Demonstrating Dynamic Wireless Charging of an Electric Vehicle

The benefit of electrochemical capacitor smoothing

by John M. Miller, Omer C. Onar, Cliff White, Steven Campbell, Chester Coomer, Larry Seiber, Raymond Sepe, Jr., and Anton Steyerl

The wireless charging of an electric vehicle (EV) while it is in motion presents challenges in terms of low-latency communications for roadway coil excitation sequencing and maintenance of lateral alignment, plus the need for power-flow smoothing. This article summarizes the experimental results on power smoothing of in-motion wireless EV charging performed at the Oak Ridge National Laboratory (ORNL) using various combinations of electrochemical capacitors at the grid side and in the vehicle. Electrochemical capacitors of the symmetric carbon–carbon type from Maxwell Technologies comprised the in-vehicle smoothing of wireless charging current to the EV battery pack. Electro Standards Laboratories (ESL) fabricated the passive and active parallel lithium-capacitor (LiC) unit used to smooth the grid-side power. The power pulsation reduction was 81% on the grid by the LiC, and 84% on the vehicle for both the LiC and the carbon ultracapacitors (UCs).

Wireless Power Transfer Technology

Wireless in-motion charging of an EV has been a topic of interest for decades and was proposed in the 1950s as a means to supply power to mining cars and later to rail cars to eliminate the pantograph sliding contact. Covic and Boys [1] provide an excellent treatment of inductive power transfer (IPT) for transportation and cite the hurdles facing EV charging while in motion. Transferring power to vehicles...
The active parallel combination of LiC energy storage and the grid supply resulted in very uniform power draw from the grid.
to the ORNL team. Active parallel means that a high-power, bidirectional controllable power flow, dc–dc converter interfaces the LiCs to the dc input of the WPT HF inverter. This configuration is used only on the grid-side experimental work.

The ORNL WPT team has demonstrated power smoothing in test drives of the GEM EV over an energized track consisting of six primary coils to which HF current is supplied sequentially and in synchronism with vehicle position. This article summarizes the results obtained from the use of a carbon UC in passive parallel with the demonstration vehicle battery pack and for the LiC in active parallel at the grid side, and a second LiC is used in passive parallel with the vehicle battery.

**ORNL In-Motion Wireless Charging**

In-motion wireless charging consists of a sequence of roadway embedded coils, an energized track, in which individual coils or pairs are sequentially energized by a trackside HF power inverter in synchronism with vehicle position. The ORNL in-motion charging demonstrator is shown schematically in Figure 2 having the following key functions:

- the primary coils connected in pairs and in phase (i.e., fountain field), singly tuned to 22 kHz
- the coil sequencing controlled by vehicle passage using trackside photocell interruption
- the power level controlled by HF inverter rail voltage
- the single secondary, or capture coil, centrally mounted to the demo vehicle chassis
- the Maxwell Technologies UC pack in passive parallel with demo vehicle battery pack
- the ESL LiC rack in active parallel with the grid-side power inverter (this apparatus was designed for both passive and active parallel connection)
- Zlinx radio communications between the vehicle and grid-side controller.

**In-Motion Coupler Design**

A great deal of experimental design work has been performed at ORNL on WPT couplers, the results of which favor square over circular designs. The in-motion demonstration system used these earlier circular coils with half-to-full Litz cable diameter spacing of the planar spiral winding. The rectangular designs having more compact planar windings are now viewed as superior for in-motion charging due to better coupling during overlap.
All couplers are characterized in the laboratory for self-inductance, ac resistance, and coupling coefficient as a function of gap. Figure 3 shows the circular coil and characterization results. The coil is planar spiral wound with seven turns using cable guides interspersed with wedge-shaped ferrite flux guides. The ferrite plates are covered with a Kapton sheet for voltage isolation.

The circular coil shown in Figure 3 was designed for operation at 48 kHz and a working gap of 100 mm, which is the ground clearance of the GEM EV. For this ground clearance, the coil should have a diameter of approximately four times the gap, \( d \), or 400 mm. The results of coupling coefficient, \( k \), testing are shown in Figure 3, where three independent test methods were used. Note that at the working gap of 100 mm, both the open circuit and compensated methods are in excellent agreement, while the inductance-aiding method obtained using an Agilent instrument is somewhat lower [2], [3]. A comprehensive list of WPT references that cover the main aspects of wireless and IPT is included in the “References” section. The coupling coefficient is defined as the ratio of secondary coil captured flux to the primary coil total flux generated by a specified current, taken as 10 A\(_{\text{rms}}\) in these laboratory characterization tests.

Coil resistance is a dominant contributor to coupler inefficiency, plus the core loss contribution of the soft ferrite materials used to guide flux and minimize fringe fields. Figure 4 shows the results of ac resistance testing on the planar coil of Figure 3 at both 22 and 48 kHz. The experimental fit to characterization data is given as (1) and shows that the exponent was reduced to 1.4 and lower.

The importance of \( R_{\text{ac}} \) will become evident in later discussions on efficiency. The key components of frequency-dependent \( R_{\text{ac}} \) shown in Figure 4 include \( R_{\text{tr}} + R_{\text{str}} + R_{\text{prox}} \), where the proximity effect resistance \( R_{\text{prox}} \) depends strongly on the cable type (i.e., Litz cable bandwidth) and spacing.

\[
R_{\text{ac}} = R_{\text{tr}} \left[ 1 + 0.147 \left( \frac{f_{\text{kHz}}}{20} \right)^{2} \right] + R_{\text{prox}}. \tag{1}
\]
WPT Fundamentals

The HF power inverter shown in Figure 2 consists of power insulated-gate bipolar transistors (IGBTs) configured as a fully controlled H-bridge. Over the course of this project, the ORNL team used 600-V silicon IGBTs operating at 23 kHz but capable of operating up to 28 kHz. With the availability of next-generation 150-kHz IGBTs, a trial inverter was fabricated for operation at 48 kHz, with the intent of comparison testing in-motion WPT at a higher frequency. Hence, the need to characterize WPT components in this range is evident. The coupler performance is not affected by the frequency, other than cable and core losses. However, lacking suitable high-power modules, multiple IGBT TO247 devices connected in parallel resulted in more burden on the gate drivers. Therefore, this design was set aside for a silicon carbide (SiC) power inverter [2]. In addition, the ORNL team made significant contributions to WPT technology [3]–[13], much of which was necessary for the proper execution of this in-motion demonstrator.

Primary-side HF power is synthesized by the H-bridge inverter shown schematically in Figure 5, to which commands are sent for frequency and duty cycle from a digital signal processor (DSP) controller. More recent WPT designs at ORNL employ a controllable power factor corrector stage for variable dc link voltage, hence power regulation. In the present configuration, the duty cycle is fixed at \( d = 0.8 \) based on earlier work that revealed a very rapid escalation in reactive power at the source (Fig. 5) as \( d \rightarrow 0.2 \).

The source voltage \( V_s \) in Figure 5 has two control variables, voltage, \( U_{dc} \), and frequency, \( \omega_0 \), given by

\[
U_s(t) = \frac{4U_{dc}}{\pi} \sin\left(d \frac{\pi}{2}\right) \cdot \cos(\omega_0 t) \cdot V_{\text{rms}}.
\]

The primary-side track coils shown in Figure 1 and schematically in Figure 5 are series tuned to 22 kHz, and the dc link voltage, \( U_{dc} \), is controlled for the charging power plus traction motor demand of the GEM EV.

The power modules fabricated at the ORNL power electronics packaging laboratory are mounted to the liquid-cooled heat sink shown in Figure 5, along with in-house-fabricated gate drivers and bus

![Figure 6](image-url)  
**Figure 6** The trackside power electronics and thermal management: from left to right, the input power contactor and filter, the HF power inverter and coolant lines, a pair of terminal blocks to which the HF transformer is attached, and, at the far right, the liquid-cooling reservoir, pump, condenser, and cooling fans. (Photo courtesy of ORNL.)

![Figure 7](image-url)  
**Figure 7** The voltage and current waveforms for WPT at 23.5 kHz: (a) the primary voltage (square wave) and sinusoidal current and (b) the secondary voltage (clipped sine) and sinusoidal current. (Figure courtesy of ORNL.)
work. This inverter was used for testing at 23 and 48 kHz using gate drivers rated to 85 kHz.

The trackside power inverter and supporting thermal management apparatus are shown in Figure 6. The control signals are brought in from the trackside control electronics and sequencing box. The control and sequencing the National Electrical Manufacturers Association (NEMA) box is shown at the left in Figure 1, and it also contains the track tuning capacitors.

**Primary-Side Power Regulation**

ORNL researchers devoted considerable analytical effort and experimental work to understanding the intricacies of wireless charging, including this dynamic case. The most succinct explanation is that WPT consists of a loosely coupled transformer, tuned to resonance on the primary and secondary to manage its high leakage flux, and excited with quasi-square wave voltage (2). The LC tuned circuits on both the primary and secondary result in fundamental, sinusoidal current, as shown in the screen shot in Figure 7, which was taken from the Yokagawa PZ4000 power meter used in the experimental work on larger-size square coils.

Circular coils exacerbate the magnitude of the power pulsation. Shifting to rectangular coils for in-motion charging would be preferable.

For series–parallel (S–P) tuned WPT (secondary parallel tuned), it is expected to see leading power factor at the secondary. This is evident in Figure 7, where secondary current (taken at the coil terminal before the tuning capacitor) leads the terminal voltage (i.e., rectifier input). The ringing on the clipped sine-wave secondary voltage is due to rectifier recovery. The power is regulated by controlling the dc link voltage of the HF inverter.

When the coupling coils (as a pair) shown in Figure 3 are tested at a nominal \( z = 75 \text{ mm} \) working gap, a duty ratio of \( d = 0.8 \), tuned to 22 kHz and operating at \( f = 23.5 \text{ kHz} \) into a battery emulator at dc output power \( P_b = 2.0 \text{ kW} \), the real and reactive power flows are shown in Figure 8. This figure shows that S–P tuning results in a power transfer that is peaked but with gentle skirts when off frequency. Note that the reactive power is always leading on the secondary (parallel capacitor effect), but the primary reactive power switches from leading to lagging as the operating frequency crosses the tuned point. As expected, the coupler reactive power will be large.

Other investigators have worked and are working on WPT power flow control and regulation [14]–[33]. Research
In-Motion Wireless Charging Without Power Smoothing

In-motion wireless charging is not a new concept, and early investigators sought out contactless power transfer for mining vehicles and rail cars in the mid-20th century. Most recently, the Korean Advanced Institute for Science and Technology has made dramatic progress using buried cable concepts, similar to [45], that are excited at one end of a long hairpin-style primary over which vehicles having polarized pickup coils move longitudinally [47]–[49]. Such systems use HF current injection to manage the high reactive power demand. The alternative, sequentially energized coils embedded into a roadway that transfer power only when the vehicle secondary coil moves across them, is the preferred method in the ORNL system. The issue, as discussed in depth in [12], is the power pulsations on both the grid and vehicle sides; this is repeated in Figure 9, where the pulsations are taken for the ruled position of secondary coil moving across the primary coil pair. Note the exchange of the primary real and reactive power with position but the consistently leading secondary reactive power. The GEM EV onboard charger is rated 1.5 kW but also has some short-term faster charging capability. The ORNL system was designed to match this charging requirement while in motion. It is also apparent that circular coils exacerbate the magnitude of the power pulsation. Shifting to rectangular coils for in-motion charging would be preferable.

In ORNL’s experimental testing of the GEM EV driving over the six-coil sequentially energized track, the power pulsations shown in Figure 9 are reflected in the primary coil (two coils in series, singly tuned) current. This is shown in Figure 10 as the HF inverter output current waveform. In this compressed timescale view, the vehicle is traversing the coils at ~15 mi/h resulting in three sets of double pulsation, with each set the same as in Figure 9. The sequencing transitions as a coil pair is dropped, and the adjacent pair is energized. This is clearly shown as the vertical dead bands. In this particular test run, the vehicle passes over the coils and then parks over the last coil to illustrate stationary charging.
With this preliminary testing, our experimental results validate the concern raised by others over power pulsations and their impact. Therefore, the ORNL WPT team and our collaborator, ESL, undertook experimental work using high-power capacitor technology for both grid-side and in-vehicle application to smooth the power flow during vehicle passage.

Consistent with LCR circuit response, primary current quenching is very rapid due to the inverter shutoff and the coupler stored energy being absorbed in the HF inverter dc link capacitor. During primary coil excitation, the current ringup is consistent with the \( L_{\text{coil}}/R_{\text{cc}} \) time constant of the system \( (L_{\text{coil}} \sim 18 \mu\text{H}) \). The ringup time constant is \( \sim 175 \mu\text{s} \), as can be observed in Figure 10(c).

For a high-leakage transformer (coupler) and coupling coefficient, \( k \sim 0.22 \) in this experimental work. For two primary coils in series, the resultant primary current will be the vector sum of the purely reactive magnetizing current and the load current (harmonics excepted). Carrying out the computations for \( P_{\text{th}} = 2 \text{ kW} \) of throughput power and given the dc link voltage, \( U_{\text{dc}} = 135 \text{ V} \), then according to (2), the combined primary is being excited by \( U_s = 115.6 \text{ V}_{\text{rms}} \). The magnetizing current is therefore

\[
I_m = \frac{U_s}{\sqrt{2} \omega k L_{\text{coil}}} = \frac{-j115.6}{2(1.476e5)(0.22)(18e-6)} = -j98.88 \text{ A}_{\text{rms}}. \quad (3)
\]

**FIG 11** (a) The ESL equipment rack and (b) the LiC modules installed in the GEM demo vehicle (used with permission from ESL). (Photos courtesy of ORNL.)

**FIG 12** The ESL equipment rack.

**FIG 13** The grid-side currents for the passive parallel LiC system: (a) the grid-side LiC voltage annotated by coil number and (b) the LiC current for the grid-side passive parallel test.
Similarly, the rectified load current can be approximated as the ac equivalent, $I_r$, of dc load current into the battery pack according to (4). The primary line current in resonance is then the vector sum of real and quadrature currents (5).

$$I_r = \frac{\pi}{2\sqrt{2}} \frac{P_b}{U_b}$$

$$= 1.11 \times \frac{0.000}{80} = 27.8 \text{ A}_{\text{rms}}$$

$$I_{\text{rms}} = \sqrt{I_{\text{re}}^2 + I_{\text{im}}^2}$$

$$= \sqrt{(98.88)^2 + 27.8^2} = 102.8 \text{ A}_{\text{rms}}.$$  

This is consistent with the current magnitudes shown in Figure 10, where (5) is equivalent to $145 A_{\text{peak}}$.

**Experimental Results with LiC on the Primary Side**

The main body of testing done at ORNL involved high-power capacitors. ESL fabricated the LiC equipment rack shown in Figure 11 that contains components for three individual tests: 1) a standalone LiC consisting of four 40-V modules in series for grid-side passive parallel; 2) an LiC plus dc–dc converter for active parallel demonstration on the grid side; and 3) a pair of 40-V LiC modules for in-vehicle installation and comparison with carbon UC in passive parallel with the GEM battery.

Figure 12 shows a block diagram of the active parallel converter system used only on the grid side. It consists of a multiphase bidirectional half-bridge dc–dc converter, an LiC module, and a controller. The dc–dc converter matches the voltage and current levels of the LiC module with the requirements of the wireless charger bus. The specifications of the LiC module depend upon the acceptable charging power level from the grid and the pulse duration and duty cycle of the power required by the wireless charger. During high-power transients, such as when a vehicle drives over the charging coils, the controller uses the dc–dc converter to transfer energy out of the LiCs to load level the grid-side ac–dc converter bus. Otherwise, the converter is used to recharge the capacitor bank. Figures 13 and 14 show the benefits of using this system.

Figure 13(a) shows the grid-side LiC voltage as the GEM vehicle drives over the charging coils with the grid-side passive parallel system enabled. Figure 13(b) shows the grid-side LiC current during this same event. Large pulsations would be present. However, here, the LiC supplies the transient currents. Notice that the magnitude of the LiC current is larger than the inverter current because the LiC stack is at a lower voltage than the bus, and the dc–dc converter matches the LiC output power to the required inverter power.

Figure 14 shows the grid supply and HF inverter currents when the grid-side active parallel system is enabled. The large peak current pulse on the grid side has been eliminated and replaced by a regulated and leveled current load needed to recharge the LiC system. Moreover, most of the

---

**FIG 14** The grid-side currents with active parallel LiC system: (a) the grid-side supply current (13 A) and (b) the current delivered to the HF inverter.

**FIG 15** The in-vehicle battery-only current (16 $A_{\text{peak}}$).

**FIG 16** The in-vehicle UC installation: (a) the ultracapacitor pack during precharging operation and (b) the charged ultracapacitor pack installed in GEM and connected in passive parallel with battery. (Photos courtesy of ORNL.)
HF harmonics reflected to the grid have also been removed. The LiC system provides the transient energy to meet the power requirement of the charging coils while isolating the grid from high peak power and HF harmonic content.

Figure 15 shows the baseline in-vehicle battery current that is used as a comparator for the two cases to follow for carbon UC and LiC smoothing. These tests are passive parallel with the GEM battery only.

**Experimental Results with Carbon UC in Vehicle**

In the previous section, for an LiC in active parallel with the output of a grid-connected power supply, it was demonstrated that the active parallel combination of LiC energy storage and the grid supply resulted in very uniform power draw from the grid—the power pulsations are absorbed by the LiC as expected. This section reports on the use of Maxwell Technologies UCs in passive parallel with the GEM lead–acid battery pack. The Maxwell Technologies UC module consists of a single string of $30 \times 650 \, \text{F}, 2.7 \, \text{V/cell}$ for a combined $21.7 \, \text{F at 81 V pack}$, shown in Figure 16, capable of $52 \, \text{kJ (14.4 Wh)}$ if discharged from maximum to half-rated voltage.

The carbon UC pack ($30 \times 1 \times 650 \, \text{F}$) shown in Figure 16 was precharged to match the GEM battery pack voltage prior to installation. This was necessary to avoid any current surges between the UC pack, GEM battery, and WPT secondary-side filter capacitors during connection. The UC pack was then installed in the GEM and connected to the battery, as shown in Figure 16. In addition, a Yokagawa power meter and isolation modules were installed in the vehicle to record currents and voltages, at the UC and to the battery pack.

**Vehicle Charging Current Smoothing Using Carbon UC**

With the equipment configured as in Figure 16, for in-vehicle instrumentation and with a pair of power analyzers—one monitoring the grid side and the second installed in the vehicle—to record the UC and battery currents. The in-vehicle UC and battery currents (peak UC current $\approx 13.4 \, \text{A}$ and peak battery current $\approx 2.6 \, \text{A}$).

![Figure 17](image)

**Figure 17** In-motion wireless charging is tested at ORNL using electrochemical capacitor smoothing. (Cliff White is monitoring the grid-side equipment, and Steven Campbell is driving the test vehicle.) (Photo courtesy of ORNL.)

**Table 1. A summary of the current pulsation reduction.**

<table>
<thead>
<tr>
<th>Experimental Test</th>
<th>Grid-Side WPT Base Station</th>
<th>In-Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>No smoothing</td>
<td>53 A</td>
<td>16 A</td>
</tr>
<tr>
<td>Grid side only with LiC</td>
<td>10 A</td>
<td>16 A</td>
</tr>
<tr>
<td>Vehicle side with UC</td>
<td>10 A</td>
<td>2.6</td>
</tr>
<tr>
<td>Vehicle side with LiC</td>
<td>10 A</td>
<td>2.6</td>
</tr>
<tr>
<td>Pulse reduction</td>
<td>81%</td>
<td>84% for UC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>84% for LiC</td>
</tr>
</tbody>
</table>
 vehicle—the current smoothing results are dramatic, as shown in Figure 18.

**Battery Current Smoothing with LiC in Vehicle and LiC on Grid Side**

The final experiment was to use the LiC on both the grid side as active parallel and in the vehicle as passive parallel. In this test, a pair of ESL LiC 40-V modules are connected to the power supply output via a dc–dc converter, and a second series-connected pair of 40-V LiC modules are placed in the GEM vehicle, as shown schematically in Figure 2 and experimentally in Figure 11. As with the Maxwell Technologies UC module, the LiC modules are also precharged to match the GEM pack voltage. Figure 19 shows an excerpt of the measured currents taken during testing.

**Power Pulsation Reduction**

The implementation of local energy storage was shown to be very effective in reducing the ratio of peak-to-average current, resulting in lower power pulsations of the grid-supplied power and vehicle battery pack charging power. Table 1 summarizes the previously mentioned results. In Table 1, the experimental test results for grid-side power supply current and vehicle traction drive electronics load current are given as peak values for comparison.

The use of electrochemical capacitors as high burst power sources and sinks has been shown to dramatically reduce power pulsations at both the grid and vehicle battery pack. The implications are that grid demand response resources will be substantially reduced by the use of local high-power capacitor storage at roadside WPT base stations and in vehicle to mitigate battery ripple current during in-motion charging for the case of energized and sequenced roadway embedded wireless charging coils. Figure 20 shows ORNL’s concept for dynamic WPT installed in special charging lanes on highways. This concept was presented to the U.S. Department of Transportation research and innovative technologies administration to assist in long-term highway research [50].

The key attributes of this concept are that WPT modules are controllable, modular, scalable, and replaceable, and the energized track sections are powered by highway dc distribution and multifailure-point survivable. The coil sequencing is synchronous, with the vehicle under charge regardless of speed or congestion. WPT roadside units (RSUs) supply the dc distribution from grid connections at various intervals along the highway corridor.

**Conclusions**

This article focused on just one of the many technical challenges posed by the dynamic charging of EVs—power pulsations. Equally challenging, if not more technically challenging, are concerns over lateral alignment for lane keeping and optimum power transfer coupling, low-latency private and secure communications for vehicle to infrastructure, highway construction and maintenance, utility power distribution to WPT RSUs, time of use and revenue structure, and so on. Not listed among these
challenges are leakage fields, which for WPT are the magnetic, $B$, and electric, $E$, fringe fields associated with HF magnetic resonance power transfer. This issue is further complicated by the fact that maximum $B$-fields are not necessarily colocated with maximum $E$-fields [51]. ORNL researchers recognize the issues associated with electromagnetic fields from cables carrying HF currents. This is why ORNL focused on energized tracks of embedded roadway coils that are sequenced in synchronism with vehicle passage. The active fields remain strictly beneath a vehicle that is charging. To mitigate the power pulsations inherent in coupling power from a series of embedded coils, the ORNL team, in collaboration with ESL researchers, installed high-power capacitors at both the grid and in vehicle. The result was a dramatic reduction of 84% in charging current to the vehicle battery and 81% from the grid connection. Using electrochemical capacitors, such as Maxwell Technologies carbon UCs and the ESL LiC unit, it was demonstrated in an experiment that peak currents associated with power peaks were reduced to their average value. Similar results have been found by others in experimental work on capacitor–battery combinations [52], [53]. The benefit of power capacitors in energy storage systems is a dramatic reduction of ripple current, which facilitates longer service life of the vehicle battery, as validated by Argonne Laboratory researchers [54].

Acknowledgments
The authors would like to thank the members of the ORNL Power Electronics and Electric Machinery Group for their contributions to WPT experimental fabrication, testing, and data acquisition. The authors especially commend team members PT. Jones and Paul Chambon for their assistance in vehicle systems aspects of this program.

This manuscript has been authored by UT-Battelle, LLC, under Contract DE-AC05-00OR22725 with the U.S. Department of Energy.

About the Authors
John M. Miller (jmiller35@aol.com), distinguished staff, Oak Ridge National Laboratory, Tennessee, is currently a principal engineer with JNJ Miller PLC, Oak Ridge, Tennessee.

Omer C. Onar (onaroc@ornl.gov), Weinberg Fellow, R&D staff, is with Oak Ridge National Laboratory, Tennessee.

Cliff White (whitecp@ornl.gov), R&D staff, is with Oak Ridge National Laboratory, Tennessee.

Steven Campbell (campbells@ornl.gov), R&D staff, is with Oak Ridge National Laboratory, Tennessee.

Chester Coomer, R&D staff (retired), is with Oak Ridge National Laboratory, Tennessee.

Larry Seiber (seiberl@ornl.gov), R&D staff, is with Oak Ridge National Laboratory, Tennessee.

Raymond Sepe, Jr. (rspe@electrostandards.com), vice president for research and development, is with Electro Standards Laboratories, Cranston, Rhode Island.

Anton Steyerl (antons@lab.electrostandards.com), research engineer, is with Electro Standards Laboratories, Cranston, Rhode Island.

References


