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Inductive charging – simplifying the charge to enable mass adoption

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Abstract

Siemens, along with its partner BMW, recently concluded a feasibility study that focused on inductive charging of passenger electric vehicles. The objective of the study was to verify that automatic wireless charging could be accomplished with a comparable level of efficiency to today's conductive solutions and without impact to human or vehicle safety. In its first phase, the study began with testing of a non-vehicle integrated solution. After verification of KPIs, the second phase of the study proceeded to integrate the technology into two BMW ActiveE electric vehicles. The study specifically measured power transfer efficiency with varying levels of coil to coil air gaps and misalignments between the road side and in-car coils while observing the most influential factors. Key findings of the study were that two areas merited further focus - the design of the coil system and the necessity for air gap observation. It is clear that as the automotive OEM community continues to seek inductive solutions that are smaller, lighter, more efficient, and less costly, these areas along with positioning guidance technology will be critical topics of further research. Siemens is using the results of the study to enhance their 2^{nd} generation prototype which seeks to significantly reduce the size and weight of the inductive coils while adding in compliances and certifications to in-car safety and quality standards.

Keywords: efficiency, EMC, inductive charger, infrastructure, wireless charging

1 Introduction

A major challenge to the expansion of electric mobility is the availability of an extensive and reliable charging infrastructure. Because electric cars have to recharge their batteries more often than vehicles with combustion engines need to refuel, various charging techniques are required that are adapted to the needs of the drivers and vehicles. Electric vehicle supply equipment (EVSE) has been rapidly evolving over the past couple of years and now that more electric vehicles (EVs) are arriving in the market with relative consistency, there will be a need for more infrastructure deployment. Stakeholders seeking EVSE already have a large selection set of hardware and software solutions that address a wide range of applications, delivered by an increasing pool of vendors. Yet, mainstream acceptance of this new technology is still on the horizon, attributed to factors such as vehicle availability, battery technology, and economic forces, all impacting the adoption curve. However, if not held to the same standards as current mainstream refuelling solutions, the EVSE technology itself can also significantly delay mass EV adoption.

2 Why Inductive Charging?

To facilitate mass adoption, EVSE technology needs to be *simple, convenient, safe, and reasonably fast.* Acceptance could be further accelerated if the technology was shown to minimally affect the environment. The focus of charging solutions currently in the marketplace mostly address applications where level two charging will be common. These solutions tend to meet the aforementioned expectations to a degree;

however from a cursory perspective, inductive charging technology appears to offer a far greater enhancement over the current cable charging technology, especially when charging is frequent and/or performed outdoors.

With the aid of wireless energy transmission, the charging experience is simplified by removing the need to plug in – drivers can effortlessly park in a spot fitted with an inductive charger. Since the charging session is initiated automatically, there is a reduced possibility of operating errors and/or misuse.

The contactless nature enhances driver convenience by eliminating issues such as handling dirty, oily, or even frozen cables associated with conductive charging systems and takes authentication and payment one step further than today's petroleum refuelling methods by offering automatic authentication and payment without manual intervention. Drivers are also given peace of mind knowing that there is no chance for someone to accidentally or maliciously unplug your vehicle during a charge session. Additionally, since the technology has the same natural applications as conductive charging {which includes home charging, fleet charging, semi-public charging, and public charging} – accessibility is not sacrificed.

For EVSE owners, especially in the semi-public and public space, cable management will no longer be a concern, improving safety and liability concerns by eliminating trip hazards. Costly cord management systems are now not needed and maintenance/replacement costs are minimized as there is no plug/connector to wear out, cables that could be cut, or units to clean. Aesthetics are a clear additional benefit of the pseudo invisible floor flush design, which does not require the installation of protection barriers occasionally seen with public conductive charging stations.

Figure 1: EVSE with Protection Barriers

While the perceived benefits are numerous, there are still many challenges to overcome. Siemens realizes that inductive charging will be an important component of EV infrastructure in the near future and is developing this future application today! At the request of the German Federal Ministry for the Environment, for the past year and a half Siemens and BMW have been applying their expertise to the IndiOn research project. This article presents the objectives, results, achievements, conclusions, and next steps of this exciting collaboration.

3 Project Details

3.1 Project Objectives

The project collaboration between Siemens and BMW, named the IndiOn research project, began in May 2010 and finished in December 2011. The study and testing took place at the corporate research and testing facilities of BMW and Siemens located in Munich, Germany.

There were several stated objectives of the project. First, to verify feasibility of inductive charging technology delivering power levels consistent with today's conductive charging solutions (3.6kW) at efficiencies greater than 90%. Second, to test automatically controlled charging within a pre-determined range of coil to coil distances (between 7-12cm) and various coil misalignments. Third, to design a totally integrated solution, in-car and roadside, complete with an intelligent parking positioning system. Lastly, to design a system that met EMC requirements for in-car and off-car technology and avoided interference with other electronic components in the vehicle. As this application of this technology to EV charging is in its early stages of development, costs were not a focus of the study and are not reported in this document.

3.2 Project Responsibilities

Siemens developed both the wireless charging system inside and outside of the vehicle as well as communication between the charging unit and the vehicle. BMW defined requirements for the vehicle's on-board charging and communication system and was responsible for integrating the inductive charging unit into two BMW ActiveE series electric vehicles.

3.3 Project Specifications

3.3.1 Project Setup

The primary coil is connected to the public grid by the infrastructure unit comprising the grid-side power electronics. A secondary coil of similar size is mounted to the underside of the car and is connected to the battery management system. When the charging process is initiated, an electric current begins to flow through the primary coil. The resulting magnetic field induces an electric current in the secondary coil, which recharges the battery on board the vehicle. Proof of concept of the energy transfer was first attempted with the secondary coil not integrated inside the vehicle. After first tests verified initial proof of concept, integration into the vehicle side was performed.

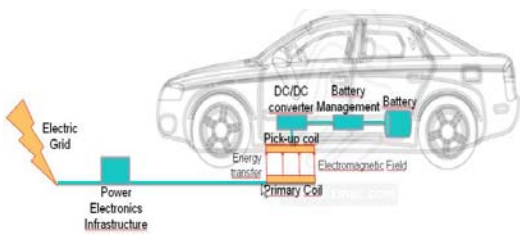

Figure 2: Wireless Energy Electronics Transfer

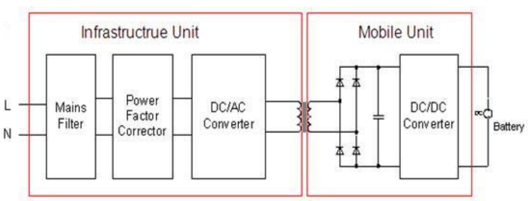

Figure 3: Setup of Test Equipment

3.3.2 Design Specifications

The first generation coil designed by Siemens for this study was 600mm in diameter. The weight was fairly heavy at 38kg (83lbs), suitable for testing, but not practical for a commercialized solution. The weight of this design was attributed to its prototype character and the requirement to maintain the stability of the prototype housing which also contained the power electronics. The dimensions were 91cm (35.8”) in length, 69cm (27.1”) in width, and 3cm (1.18”) in height.

A charging power of 3.6 kilowatts was designed for the system, deliberately limited to the level available in a residential area, and consistent with current conductive charging systems connected to the grid at 230V @ 16A, a common European specification. With this power delivery service, the charging time for average-sized batteries with a 20 kWh capacity is around six hours. The operating frequency of the magnetic fields was designed to be variable between 130kHz and 190kHz.

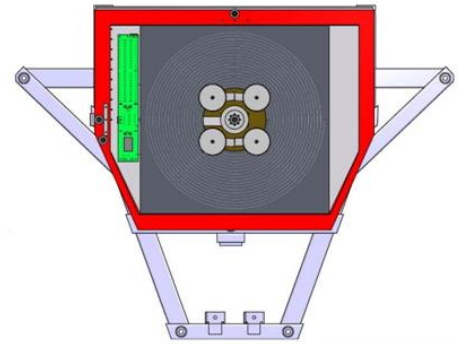

Figure 4: Prototype mounted on a front crash frame

3.3.3 Independent Variables

For the tests described in this document, there were primarily two independent variables. The first, coil to coil displacement, also known as air gap, is the distance between the two coils. Based on pre-analysis of the vehicle design and road-side charging pad specifications, it was determined that this may be as large as 16 cm for passenger cars during charging, which takes into account the necessary tolerance in ground clearance and vehicle positioning. The minimum overall ground clearance (ground to chassis) of passenger type vehicles is 110mm [1]. For our tests, the air gap was varied between 70 and 130 mm.

The second independent variable, coil alignment, is defined as the degree to which the coil in the vehicle is positioned over the coil on the road. Total alignment would result if the coils were positioned directly over one another. Anything other than total alignment is considered misalignment and is measured as the shift left, right, forward, and/or backward between the two coils. For our tests, coil alignment was varied between 0 (total alignment) and 14cm of misalignment independently in both the x-direction and the y-direction, and then at various misalignments in both directions.

A third independent variable, charging time, was also varied in a separate set of tests to observe changes in efficiency. Over a charging time period of 0 to 600 minutes with varying coil misalignments, no significant changes in efficiency were observed and therefore, these results are not the focus of this document.

3.3.4 Safety

From the onset of this study, safety was the highest priority. The magnetic field is generated only in an exact predetermined area between the two coils that is not accessible to the driver, passengers, or passersby. Our system generates a magnetic field whose strength is below the previous international recommended limit of 6.25 µT (micro-Tesla) at a distance of 20cm from either coil (door sill), and thus poses no health hazards to persons in or around the vehicle. Also, in the primary and secondary coils there is a sensor system that detects the position of the two coils. If misalignment is too large, it will not engage the system for safety reasons, because the primary coil may be too exposed creating a health hazard. Similarly, if there is movement during the charging process, a communication unit immediately stops the charging procedure courtesy of a position detector that instantly registers the movement.

It is important to note that in 2010 the ICNIRP (International Commission on Non-Ionizing Radiation Protection) increased the standard from 6.25 µT to 27µT. Despite the relaxed standard, Siemens' goal remains to stay below the previous standard of 6.25 µT.

3.3.5 Performance Targets

The power efficiency of the energy transfer (at 3.6 kW) from the grid through all the components to the battery was targeted at over 90 percent in the prototype, which does not include the DC/DC converter on board the vehicle. Typical conductive systems operate at around 93 percent. All results presented in this document are valid for the entire energy chain w/o the DC/DC converter expect when otherwise stated. The entire energy chain is defined from wall outlet to battery and includes the Power Factor Correction module, the inverter, the power electronics grid, coils, rectifier, and the DC/DC converter in the vehicle.

3.4 Critical Topics not in Focus

For this study, we used WLAN communication between the vehicle and grid-side infrastructure unit because it was already available integrated into our power electronics. However, this technology is quite power consuming in stand-by mode from a vehicle perspective, and therefore not desirable. This was identified upfront after reviewing the vehicle specifications and it was decided to leave it in place. We acknowledge that commercialized versions will require a lower power communication between the vehicle and the infrastructure, so it is likely that a different technology will be chosen to achieve these functions in our next generation prototypes.

4 Results

4.1 Efficiency as a Function of Air Gap

In Test Scenario #1, the objective was to measure power transfer efficiency as a function of air gap with no coil misalignment. The power delivery was fixed at 2.7kW due to limitations of the grid connections; usually cables and power outlets are designed for 16A peak but cannot withstand 3.5 kW energy supply continuously. Additionally the ideal operating point of the vehicle battery system used in the testing was designed at 2.7kW.

Testing between displacements of 70mm and 130mm, we were able to maintain efficiency at a level greater than our target of 90% until the air gap was increased to 105mm. The full complement of data is reflected in the chart below, showing the efficiency traces as a function of air gap for the entire energy chain (power electronics (PE) + the inductive coils) with and without the DC/DC converter on board the vehicle. The displacement of the two efficiency curves, on average around three and a half percent, is explained by the consumption of the DC/DC converter in the vehicle and results in a reduction of the efficiency of the total system. In general, the results show a gradual decline in efficiency as air gap increases, with the fastest rate of change between 95mm and 110mm.

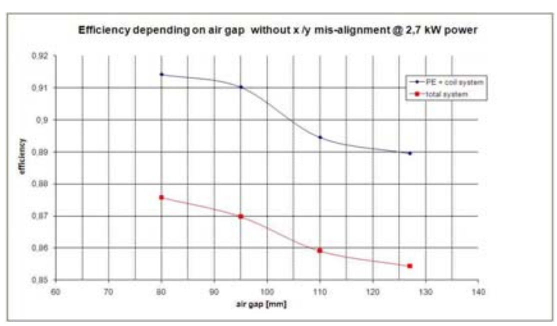

Figure 5: Efficiency depending on air gap without misalignment at 2.7kW power

4.2 Efficiency as a Function of Misalignment

In Test Scenario #2, the objective was to measure power transfer efficiency as a function of misalignment with a fixed air gap. A value of 120mm was chosen for the air gap because it is slightly above the lower limit of average passenger vehicle ground clearance. The power delivery was fixed at 2.7kW.

In these tests, the coils were misaligned both vertically (x-axis) and horizontally (y-axis), and then both directions simultaneously. Testing began with a misalignment of 0cm (total alignment) and was measured through misalignments of 12cm. For safety reasons, the systems were programmed to disable charging when misalignment exceeded 12cm.

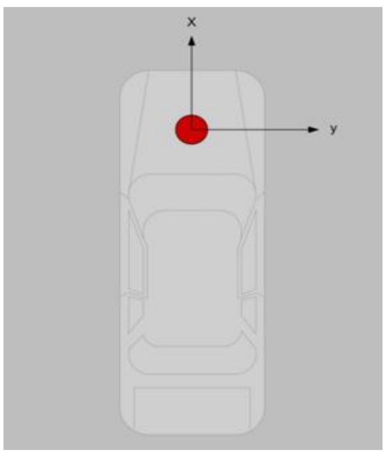

Figure 6: Reference System

In both sets of independent misalignment tests, we were able to maintain efficiency at a level greater than 90% until the misalignment was increased to 100mm. Since the coils are of circular design, we would expect that the curves should have similar traces and this is confirmed. The resulting efficiency is influenced by multiple factors that can operate simultaneously (frequency of magnetic field; transferred power etc.) therefore peak efficiency can be seen at smaller misalignment values. The greater the misalignment the higher the reactive power and hence the efficiency drops continuously starting at a misalignment greater than 5 cm in both cases.

The full complement of data is reflected in the charts below, showing the traces for the entire energy chain (power electronics (PE) + the inductive coils), with and without the DC/DC converter on board the vehicle as a function of the misalignment. The displacement of the two efficiency curves, on average around three and a half percent, is explained by the consumption of the DC/DC converter in the vehicle.

Figure 7: Efficiency over X Misalignment

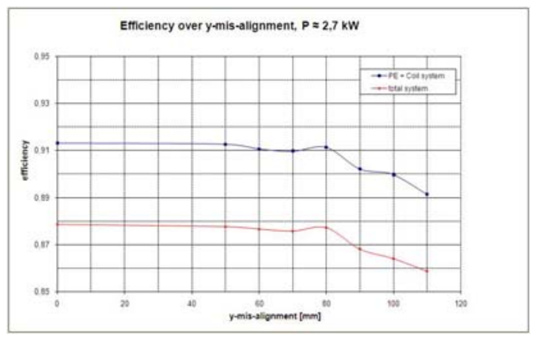

Figure 8: Efficiency over Y misalignment

In the final study under scenario #2, different combinations of x and y misalignments were tested. The root sum square (RSS) of the misalignments is plotted against the efficiency in the chart below. This graph shows a similar gradient compared to the graphs in figure 7 and figure 8 with the efficiency drops beginning slightly sooner (around 3.5cm) as we would expect from the combined x-y affect.

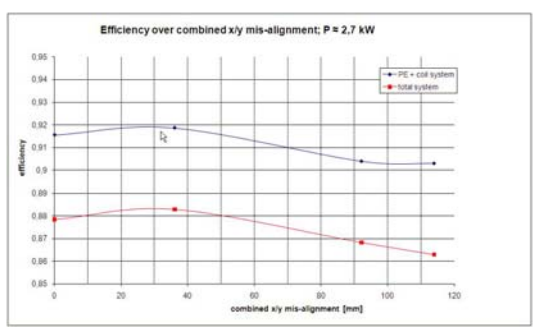

Figure 9: Efficiency over XY misalignment

4.3 EMC and Interference

The system was able to meet all EMC requirements for in-car and off-car technology and avoided interference with other electronic components in the vehicle with the exception of the passive keyless entry function. Outside the vehicle, the system passed testing according to standards used for electrical equipment in public places: ICNIRP and EN 61000-3-2. The cars were certified by TÜV Germany (single approval acc. to IEC 61851-22). The system follows the international threshold for the magnetic field strength in every accessible part of the vehicle.

With respect to the passive keyless entry function, this is a premium option to the vehicle that allows the driver to carry keys in their pocket and soon as they approach the vehicle it will open the door as the door handle is touched. This system operates at a frequency of 125 kHz and was blocked when the inductive field was active. The typical remote entry system that opens the door when the key fob is pressed operates in the MHz frequency range and was not affected by our testing. In the next generation system, Siemens is pursuing a solution that will allow the two systems to co-exist.

4.4 In-Vehicle Integration Testing

Prior to and after vehicle integration, the secondary coil system was able to pass all BMW conducted tests including temperature change, shock, vibration, salt water, and dust.

Figure 10: Secondary Coil after Vehicle Integration

5 Achievements

5.1 Vehicle Integration

The foremost achievement of the research project was the successful development of a complete infrastructure to vehicle inductive power chain including the on-board DC/DC converter for charging of the car battery. Accompanied with this integration was the successful communications connection to the private vehicle CAN Bus and exchange of bus messages along with sensor positioning data to enable automatic start/stop of the system and to automate the charging process. A final achievement of the vehicle integration was the ability to test and verify the influence of the inductive system on all other car components.

5.2 Vehicle Positioning System

An achievement necessitated by the requirement to attain maximum efficiency was the development of a vehicle positioning system. Using coil position data measured by advanced integrated sensing technology and communicated over WLAN between the vehicle and the charging infrastructure, simplified parking assistance was integrated into the multi-functional vehicle display to guide the driver via navigation instructions as close as possible to total coil alignment.

5.3 Closed Loop Automatic Controlled Inductive Charging

One of the original design concepts of the system was to use the power and voltage readings from the primary coil to adjust the field frequency on the secondary coil side. This was performed without transferring data from the secondary coil side to the primary coil side. During the study, this was modified to a system more resembling a closed loop control that included voltage and power data from the secondary coil sent via the WLAN communications. Combined with the aforementioned vehicle positioning technology, we were able to achieve an automatically controlled charging process using charging control units in the vehicle and the road side charging spot that dynamically adjusts the frequency of the magnetic field within a fixed range depending on the air gap and the misalignment to achieve the maximum efficiency.

6 Conclusions

There were two overarching takeaways from the research project. First, coil design is extremely critical. OEMs will demand the smallest and lightest coils possible. The smaller coils will have undesirable side effects and they will be harder to position the coils, meaning misalignment will play a much larger role. Differences in coil to coil distance are not so important and can be overcome with automatic adjustments in power electronics. We anticipate that the end result of these conclusions is the creation of a design guideline that educates the OEM on the array of effects that varying designs will have on both performance and cost.

Second, the 60cm diameter system such as the one used for this initial study does not generate a strong magnetic field and therefore no intense heating of objects between the coils. This means that foreign objects entering the air gap during the charging process are not at risk. However, future versions of the system that attempt to reduce the size and weight will result in more compact coils. This in turn will increase the field strength and the probability of more intense heating of foreign objects between the coils, another undesirable side effect. Therefore, we will also need a foreign object observation system because it is likely that objects may enter into the field such as drifting or blowing debris, organic materials etc. and will become heated, possibly causing harm to humans and other creatures.

7 Next Steps

7.1 2nd Generation Feasibility Study

Siemens recently completed work on their second generation inductive coil system. In the new design, there were three main areas of focus. First, an emphasis was placed on application. Specifically, the new system was designed for use in the home area because this is where charging has been most frequent in the EV introductory stages and this is where the driver can experience the most convenience. The focus will be on home comfort charging with a customer experience that is automatic, contactless, invisible, and safe.

Second, there was a continued focus on vehicle integration. Some early achievements of the new design include a significant reduction in the size and weight. The new dimensions measure 440mm (length) x 380mm (width) x 25mm (height) with a coil diameter of 300mm. Overall, the system is half the size of the first generation system delivering the same 3.6kW power transfer at an efficiency of greater than 90 percent (proven in lab measurements). Segregation of the power electronics from the secondary coil also contributed to the thinner design. The weight of the new system is a mere 6.5 kilograms, approximately 17% of the first generation system. These improvements are critical to cover the significant differences in BEV and PHEV platforms as well as the wide variation in ground clearances, up to 190mm in some cases, and even higher for vehicles like SUV's.

Lastly, we included a focus on infrastructure integration, ensuring that the road side charging system is tested under EU and North America energy grid conditions.

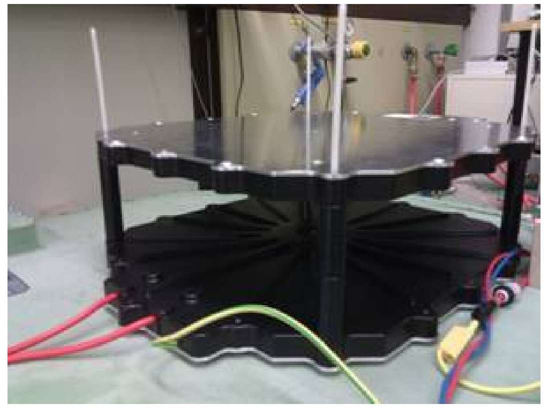

Figure 11: 2nd generation system

7.2 A-Sample System Evaluation

Between January and September 2012, Siemens will aim to create and test an A-sample inductive charging system prototype capable of meeting and certifying to automotive quality and safety standards. One of the objectives of this effort will be to determine what improvements are needed to integrate the system into series-produced vehicles under real-life conditions. As part of the study, we will setup a team to define scope and features of the A-Sample, define the timeline to finish the A-Sample by September 2012, to design the power electronics (infrastructure and vehicle side) and coil system to meet OEM expectation and cost position, and align with OEM activities to integrate into vehicles.

Specific technology improvements to be addressed during the A-Sample study are 1) investigating solutions for air gap observation, 2) improving the existing vehicle positioning system, 3) integrating into a low power, low range communication system for vehicle to infrastructure communications and 4) finding solutions for co-existence of any infrastructure and vehicle electronics operating at the same frequency.

Initially, the project will aim to deliver power and efficiencies at the same levels as the IndiOn project. In later phases of the trial post September

2012, higher power levels will begin to be explored.

Overall, the data and knowledge gained from the IndiOn project have contributed to the developments in our 2nd generation technology and have proved that, indeed, in the near future electric cars may be able to charge their batteries wirelessly. The proximity technology developed by Siemens for wireless charging is safe, convenient, and allows charging even during brief stops. The charging stations can be easily incorporated into practically any setting, making them nearly invisible and effectively protecting them against vandalism and wear and tear. By demonstrating an automated charging cycle using inductive charging technology, these trials should significantly increase customer acceptance of electromobility and pave the way for mass adoption.

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