

More Efficient Inductive Electric Vehicle Charger: Using Autonomy to Improve Energy Efficiency

Edward C. Fontana, Rick Barnett, Robert Catalano, James Harvey, Jiacheng He,
George Ottinger, and John Steel
GE Critical Power

ABSTRACT

Electric cars can help cities solve air quality problems, but drivers who live in apartments have no convenient way to charge daily, absent the well-controlled private garages where most electric vehicles (EVs) are currently charged each night. Environmentally robust, hands-free, inductive chargers would be ideal, but energy efficiency suffers. We asked whether the precise parking alignment provided by self-driving cars could be used to provide convenient inductive charging with improved charging efficiencies.

To answer this question, we split an inductor-inductor-capacitor (LLC) battery charger at the middle of the isolation transformer. The power factor correction, tank elements, and transformer primary windings are stationary, while the transformer secondary, rectifiers, and battery control logic are on the vehicle. The transformer is assembled each time the EV parks. A variety of transformers were tested for efficient energy transfer coincident with spacing to accommodate insulation on both the charger and vehicle side of the interface. Testing with different transformer parameters demonstrate a wall to battery energy efficiency of 95%, comparable to an onboard charger.

A hands-free, inductive, battery charger can deliver charging efficiencies comparable to galvanically connected onboard chargers – with no degradation in performance or safety when covered with a variety of contaminants. This shows promise for night charging of EVs at apartments, thus providing high public benefit with minimum public infrastructure expense.

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INTRODUCTION

Electric vehicles (EVs) provide a zero-emissions solution for transportation in cities. In 2013, sixty percent of over one thousand respondents were open to the idea of purchasing an EV [1]. Unfortunately, 48% of people surveyed do not have the ability to charge at home, due to lack of electrical outlet or space for a charger [1]. A wireless, hands-free charger that is durable enough to withstand environmental factors would be well suited to strategically important uncontrolled parking environments, like apartment parking lots and public garages [2], for overnight charging [3].

Modern inductive EV chargers provide low-clutter, ground-mount charging that is impervious to chemicals and electrically safe, as there are no exposed galvanic connections to create a shock or spark hazard. Today's systems are also hands-free. The existing designs available to consumers, though, are not energy efficient. Wall-to-battery inductive charging efficiencies are right at 85% [4, 5], with state-of-the-art research in the low nineties [6, 7, 8]. Galvanic chargers deliver 85 to 95% wall-to-battery efficiency [9, 10], and address hands-free operation by using a robot to make the high precision galvanic connections at waist level [11].

As vehicles become more autonomous and begin to park themselves with robot-precision [12], the need for a robot function in the charger is eliminated. The car can precisely drive into a docking station where the charging connections are made. We wondered, "Is there a way to use the precision of autonomous vehicle parking and modern circuit topologies to make ground-level inductive chargers as efficient as hot contact chargers?" GE Critical Power produces rectifier circuits that are 95 to 97% efficient [13]. The goal was to start there and use the transformer as the interface for inductive energy transfer to the vehicle—with single-owner apartment-home night charging as the use model. [Figure 1](#) demonstrates our desired product.



Figure 1. CAD model of desired compact, efficient, inductive solution [14]



APPROACH

We based our design on experience designing, producing and supporting over a million products using this circuit, references including [15] – [20] and two guiding principles.

The first, which is the foundation for the heart of this work is: “Everything is linear if you get close enough.” We know this circuit delivers 95-96% efficiency with a separate resonant inductor and highly interleaved transformer. Our goal is to demonstrate a single transformer that can be assembled each time a vehicle parks that delivers conversion efficiencies that are comparable to that highly interleaved transformer that requires 20 minutes of assembly time to construct. To do that we needed to make all the key parameters close to those of our reference circuit.

The second guiding principle is: “Space allocation is key to product success.” We had a team working to package the circuit in way that is practically useful. Heat dissipation, alignment, and customer acceptance are all important, if this product is to serve society well. These efforts act as bookends around the theoretical and experimental work that is the heart of this paper. These space allocation efforts form a blueprint for *future work* and appear only in that section.

Resonant LLC Circuit Topology

Basing our design off of proven GE Critical Power rectifier topologies, we used the resonant LLC converter circuit with a half-bridge and output voltage doubling [21], Figure 2.

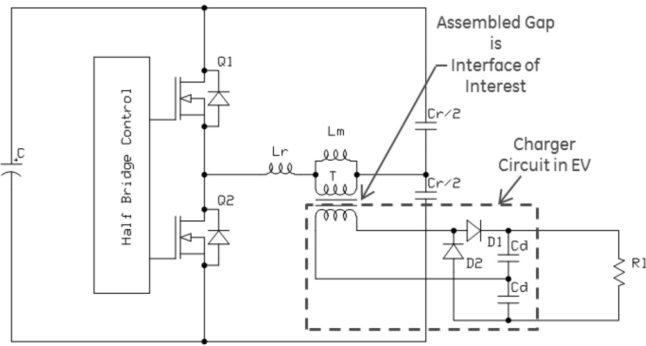


Fig. 2. Resonant LLC converter circuit with vehicle-side highlighted

For an environmentally robust design, we wanted to accommodate bumper covers and other plastic elements needed for 10,000 charging cycles of operation. Any separation in the magnetic structure caused by plastic covering prevents ideal coupling, creating leakage inductance. This intrinsic leakage inductance can be treated as beneficial. It allows us to forego the inclusion of a discrete resonant inductor and use the single assembled magnetic structure to establish resonance [21, 22].

Desired Characteristics

With GE’s in-house analysis tool, we calculated the First Harmonic Approximation for the circuit. The inputs were our desired input voltage, output power, and power efficiency, gathered from [10] for market needs. The tool produced the required turns ratio, magnetizing

inductance, resonant inductance—in our case, the leakage inductance, frequency range, and expected output voltage range. Table 1 shows our goals for the reference prototype; Figure 3 is an example of the tool’s output as we work to hit the corners of the envelope.

Table 1. Design objectives for electric vehicle charging

Characteristics	Value
Input voltage range	390V – 420V
Nominal input voltage	400V
Output voltage range	280V – 420V
Maximum output power	3kW
Desired efficiency	95%
Desired magnetizing inductance (L _M)	110μH
Desired leakage inductance (L _L)	10μH

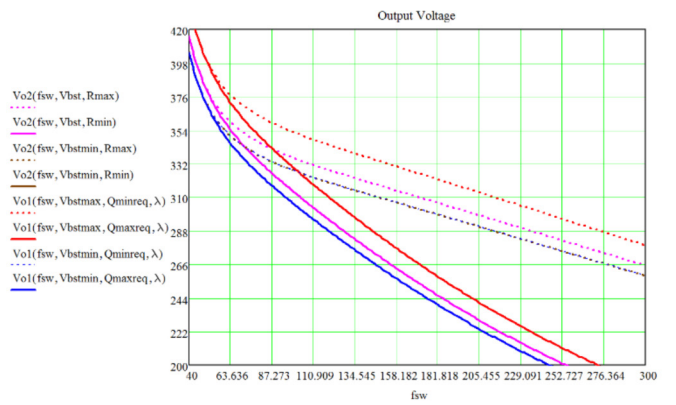


Figure 3. Example simulation produced by in-house analysis tool

Resonant Frequency Range

Efficiency and power loss is optimized when the circuit runs at or slightly above the resonant frequency—where the current running through the transformer is almost a perfect sinewave [21]. Our in-house analysis tool outputs a frequency range, with the minimum determined by the magnetizing inductance and the maximum determined by the leakage inductance. At high frequencies, current does not run efficiently through standard wire—the skin effect causes AC losses, and the proximity effect of the windings on each other reduce the efficiency, too. To decrease the effect of the variation of frequency on our transformer losses, we chose to use Litz wire for all of our windings.

Core Gap Determination

Determining the transformer core gap, Figure 4, was an important decision at the start. The larger the core gap, the less the coupling [23]. For our environmental protection purposes, we wanted a large core gap. To find the optimal core gap, we first measured the effect of core gap on magnetizing and leakage inductance, and then found an operating point where variations in core gap would not create large variance in the inductances. We determined an insulator thickness of 1.5mm on each surface of the ground-side and vehicle-side would be durable and manufacturable with standard injection molding processes.

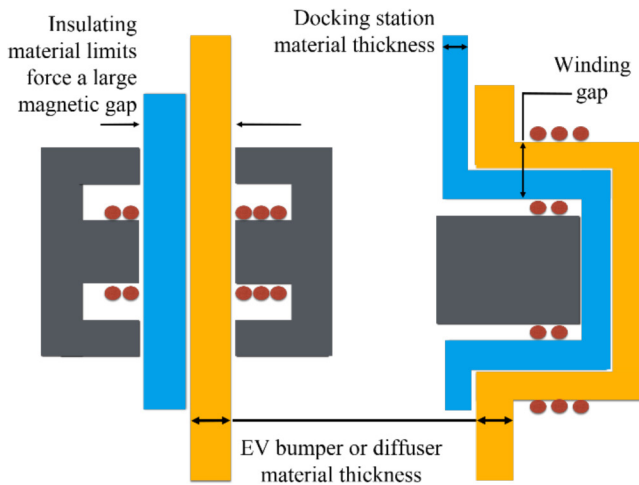


Figure 4. Model of transformers with core gaps

INITIAL EXPERIMENTATION

We used a set-based concurrent engineering approach [24] to design the integrated transformer, so we wound and evaluated many transformers with a variety of geometries. For each geometry, we measured magnetizing inductance, leakage inductance, and AC resistance on the Keysight E4980A Precision LCR Meter.

The four primary geometries we began with are shown in Figure 5.

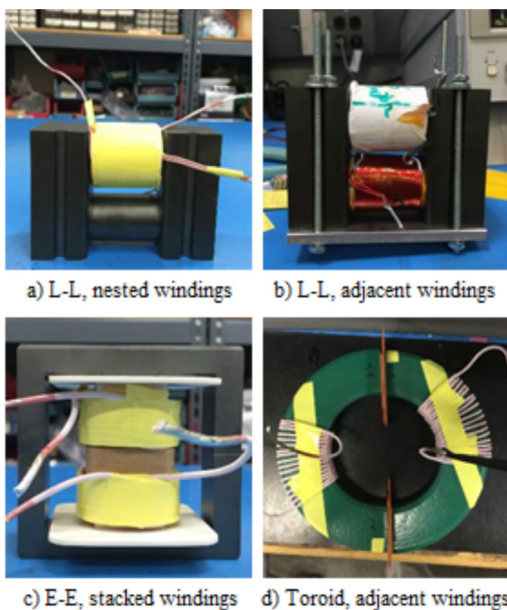


Figure 5. First designs tested for feasibility a) L-L, nested windings b) L-L, adjacent windings c) E-E, stacked windings d) Toroid, adjacent windings

Since the objective was to test a wide range of possibilities, we began with both "core" and "shell" type transformers [23]. Since theoretical calculation methods vary depending upon the type of core, we elected to wind and experiment instead of focusing on models and mathematics. The first geometry, Figure 5a, was an L-L core with the primary and secondary windings on the same leg. The primary winding nests into the secondary winding. From a theoretical

perspective, this winding should couple well, so the leakage inductance should be relatively low. The downside to this design is the accuracy necessary for the nesting of the windings. The second winding, Figure 5b, also uses an L-L core, but has the primary on one leg and the secondary on the other. Because there is no overlap of the windings at all, this winding was expected to have higher leakage and thus, lower magnetizing inductance. The third geometry, Figure 5c, was a "shell" type, an E-E core, with the primary winding on one end of the middle leg and the secondary on the other. The main benefit of the E-E core is the ability to have the windings close to each other, even though they do not overlap. Finally, we had a toroid core, Figure 5d, that was split in half, with windings on each side. Measurements were taken with the windings at a range of locations, from close together to far apart.

Additionally, we experimented with different configurations of core gap, turns ratio, number of turns per side, and frequency. We experimented from no core gap up to 13mm per leg. From our analysis tool, we theoretically wanted a turns ratio of approximately 1.25:1, but we tested more variations, too. Theoretically, the number of turns on the primary side effects the magnetizing and leakage inductances, so we wanted to see how that varied experimentally. Finally, because we chose to use Litz wire, we expected to see little variation at different frequencies. We tested frequencies from 20kHz to 120kHz to verify the effectiveness of the Litz wire.

Figure 6 shows a compilation of our initial magnetizing and leakage inductance measurements. The orange circle denotes the ideal values of 110μH and 10μH, respectively. This data shows that points from the same geometry were clustered closely, separated from the others. The clusters consist of the 102 configurations we tested. This suggests that core shape affects magnetizing and leakage inductance most.

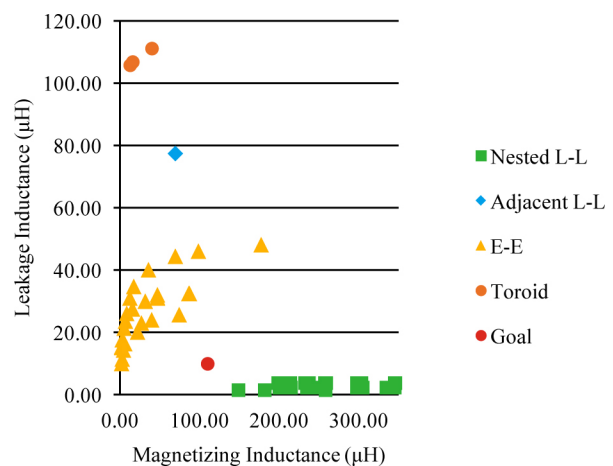


Figure 6. Effects of geometry on magnetizing and leakage inductance

Evidently, the adjacent windings on the L-L core and the split toroid core are not at all close to the ideal values. Meanwhile, some of the nested L-L core data points are close for magnetizing inductance, but all are too low in leakage inductance. The E-E core data points show a possibly ideal leakage, but low values for magnetizing inductance. We made the decision to focus on improving the nested L-L core and the E-E core [25].