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Wireless Inductive Power Supply of Electric Vehicles while Driving Along the Route

Peter Russer, *Life Fellow, IEEE*, Michael Haider, Mirco H. Metz, and Johannes A. Russer
TUM School of Computation, Information and Technology
Technische Universität München, Germany, e-mail: russer@tum.de

***Abstract*—The concept of an electrified road (E|ROAD) is based on electrically powered vehicles, and can overcome the problem of range limitation with minimal, cost-effective energy storage. A moving Field Inductive Power Transfer (MFIPT) system for supplying power to electric vehicles while driving along the route using primary coils arranged below the pavement is described. These primary coils transmit the energy via an alternating magnetic field to a secondary coil fixed to the vehicle below its floor. Only those primary coils located below the secondary coil of a vehicle are excited. By switching the compensation capacitors between the primary coils, the magnetic or electrical energy stored in the primary coils and compensation capacitors is passed on in the direction of travel, thereby achieving a high level of efficiency.**

***Keywords*— electric vehicles, wireless power transfer, inductive power transfer, electric road, moving field inductive power transfer, energy transfer for electric vehicles**

I. Introduction

In order to achieve the climate goals by reducing carbon dioxide emissions, only purely electric vehicles can be considered. All internal combustion engine fuels are either not carbon neutral or extremely expensive, as their use requires up to five times more renewable energy than powering electric vehicles (EVs) directly from electricity [1]. The share of battery electric vehicles (BEVs) amongst the cars on Germany's roads has increased continuously in recent years but is still below expectations. The main reasons are the high purchase price due to the high cost of conventional lithium-ion batteries, the limited range and the inconvenient and time-consuming charging process. There is currently a trend towards heavy and expensive cars, such as SUVs. This is, among other things, due to the need of accommodating heavy and large batteries in order to achieve a long range. The heavy weight in turn leads to high energy consumption. In BEVs, the traction battery increases both the vehicle weight and the purchase price compared to vehicles with internal combustion engines [2], [3].

To overcome these problems, the mobility concept of an electrified road (E|ROAD) was developed based on electrically powered vehicles, which can eliminate the problem of range limitation with minimal, cost-effective energy storage. While conventional combustion engine-powered vehicles still have to carry their drive energy with them and thus unnecessarily tie up space and resources and waste time when refueling, contactless energy transfer from an electrified road should be able to provide a constant supply of energy to the electric vehicle [4]–[7].

The *"Moving Field Inductive Power Transfer"* (MFIPT) system concept for the wireless inductive power supply of electric vehicles enables contactless energy transfer from an electrified road to the electrically powered vehicles through dynamic inductive charging while driving. In order to achieve high efficiency, only the energy channels for which the energy provided can be received by electric vehicles are activated, and the energy stored in an activated primary coil is completely passed on to the next primary coil when switching from the activated primary coil to the next primary coil [8]–[17].

II. Inductive Power Transfer Systems

In systems for the wireless inductive power supply of EVs, the energy is transferred without contact from a primary coil to a secondary coil. We distinguish between stationary IPT systems for charging the car battery on a parking lot and dynamic IPT systems for EV power supply and battery charging while driving on the road. Systems for inductive charging of EVs are described in [18]–[20]. The application-related and variable distance between primary and secondary coils results in high leakage inductances, which limit the coupling. To compensate for these leakage inductances, capacitances are added to the primary and secondary coils [21]–[23]. In 1997, A. Laoumar et al. proposed inductive charging for fully automatic BEV charging stations [24]. A stationary IPT system for overnight recharging of electric vehicles is described in [25]. Automatic impedance matching in IPT systems is described in [26]. Detailed studies of the influence of geometry and material parameters on the coupling of primary and secondary coils and on the IPT system efficiency were made in [27].

A Dual Mode Electric Transportation (DMET) system in which energy is inductively transferred from a powered roadway to moving EVs is described in [28], [29]. The energy from the roadway can be used for high-speed, long-range travel and for replenishing energy stored in the vehicle in batteries. The stored energy is available for short-range travel off the powered highway network. Inductive dynamic energy supply while driving is also discussed in [30]. By connecting the vehicle almost continuously to the power grid, the battery capacity can be reduced to a minimum, while at the same time eliminating the problem of how to extend the range [4], [5], [31]–[33]. A method for controlling the resonant frequency in IPT systems for charging of moving EVs is described in [34]. Overviews on the performance of BEVs and on wireless charging technologies are presented in [35]–[46].

III. MFIPT System

The MFIPT system described in this paper uses primary coils arranged below the pavement of the road. Fig. 1 shows a schematic representation of the roadway and a vehicle equipped with MFIPT system [9]–[11]. Below the pavement, primary coils are arranged and a secondary coil is mounted below the vehicle floor. The primary coils transmit the energy via an alternating magnetic field to a secondary coil located at the vehicle below its floor. Only those primary coils located below the secondary coil of a vehicle are excited. Compensation capacitors connected with the primary and secondary coils yield resonant energy transfer. The MFIPT system differs from other IPT systems by the circumstance that the energy, which is stored in the resonant circuits formed by primary coils and compensation capacitors, is completely passed on to the subsequent primary coil following in the direction of traveling when switching the activation from one primary coil to the next one [8]–[16].

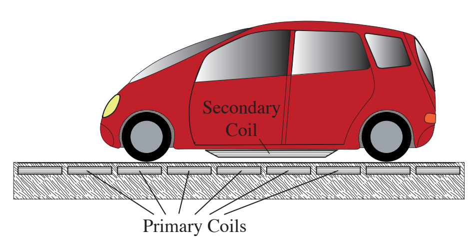

Fig. 1. Coil arrangement in MFIPT system.

In the previously known solutions, there is either no resonant energy transfer, which has a negative effect on the efficiency of the energy transfer, or, when using resonant tuning with a fixed assignment of primary coils and compensation capacitors in a permanently

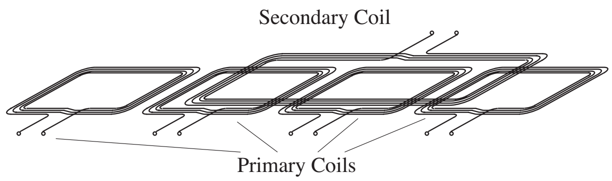

Fig. 2. Primary and secondary air coils.

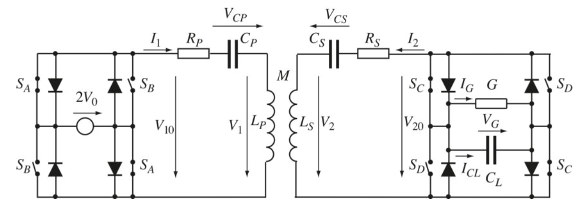

Fig. 4. The bidirectional inverter basic cell.

connected resonant circuit, the stored energy in the resonant circuit is not passed on to the next resonant circuit, when switching from one resonant circuit to the next resonant circuit.

Fig. 2 shows the schematic arrangement of the primary and secondary coils. The secondary coil has a length larger than that of two primary coils. So at any time the secondary coil covers at least one primary coil. The primary coil is fully covered by the secondary coil and excites an alternating magnetic field which induces a voltage in the secondary coil. For a short time interval the secondary coil of the moving car covers two primary coils. Within this time interval the activation is passed over to the next primary coil unit.

The MFIPT system is based on a switched DC-DC inverter that converts the direct current supplied by a stationary power line into direct current that is delivered to the electric vehicle on the road. Such inverter circuits in connection with stationary systems for inductive power transmission have been already discussed [23], [47], [48]. Primary coils arranged under the road are used, which transmit the energy via an alternating magnetic field to a secondary coil located below the vehicle floor.

Resonant inductive power transmission enables the very efficient high power transmission over large air gaps between transmitting and receiving coils. Circuit designs for resonant inductive power transfer were investigated using network modeling. The ability to achieve efficiencies of up to 97% has been demonstrated [49].

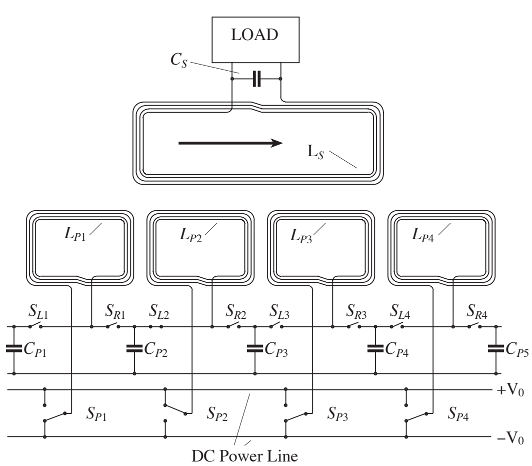

Fig. 3. The MFIPT circuit.

In [50] the parameters of circular and rectangular coil transformers were modeled under different conditions. The feasibility of power transfer over large air gaps has been shown. Automated assembly and manufacturing technologies, high volume production concepts for contactless power transfer systems, and the rationalization of the winding process of the HF-litz wire coil structures together with flexible automation concepts for this process are presented in [6].

In the circuit shown in Fig. 3, only one primary coil L_{Pi} overlapped by a secondary coil L_S of a vehicle is excited by periodically switching the switch S_{Pi}. To increase the efficiency of power transmission, primary and secondary circuits are tuned to resonance with the capacitors C_{Pi} and C_S. When the secondary coil is covered by two primary coils the primary coil is replaced by the next primary coil in the direction of motion of the vehicle and also the primary capacitor is replaced by the next one. The advance takes place in the currentless state of L_{Pi} and in zero voltage state of C_P.

The circuit arrangement described in Fig. 3 and the method associated with it effectively yields an oscillating circuit consisting of a primary coil and a compensation capacitance, which is in the steady state and follows the vehicle to be supplied with energy. As described above, a primary coil is replaced at the instant of zero crossing of the coil current by the primary coil following in the direction of travel, with the entire energy of the resonant circuit being stored as electrical energy in the capacity arranged between the two primary coils, at this instant of time when switching from one primary coil to the next. By switching, the resonant circuit is now formed by this capacity and the newly connected primary coil, whereby the newly formed resonant circuit is already in the steady state since the capacity is fully charged. Thereafter, at a time when all of the energy is stored as magnetic energy in the newly connected primary coil and the capacitances are in a zero voltage state, the connection of the primary coil to the preceding capacitance is interrupted and the subsequent capacitance is switched on.

By this way the resonant circuit formed by a primary coil and a compensation capacitor is now shifted by one primary coil segment in the direction of travel. The process is repeated at a time when the next primary coil in the direction of travel is located under the secondary coil of the vehicle. In this way, the arrangement acts as if a resonant circuit formed by a primary coil and compensation capacitor in the steady state were moving with the vehicle.

An exemplary system was designed for a resonance frequency of 20 kHz, since this frequency is, on the one hand, high enough to enable implementation with air coils and a sufficiently large distance between primary and secondary coils, and, on the other hand, sufficiently low to prevent electromagnetic energy from being radiated into the environment. The efficiency of inductive wireless energy transfer was calculated for a system with a transmitted power of 20 kW [12]. The primary and secondary coils were assumed to be rectangular air coils with edge lengths of 1.5 m × 1.5 m and 1.5 m × 3 m, respectively, and an air gap of 30 cm was chosen between the coils. For exemplary implementations, the calculations show efficiencies of 83% and 95% for resonator Q factors of 100 and 400, respectively.

IV. Switched DC to DC Converter

The IPT system is powered from a high-voltage DC line via inverters. An IPT system where the power transfer ability of the transformer is improved by using a parallel capacitor connected to the secondary coil and a voltage resonant are described in [51]. The inductive energy transmission principle enables the implementation of high-efficiency, high-power-density, systems suitable for applications with a wide input and load range [52]. The bidirectional inverter basic cell of the IPT system is depicted in Fig. 4. This cell comprises a full-bridge switched inverter and a resonant transformer. Switched inverter circuits based on a load-adaptive modulated phase have been already described in literature [53]–[56]. Bidirectional switched inverter circuits allow to enforce power transfer in both directions. In the bidirectional switched inverter circuit, the rectifier on the secondary side is replaced by controlled switches [57]–[59].

V. Primary Coil Control Circuit

The primary coil control (PCC) circuit fulfills the task of controlling the switches S_{Pi}, S_{Li}, and S_{Pi} in Fig. 3 in such a way that by switching S_{Pi} the AC current flowing through the primary coil is generated and by the corresponding position of the switches S_{Li}, and S_{Pi} a primary coil that is completely covered by a secondary coil is connected to an oscillating circuit. The duration t_T of complete overlap of the secondary coil with a single primary coil is $t_T \approx 30$ ms for an electric vehicle moving at a speed of 130 km/h, corresponding to 36 m/s with a primary coil length of 1m and a secondary coil more than twice as long. Detectors are arranged on the primary coils, which indicate the position of a secondary coil above the primary coil. The switching processes described for replacing a primary coil with the next primary coil following in the direction of travel are then triggered when the secondary coil is in a suitable position.

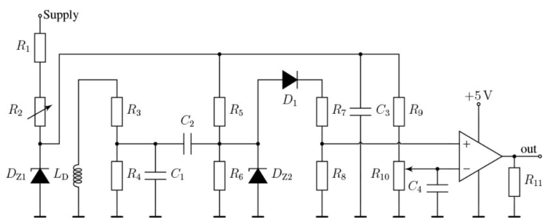

Fig. 5. Power supply and PCC circuit diagram [17].

A scaled experimental setup to investigate the primary coil control process is described in [17]. Fig. 5 shows the part of the PCC circuit for detecting the coil overlap. The two principles of the coil detector (CD) and the zero-crossing detector (ZCD) were examined. The CD determines whether the position of the secondary coil is above the subsequent primary coil. A full overlap of the primary and secondary coils is indicated if the coupling factor assumes its maximum value. Fig. 6 shows the power supply and PCC circuit and primary coils of a scaled experimental arrangement with three primary coils.

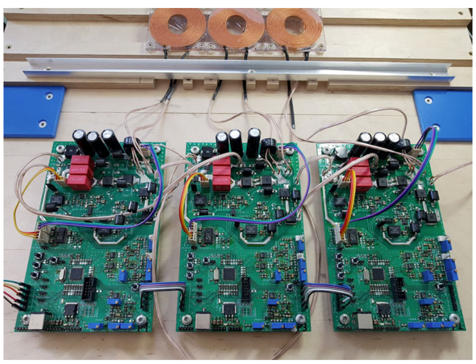

Fig. 6. Power supply and PCC circuit and primary coils [17].

VI. Power Balance

A. Power Balance

High costs and limited range are the main obstacles to the spread of electric vehicles. Both are connected to the vehicle's battery. Reducing the vehicle's energy consumption enables a reduction in the required battery capacity and the resulting costs. The development of energy-efficient electric vehicles is promoted by modern lightweight construction [60].

A detailed discussion of the power balance of MFIPT EVs is presented in [12], [15]. Driving without acceleration and without wind forces yields an electric power consumption

$$P_A = \frac{1}{2}\rho_L c_W A v^3 + m_{tot} g (f_R \cos\alpha + \sin\alpha) v \,,$$

where $\rho_L \approx 1.2$ kg/m^2 is the density of the air, and c_w is the drag coefficient of the vehicle, A is the projected end surface of the vehicle, and v_{rel} is the relative speed of the vehicle to the surrounding air, m_{tot} is the entire mass of the vehicle including payload, $g = 9.81$ m/s^2 is the acceleration due to gravity, α is the slope angle of the roadway, and f_R is the rolling resistance coefficient. Fig. 7 shows the driving power P_A required to achieve a vehicle speed v for 1200 kg total vehicle weight, cross section $A = 3$ m^2, drag coefficient $c_W = 0.3$, rolling resistance coefficient $f_R = 0.01$ and different slopes [12]. In case of negative slope the MFIPT system yields energy recuperation [11].

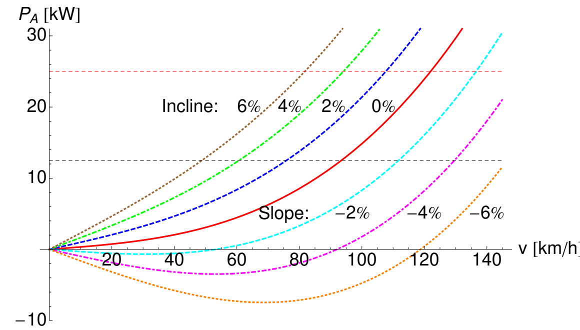

Fig. 7. Driving power P_A required to achieve a vehicle speed v for 1200 kg gross vehicle weight, cross section $A = 3$ m^2, drag coefficient $c_W = 0.3$, rolling resistance coefficient $f_R = 0.01$ and different slopes [12].

The efficiency was calculated for a 20 kW MFIPT system designed for a frequency of 20 kHz with primary rectangular air coils with edge lengths of 1.5m×1.5m and a secondary rectangular air coil with dimension1.5m×3m and an air gap of 30 cm between the coil in [10]. The calculations yielded a high efficiency of 83% or 95% at a resonator quality factor $Q = 100$ and $Q = 400$, respectively, for the power transmission of the MFIPT system.

VII. Human EM Exposure Limits

Wireless power transfer systems must comply with human EM exposure limits. Methods for both numerical analysis and measurements are discussed in [61], [62]. Shielding can reduce the EM exposure effectively [63]. Limits for non-ionizing electromagnetic radiation affecting the human body are defined in the ICNIRP guidelines [62], [64]. In [14], [15], the effect of shielding on the mutual coupling between a primary coil embedded in the road and a secondary coil in the electric vehicle, and resulting magnetic field levels in the passenger area have been investigated. This includes simulation of the field magnitude inside the passenger cabin of the car, as well as the fringing fields outside the vehicle. The main contribution to the field inside the passenger cabins are due to the fringing fields entering the car through the windows [15]. These investigations have shown moderate field levels inside the cabin, however, close to the windows limits of ICNIRP(1998) are exceeded slightly. An optimized design with effective shielding of the field radiated into the environment can further reduce the field strength inside the passenger cabin.

VIII. E|ROAD System Costs

To assess the economic competitiveness of E|ROAD traffic systems, the total costs of ownership (TCOs) of some vehicle types were compared in [4], [65]. In [15], [65] estimates of the total costs of ownership for E|ROAD EVs were presented. Seven scenarios with their parameters and the TCOs according to the calculation in [4]. The investigation of seven scenarios with their parameters and the TCOs as calculated in [4] have shown that the pure electric E|ROAD vehicle will be the cheapest alternative to the automobile due to lower battery costs and longer battery life. On the basis of the approximate length of 13,000 km of the German highway network, the total costs for installation and maintenance of an inductive charging system on these highways were calculated for equipping one lane in each direction [4], [15], [65]. Several cost estimates for the electrification of the entire German motorway network are compared in [15]. According to this, the total costs of electrification are between 19.7 and 138.8 billion euros. If a depreciation period of 30 years is taken into account, this results in costs of €0.66 to €4.63 billion per year. The annual financial requirements are therefore at the same level as the last federal budget for the motorways or the revenue from the truck toll. This corresponds to a good 1% of the total budget of the federal government in 2015. The amount of development costs can therefore be financed as far as politically desirable.

IX. Conclusion and Outlook

An MFIPT E|ROAD system implemented for EVs on highways makes it possible to get along with smaller battery capacities. The batteries are used only in local traffic and on side roads where no MFIPT system is installed. In areas without inductive supply roads available, the inductive energy transmission system may be used in stationary charging stations. Since only the primary coils below the vehicles are activated, high efficiency is achieved and the magnetic field is shielded by the EVs against the environment. According to [66], [67] wireless power transfer technologies are a key enabling technology to increase the acceptance of EVs and has the potential to shift $180 billion per year from oil production to jobs in local power generation and development, construction, and maintenance of electrified roadways and new electric vehicles.

An MFIPT E|ROAD system implemented for electric vehicles on highways makes it possible to manage with low battery capacities, as the batteries are only used in local transport and on secondary roads where no MFIPT system is installed. In areas without existing MFIPT E|ROAD tracks, the MFIPT system can be used in stationary charging stations. Because of the lower battery capacity required in MFIPT EVs, sodium batteries can be used instead of lithium batteries. Sodium chloride is the second largest component of seawater. This results in a cost advantage for raw materials for battery production and independence from the raw materials required for lithium-ion technology [68]. According to a communication from the Fraunhofer Institute for Ceramic Technologies (IKTS), industrial mass production of sodium-ion batteries could be achieved in Germany [69].

It is obvious that an MFIPT E|ROAD system will require a significant investment for laying the tracks with inductive transmitters. The MFIPT system is fully coexistent with conventional automobile traffic as well as with autonomously driving vehicles with and without V2V communication. This is important since during the introduction of a MFIPT system at the beginning only a small number of cars will be equipped with MFIPT systems and only a few highways will exhibit MFIPT E|ROAD tracks. However, also a fraction of EVs equipped with MFIPT systems will contribute to the traffic capacity enhancement of the equipped highway since groups of MFIPT EVs will gather to trains, safely driving with low distance between the EVs.

MFIPT E|ROAD transportation systems based on intelligent autonomous electric vehicles that exchange information with traffic management systems and each other can achieve smooth and energy-efficient traffic flow even at very high vehicle densities. The MFIPT E|ROAD system is well suited for embedding into an advanced cruise control system that utilizes vehicle-to-vehicle (V2V) communications and advanced collision avoidance sensor systems, significantly increasing highway capacities and reducing power consumption due to driving at a more consistent speed. Autonomous vehicles with V2V communication can increase highway capacity by a factor of 3.7 [70]. This high increase in highway capacity without highway widening for additional lanes also makes V2V communication-based MFIPT-EV systems an economical solution for future road transportation systems. Finally, comparing the cost of implementing MFIPT lanes with the cost of additional lanes to increase highway capacity, an MFIPT system based on V2V communication is economically advantageous, improves traffic safety and also reduces energy consumption.

Despite all the advantages of an MFIPT E|ROAD system once introduced, it must be taken into account that the introduction of this system represents a disruptive system change in relation to the current system of individual car transport. The question therefore arises as to how a transition to an MFIPT E|ROAD system can be carried out. There is the following possible solution:

- Since the energy supply for shorter distances comes from the batteries in the EVs, IPT lanes are only required on long-distance roads.
- If, while driving on long-distance roads, the inductive charge supplies a multiple of the power consumed by the EV momentarily, then shorter MFIPT tracks can alternate with longer routes without inductive energy supply.
- The MFIPT system is also suitable for stationary charging of EVs in private and public parking spaces and is already a simplification compared to the use of charging cables.

Strategies for a gradual introduction of an MFIPT E|ROAD system are therefore possible. As the MFIPT E|ROAD infrastructure expands, EVs can be equipped with ever smaller and lighter batteries, making EVs even lighter, smaller and cheaper.

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