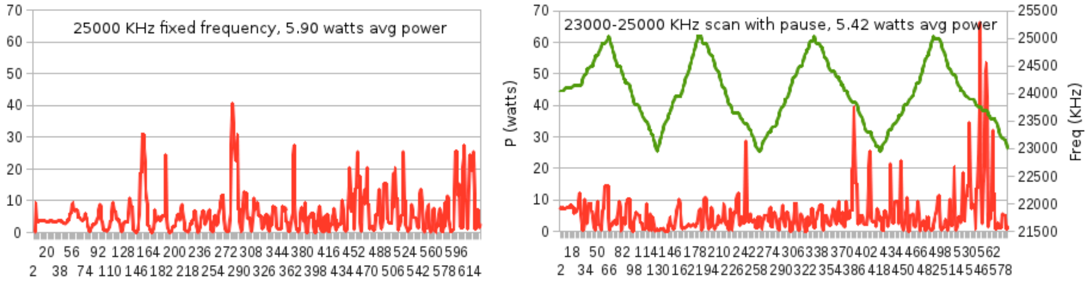

Figure 3: Sample power and frequency versus time profiles, for ~ one minute (3-4 laps of the track). Left: 25000 KHz fixed-frequency, average power 5.90 watts. Right: 23000-25000 KHz up/down/up scan, 50 KHz step and pausing if V++ exceeded Vthresh (~ 45 volts), average power 5.42 watts.

Tuning Strategy	Normalized Avg Pwr	Feedback	Comments
fixed frequency: 23000 KHz	0.885		manual assist
fixed frequency: 23250 KHz	1.058		
fixed frequency: 23500 KHz	0.979		
fixed frequency: 23750 KHz	1.065		
fixed frequency: 24000 KHz	1.361		
fixed frequency: 24250 KHz	0.923		
fixed frequency: 24500 KHz	1.576		
fixed frequency: 24750 KHz	0.797		manual assist
fixed frequency: 25000 KHz	1.150		
50 KHz step, cont. up/down 23000-25000 scan	0.742		
100 KHz step, cont. up/down 23000-25000 scan	0.930		
50 KHz step, pause on V++ > Vt	1.058	yes	
100 KHz step, pause V++ > Vt	0.878	yes	
100 KHz step, pause, reverse search on V++ > Vt	0.846	yes	
100 KHz, pause, reverse on V++ > Vt, fast step	0.902	yes	
Average power, fixed frequency	1.088		
Average power, frequency stepping, no feedback	0.836		
Average power, stepping with feedback	0.905	yes	

Table 1: Various tuning strategies and resultant average power delivered to the mobile receiver

Table 1 summarizes the results. The control for our experiments (fixed frequency operation) yielded a range of normalized average power of 0.79 to 1.57 (average: 1.09); interestingly, the two extreme values occurred only 250 KHz apart (at 24750 KHz and 24500 KHz respectively). Of the nine fixed frequencies, two were unable to operate the train for a continuous loop, due to resonance nulls on the track. In these cases, the train was manually assisted until the WPT power resumed.

Only one of the active tuning methods approached the average power level of the fixed-frequency operation - that was stepping by 50 KHz, and pausing when the telemetry indicated V++ >~ 45 volts, with a normalized power of 1.05 (statistically insignificant from the average of the nine fixed frequencies). All other active tuning modes yielded normalized powers less than 1.00 .

All active tuning modes operated the train on the continuous loop without failure. There was never any need to manually assist the train, unlike the fixed-frequency strategies which had higher total power but resonant nulls ("dead spots") on the track.

4. Conclusion

Experimental results of a mobile WPT system based on an array of coupled resonators demonstrate that the system is capable of transferring power continuously to moving devices with minimal local energy storage. Dynamic tuning methods, both with and without feedback, have been experimentally verified to guarantee power delivery to the moving device even in the presence of resonant nulls.

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