

# Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Faical Turki  
Paul Vahle GmbH & Co. KG

Andre Körner and Juris Tlatlik  
Hella KGaA Hueck & Co.

Alan Brown  
Hella Electronics Corp.

## ABSTRACT

Conventional charging systems for electric and plug-in hybrid vehicles currently use cables to connect to the grid. This methodology creates several disadvantages, including tampering, risk, depreciation and non-value added user efforts. Loose or faulty cables may also create a safety issue. Wireless charging for electric vehicles delivers both a simple, reliable and safe charging process. The system enhances consumer adoption and promotes the integration of electric vehicles into the automotive market. Increased access to the grid enables a higher level of flexibility for storage management, increasing battery longevity.

The power class of 3.7kW or less is an optimal choice for global standardization and implementation, due to the readily available power installations for potential customers throughout the world. One of the key features for wireless battery chargers are the inexpensive system costs, reduced content and light weight, easing vehicle integration.

This paper demonstrates a wireless charging design with minimal component content. It includes a car pickup coil with 300 mm side length and low volume and mass 1.5 dm<sup>3</sup> power interface electronics. After an overview of its hardware requirements, power transfer and efficiency benefits are presented, providing the anticipated horizontal and lateral deviations.

An intense magnetic field is required to transfer the target power at low volumes between the transfer units. This field heats up any metal object over the transfer coil, similar to an induction oven. Consequently, the system should be powered down whenever a metal object is detected in this area. A Foreign Object Detection (FOD) design has been developed to continuously monitor the critical high field area. Device testing results are also provided.

Field characteristics are verified alongside the vehicle, ensuring system safety for living beings; compliant with all applicable standards reference limits which is more challenging than the basic limits [13].

**CITATION:** Turki, F., Körner, A., Tlatlik, J., and Brown, A., "Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles," *SAE Int. J. Alt. Power.* 3(1):2014, doi:10.4271/2014-01-1892.

## INTRODUCTION

Contactless energy transfer has been available since the late 90's as a standard technology [2] where a mobile load must be supplied with energy. It is widely accepted in assembling automation. Since the advent of automobile electrification, this technology is becoming increasingly more popular. However the first systems that came onto the market had differing concepts, since the manufacturers were focusing on the actual

function and not their compatibility with other grid connected power equipment and charging applications [5]. The first systems, being strictly unidirectional, will be focused on vehicle charging. Already with such systems, power grid operators might get some control about the distribution of the network load by charging using the concept of time control.

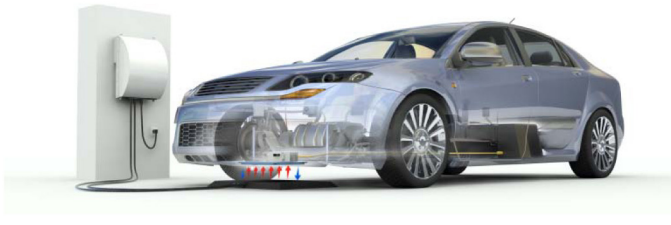


Figure 1. Wireless induction charging System

The energy transfer chain consists of two sub-systems: (1) The stationary infrastructure producing the required primary magnetic field (2) An on-road vehicle that transforms the primary field into electric power.

With the assumption of the systems complexity as constant, the optimization toward better market acceptance and lower pricing leads to a solution involving shifting the complexity to the infrastructure side and keeping the vehicle components as simple as possible. This involves the regulation of the power flow from the stationary primary side of the system.

All the systems available on the market may be represented by the structure in Figure 2:

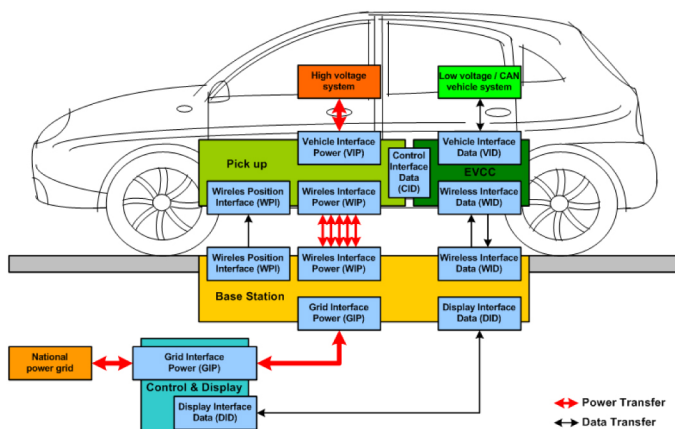


Figure 2. System overview of wireless chargers

A standard wireless power transfer system usually consists of a primary stationary inverter fed by a supply grid via a one phase or three phase grid front-end. The primary inverter is responsible for rectification, power factor correction and converting the resulting DC-link voltage into AC with a normal switching frequency in the kHz-range. This process drives a resonant induction coil. In most systems, the frequency is within the range of the resonant circuit connected to the inverter output. The primary and secondary coils are responsible for magnetic coupling. The reactive power required to transfer the power over a large air gap is provided by a combination of compensation capacitors. The capacitor values are tuned to a nominal resonant frequency of the induction coils. The induced voltage in the secondary coil is rectified and optionally converted to the required voltage/current levels. This power can then feed the HV (high voltage) battery directly since there is already galvanic separation from the grid, or may

feed the DC-link of an existing on-board charger. The latter option is a less complex scenario for resonant circuit topologies, but produces a lower efficiency.

## VEHICLE INTEGRATION

The primary objective to introduce contactless charging systems to vehicle manufacturers is to increase the ease of charging for the end customer/user. For example: picking up a charging cable in the morning, where it has sunken deep into the snow and frozen solid to the ground by Joule heating after completing the prior charging and cool down cycle. Rain and dirt are also a concern for both the charging cable and vehicle connector interface. Plug-in hybrid vehicles possess smaller batteries that potentially require charging more frequently throughout the day. Required cable and plug handling prerequisites may lead to a "forget it" style attitude when time is minimal.

The charging process must be automated, as much as possible, when compared to conventional charging, providing the ideal scenario where the driver only parks the vehicle on the charger. Charging automatically takes over and controls the process. The system provided, supports the driver, positioning the vehicle over the device. The system would possess a tolerance for misalignment between the vehicle coil and stationary floor coil (charging pad). It uses a wireless interface to authenticate the car, direct the driver's steering and braking until the vehicle coil is well aligned with the floor coil and then initiate and continuously control the energy flow.

Another important objective is the electrical safety. Cables generate the risk of trip hazards and vandalism. Electrical power contacts on the EVSE and vehicle are known to be one of the major causes of charging related failures. All this is avoided or significantly reduced inherently by implementing an inductive charging scheme.

A systems successful integration into a vehicle requires a lightweight compact design, including a minimal, low profile for the underbody. A safe and simple power control process is required. Power transfer efficiency must be 90% or greater from grid to battery, comparable to current developments, charging with a power cable and electronic system support. The electrical system's performance must meet the battery charging requirements. The process begins with a charging phase at a constant maximum current, followed by a shorter phase with continuous voltage and decreasing current. The radiated magnetic fields must comply with legal regulations and technical standards. Radio systems, including vehicle keyless entry/keyless go systems, tire pressure monitoring or non-automotive based methods cannot experience interference. The system must be innocuous including inductive heating influences on foreign objects entering air gaps between the charging pad and the vehicle pickup. Potential objects are not allowed to heat-up due to the risk of injury or fire hazards. Live objects also may have to be protected, even if no influence from low frequency magnetic fields is known today.

## MAGNETIC CIRCUIT

The magnetic circuit supporting a wireless power transfer system is equivalent to a transformer with a large air gap in its main area resulting in a relatively large leakage inductance on the primary and secondary sides.

A standard set-up for the magnetic circuit, with an air gapped transformer configuration, consists of a soft-magnetic material, usually ferrite (like most inductive components for high kilohertz frequencies) which contains the fields, and a copper winding made from litz wire to reduce the dissipation power caused by skin and proximity effects (See [Figure 3](#)).

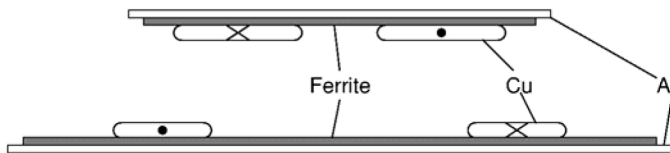


Figure 3. Magnetic design of circular coils

This type of, circular configuration has an advantage, containing the magnetic field thus preventing it from reaching the vehicle underbody. For additional protection, an aluminum plate can be added to improve the shielding at high kilo-hertz frequencies.

The bulk of the magnetic flux is located in the middle of the air gap, with only leakage fields produced at the sides. The value of magnetic coupling in the nominal working area of the transformer varies from about 0.1 to 0.3 on a typical vehicle with air gap clearance up to 250 mm. The value 0.5 can be reached only for very large coils.

In contrast to the symmetric arrangement of the induction coils, vehicle manufacturers prefer to keep the vehicle side (secondary) coil as small as possible. Making both coils smaller would disturb the positioning tolerance in such a way as to reduce the power transfer efficiency below acceptable levels [3]. Such asymmetric magnetic circuit is shown in [Figure 4](#), where the stationary primary coil is on the left and vehicle secondary coil is on the right.



Figure 4. Tested circular coils

The chosen primary and secondary coils ([Figure 4](#)) differ in dimensions: 1m × 1m for the base plate on which is mounted an 800mm × 800mm primary coil, then a 300mm × 340mm vehicle side secondary coil. It will be shown that this system is able to work with asymmetric magnetic coupling. The dimensioning of the larger primary coil (800mm × 800mm) is based on the German VDE application guide and prevents excess heating of metallic foreign objects [4].

## RESONANT CIRCUIT TOPOLOGY

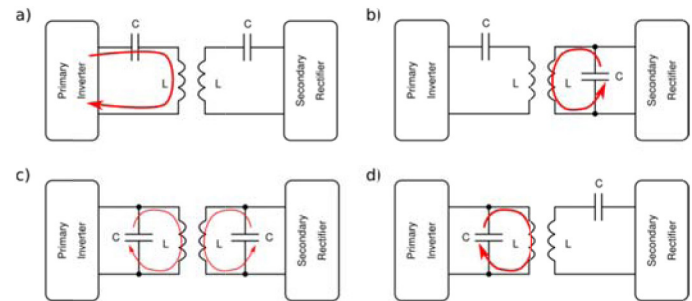


Figure 5. Resonant topologies

Depending on the decision of which side the air gap is magnetized during the light load condition and on the power electronics topology, the resulting resonant circuit may be any combination of parallel and series configurations on primary or secondary side. This leads to four combinations ([Figure 5](#)).

From a physical perspective, all of these combinations are feasible, without the need to choose one arrangement as a standard, due to the same nominal power rating; the mechanical designs for every topology are equivalent. A rule must exist for the system behavior to handle various scenarios by adapting the control loop.

The compensation strategy is a major issue, due to the major impact it has on the behavior of the transfer system. In this process, only the two-sided resonance combinations are relevant, due to inductive power transfer systems and only one resonant circuit not feasible for low coupling applications like electric vehicle charging via the underbody.

As shown in [Figure 5](#), the magnetization current may be delivered with a parallel circuit on both the primary and secondary sides ([Figure 5c](#)), but in a series resonant circuit on the secondary side ([Figure 5d](#)), the magnetization can't be utilized by the load side, if it has a simple rectifier.

The most desirable and accurate topology for the primary resonant circuit has to be selected. To realize a universal primary arrangement, a DC-link voltage has series topology and is easier to implement with a popular full bridge converter, delivering the appropriate level of reactive power to magnetize the air gap by controlling its output current. See [Figure 5a](#).

The function and behavior of the resonant circuit can be explained by first reviewing the combination of a series to series layout, ([Figure 5a](#)) which is a symmetric system with series oscillating circuits on both sides. The following diagram is the equivalent circuit of the T-System with gyrator-function.

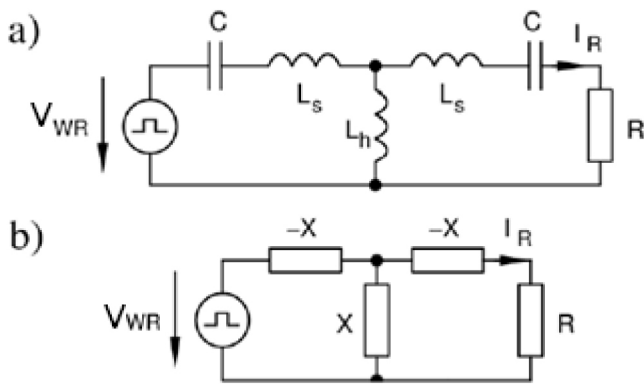


Figure 6. Gyrator circuit

The gyrator-function is shown in Figure 6: The capacitor **C** in Figure 6a compensates the total inductance of the respective windings completely. If they are split into main (mutual) inductance  $L_h$  and leakage (stray) inductance  $L_s$ , **C** can be theoretically separated into two capacitors in series. One of them compensates the leakage inductance  $L_s$  and the rest has the same reactance **X** of the main inductance  $L_h$  with opposite sign so they can compensate each other. This way, a T-system is generated with different signs as shown in Figure 6b. It follows the load resistance, transformed into  $X^2/R$  on the feeding side.

The disadvantage of this topology is the feeding inverter needs to maintain a nearly constant magnetizing current over the entire operating power range, leading to reduced efficiency during light load-operation.

This is a preferred method, but has a smaller number of components and the charging load profile on the grid connection operates mainly in the high power range. As a result the counter argument for reduced light load efficiency becomes less significant. This solution is not vulnerable to a variable air gap, changing the inductances of the system and the resonant frequency. This provides the ability for the inverter to obtain ZCS (zero current switching) / ZVS (zero voltage switching) conditions, leading to low switching losses.

A scenario to consider is a parallel pickup coupled with the universal primary system. In this case, the equivalent circuit can be assumed to be a series resonant circuit possessing a variable load resistance that does not vary from the series pickup with the exception of the gyrator effect not present, due to a current source transformed into a current source. A detailed description of the load behavior is provided in [5].

The equations governing the circuit impedance and current of the gyrator circuit are shown in Equation 1.

Equation 1: Gyrator impedance and current as a function of passive component values

$$X = 2\pi f L_h$$

$$I_R = \frac{V_{WR\text{eff}}}{jX}$$

## POWER FLOW CONTROL

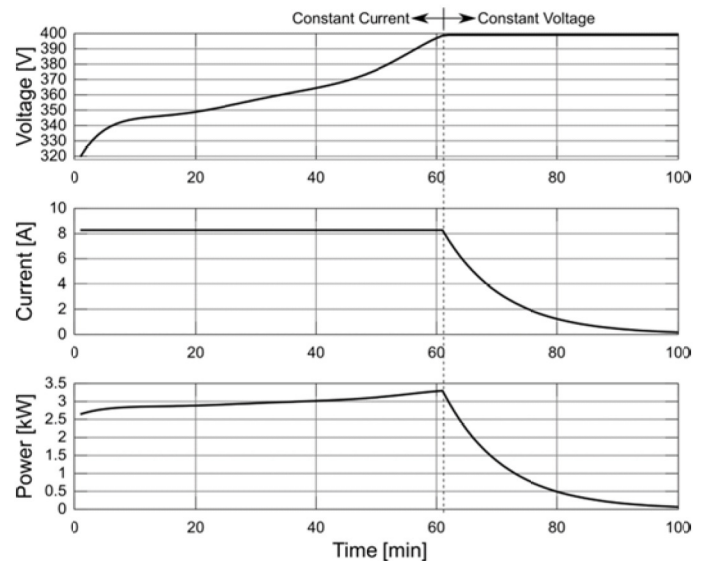


Figure 7. Typical 1C-Charging process of a Lithium-based battery

As shown in Figure 7, the charging process of an electric vehicle battery, especially lithium based, is separated into two control modes that should be supported: constant current and constant voltage. This requirement is generated by the on-board vehicle BMS (Battery Management System).

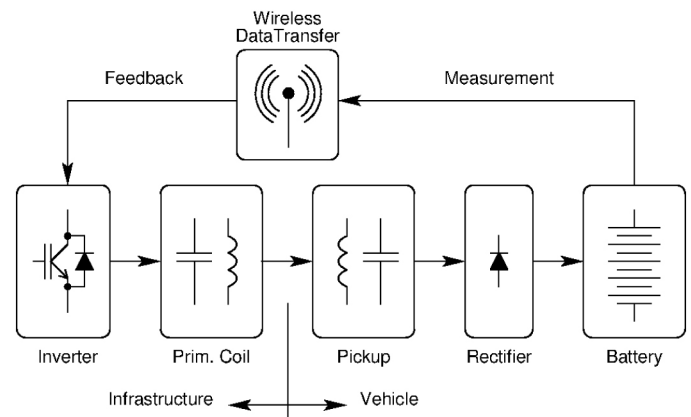


Figure 8. Closed-loop control of power flow through wireless data transfer

Due to the relatively low availability of mounting space of E-vehicles, with associated high costs of on-board power electronics and components; a simple rectifier solution is preferred versus that of an active SMPC (Switch-Mode Power Controller). This requires the information from the BMS to be