Inductive Power Transfer for Charging the Electric Vehicle Batteries

Mohammed AL-SAADI*[1], Ali AL-OMARI[2], Sarab AL-CHLAIHAWI[3], Ammar AL-GIZI[2], Aurelian CRĂCIUNESCU[1]

[1]Facultatea de Inginerie Electrică, Universitatea Politehnica din București (UPB), Splaiul independenței, nr. 313, 060042 București, România

[2]Engineering Faculty, Al-Mustansiriyah University, 10001, Baghdad, Iraq

[3]Najaf Technical Institute, Al-Furat Al-Awsat Technical University, 54001, Najaf, Iraq

(*Correspondent author)

Abstract

Wireless power transfer (WPT) technologies have been developing rapidly in recent years. Advances in technology make WPT widely used in many applications. Electric vehicle (EV) contactless charging is an important application of WPT. Broadly, WPT categorized into radiative and non-radiative power transfer. Radiative power transfer is transmitting high power density, which is unsafe for humans when it is been used for EVs charging. So, only non-radiative power transfer technologies have been using to charge the batteries. Non-radiative power transfer includes inductive power transfer (IPT) and capacitive power transfer (CPT). Inductive charging technology is based on IPT. This paper covers a comprehensive review of an inductive charging system for EVs batteries. Operation principles, equivalent circuits modelling and power transfer requirements are presented. Some system design problems are also presented. Several compensation technologies and coil shape designs proposed to enhance inductive charging performance are also described. However, the air-gap between a charger and an EV, and the magnetic coupling between them are an area of concern. The stationary and dynamic charging methodologies have discussed briefly in this research. The most challenges and limitations of contactless EVs charging have been described in terms of: battery capacity, power level, air-gap, mileage, misalignment tolerance, efficiency, and interoperability. However, battery capacity can be enhanced by dynamic charging, the power level can be controlled, while some other limitations can be improved as discussed in this paper.

Keywords: wireless power transfer; inductive power transfer; battery charging; electric vehicles; coil configurations; misalignment tolerance; interoperability

Received: April 15, 2018

To cite this article:
AL-SAADI M., AL-OMARI A., AL-CHLAIHAWI S., AL-GIZI, A., CRĂCIUNESCU A., "Inductive Power Transfer for Charging the Electric Vehicle Batteries", in *Electrotehnica, Electronica, Automatica (EEA)*, 2018, vol. 66, no.4, pp.29-39, ISSN 1582-5175.

1. Introduction

The worldwide fuel oil consumption has been increasing because of high energy demand; the most fuel oil consumption going to electric energy production, and internal combustion engine vehicles (ICEVs). Due to fuel resources depletion and environmental concern, electric vehicles (EVs) are the best solution to reduce the effect of ICEVs on the environment [1, 2]. Despite the high initial cost, EVs require less maintenance compared with ICEVs, so, the overall cost over the lifetime of the EVs is lower than that of ICEVs [3].

The main challenge of EVs is the requirement of batteries of high energy density. At present, the distances that can be travelled by EVs is limited, because of a low energy density of available storage batteries. In addition, the charging time of an extended battery capacity is relatively long [4].

To make EVs more popular, the governments and environmental protection organizations deal with all above-mentioned challenges, as well as, infrastructure, and safety concern during conductive battery charging. Contactless EVs charging technologies are an effective approach to overcome the problems of safety, due to the fact the physical connection between a charger and vehicle is removed [5].

Over 117 years ago, Tesla invented the concept of wireless power transfer. Many industrial applications based on this technology have been developed so far. The wireless power transfer (WPT) is by the time-varying magnetic field, or electric fields, or by microwaves [6].

In general, WPT can be categorized into radiative (far field), and non-radiative (near field). The biggest advantage of radiative power transfer is the possibility of long-distance power transmission with a higher efficiency, and power density. However, at present, this technology cannot be used to charge EVs batteries, because it is unsafe for humans [7]. Non-radiative power transfer includes inductive power transfer (IPT) and capacitive power transfer (CPT) [8]. The efficiency of these power transfer technologies, for short distances, depended on many parameters, such as the distance between transmitter and receiver, misalignment, the frequency of transmission etc.

An IPT technology for the EVs applications transmits power with very high frequency, which causes big electromagnetic interference (EMI) [9]. Also, human safety must be considered during inductive charging. A standard set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) specifies that 200 mA/m^2 is the current density accepted to be exposed to the public[10].

To make EVs reality, several agencies, and organizations are setting up standards and codes affecting the system requirements at the utility interface. The Society of Automotive Engineers (SAE) have been established J1773 standard for EVs inductive charging [11, 12]. The EVs manufacturers have been developing chargers that effectively interface according to these recommendations. The J1773 standard introduces three charging levels for batteries of EVs, as listed in Table 1.

Table 1. Charging Levels of J1773 standard [12]

Charging Level	Power Level (kW)	Charging status	Utility interface
Level 1	1.5	Slow	120VAC, 15A, 1-φ
Level 2	6.6	5-8 Hours	230VAC, 40A, 1-φ
Level 3	25-160	Fast	208-600VAC, 3-φ

There are many other standards related to charger requirements, such as equipment of charging system, safety, harmonics, electromagnetic interference, etc. [13].

Fast charging is used sometimes, but, in this case, the life cycle number of the batteries decreases [14].

For charging, EVs could be connected to the smart grids (SGs) of the future. An interesting technology is a vehicle to grid (V2G), which assures bidirectional power flow between EVs batteries and smart grids. This technology helps to keep the cost of electricity stable. Batteries of EVs have potential to benefit both consumers and the overall electrical grid, by feeding electricity back to the grid during peak demand [15].

In this paper, inductive charging technology for EVs batteries is reviewed.

Section 2 explains the general concept of inductive charging system based on IPT, and commonly used technologies for EVs batteries inductive charging.

Section 3 presents the design requirements of the inductive charging system, challenges, and possible solutions.

In section 4, the configurations of a coil design are described.

In section 5, the electric circuits used for inductive coupler modelling are depicted.

Then, compensation topologies, charging methodologies, interoperability, power electronic requirements, and conclusion are described in sections 6, 7, 8, 9, and 10, respectively.

2. Inductive charging system

The general structure of an inductive charging system is shown in Figure 1.

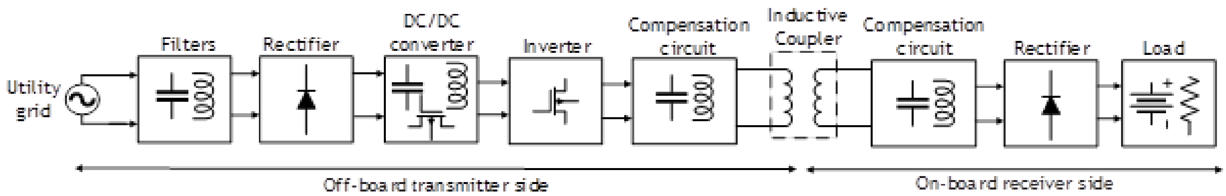

Figure 1. A general structure of an EV inductive charging system

It consists of off-board transmitter side and on-board receiver side. The transmitter side components include: filters, a half/full-bridge rectifier, DC/DC converter, a half/full-bridge inverter which produces a high frequency current which is transmitted through a power cable and a compensation circuit topology to the transmitter coil (L_1). The on-board receiver side components include: receiver coil (L_2), and rectifier where the AC current is rectified and filtered to produce a DC output for the battery load. [16, 17]. The purpose of each component will be explained briefly in section 9.

The two coupled coils of the inductive charging system are not linked through a common magnetic core and are separated by an air-gap. Due to mutual induction between L_1 and L_2, the AC power transmitted from the transmitter side to the receiver side.

The system efficiency mainly depends on the mutual inductance, M, and magnetic coupling coefficient, *k*, which are varied with the air-gap between the inductively coupled coils, and a misalignment between them [18-20]. As the air-gap between transmitter and receiver coils is increased, lower *M*, and lower *k* will result. The relation between these quantities is given by equation (1).

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (1)$$

A misalignment of the inductively coupled coils will decrease the value of k. The large leakage inductances of coils can result from large air-gap and therefore higher magnetizing currents will be produced; this leads to high reactive currents, high VA rating, and a low power factor, hence overall system efficiency is reduced [11].

Optimal power factor and transmission efficiency can be reached when the coils of transmitter and receiver (or many receivers) operate at the resonance frequency. This technology, called resonance inductive power transfer (RIPT), was created in 2007 by Massachusetts Institute of Technology (MIT) [11, 17]. The resonance can be achieved by adding capacitors at transmitter and receiver sides, to compensate reactive power; the compensation topologies will be explained briefly in section 6.

Beside inductively coupled coils, another IPT technology can be used for inductive charging: Shaped Magnetic Field in Resonance (SMFIR) technology.

This technology is based on creating a magnetic field by applying an alternating current around a magnetic core, such as ferrite; then one of the core sides will be a north and the other will be a south, as shown in Figure 2.

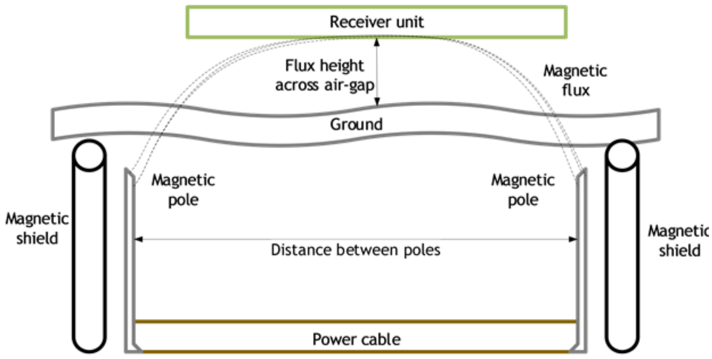

Figure 2. Inductive power transfer technology with shaped magnetic field in resonance

The shape of the magnetic field is determined by the length of the core; when the core length increases, higher magnetic field will be generated. Ferrite is the most popular non-conductive material used with inductively coupled coils. SMFIR technology is also popular, due to its high magnetic flux saturation density and low cost [21].

For an EV transmitter pad only the flux toward receiver pad, ϕ_{target} , is useful and; the leakage flux, ϕ_{leak} , according to equation (2), k decreases, accordingly M decreases [9].

$$k = \frac{\phi_{target}}{\phi_{target}+\phi_{leak}} \quad (2)$$

Magnetic fields are unaffected by dust, soil and non-metals objects, but metals and non-conductive magnetic materials do that. In the transmitter side, a ferrite core can be used to guide the magnetic flux toward receiver. In the receiver side, a ferrite core can be used to collect more flux.

This reduces the amount of leakage flux and improves overall system efficiency. Also, prevents heating up the conducting parts near the coils. The ferrites are usually used due to its free-loss at high frequencies up to several hundreds of kHz [22, 23].

Some designers add additional shielding materials (like aluminium) that cover the ferrites, which decrease the leakage flux. This solution is not only expensive but also increases the weight embedded in the EV; due to aluminium resistivity, additional losses are generated at high frequencies [24]. However, the presence of the EV chassis in a real configuration, above the inductive coupler, can be considered as an additional shielding with respect to devices or people being inside the car [25]. The commonly used ferrite core shapes are: U, E, S, H, I, Flat E, and W.

The effect of using a ferrite core on the coupling coefficient is shown in Table 2, and it is compared with a coreless structure [16].

Table 2. IPT systems coreless and with ferrite cores [16]

Coreless		Ferrite core	
Air-gap (mm)	*k*	Air-gap (mm)	*k*
200	0.16	70	0.35
2000	0.01	80	0.25
300	0.05	6	0.72

3. Design requirements and challenges

3.1. Coil material and parameters

The material of the coils has to be capable of handling high AC voltages and currents at high frequencies with minimum skin effect and eddy current losses, and low AC and DC resistances. To achieve all mentioned features with minimum loss and cost, Litz wires are the best choice.

Calculations carried out by Shin J. et al., found out that the current density of a Litz wire is 3 A/mm^2 [9]. According to the required operating frequency, the wire is chosen so that the skin depth has a value larger than the diameter of stranded conductors. With a frequency of 25 kHz, the skin depth is about 0.4126 mm [25]. At very high frequencies, hysteresis and eddy current losses drastically arise; these losses converted to heat may damage sensitive components of the system. Therefore, the shielding becomes necessary. According to its benign features and ability to protect system components and guiding the magnetic flux, ferrites are preferred to be used for shielding [16].

The number of turns, relative permittivity, coil dimensions, and shape, as well as the pitch of the coil, affect the self-inductance and capacitance of the coil.

There are many complex formulas used to calculate coil parameters: resistance, self-inductance, and capacitance [26]. Finite Element Analysis (FEA) is usually used to determine these parameters [27].

The resistance and inductance of the power cable, which connects the DC/AC inverter with a compensation circuit, as shown in Figure 1, must be taken into consideration during designing the power stage. Cable length, diameter, and weight have to be kept small, to minimize cable power losses and optimize frequency range. The coaxial cable is the best choice to meet all mentioned features [12].

Turns ratio of the transmitter and receiver coils is one of main consideration during the design of an inductive coupler. A turn ratio of 2:1 is preferred, because of lower input current; a high voltage rating results for high turn ratio, then the insulation requirement increases. Delco Electronics Corporation specified the turn ratio of 1:1 for low power level and 2:1 for high power levels, with four receiver turns [12].

3.2. Air-gap

When the air-gap between the transmitter and receiver coils increases, leakage inductances, M, and k are significantly decreasing, and the overall system efficiency is affected [26]. The charging distance range for contactless EVs inductive charging is (100-250 mm) [4]. A prototype of identical circular pads of 28 turns with ferrite bars, designed by Zheng C. et al., with efficiencies of 98% and 96.6% were obtained for 40 mm and 80 mm of air-gaps, respectively [28].

3.3. Power transfer level

A maximum active power can be extracted from the power supply when its impedance match input transmitter impedance; the former is constant while the latter is continuously varied with M, which is a function of air-gap. However, the adaptive matching network can be used between the inverter and transmitter coil, to bring impedance of latter match source impedance. At dynamic charging condition, the task becomes more complicated, due to an unspecific value of air-gap for each charging time [29].

The transmitted power from the transmitter side to the receiver side is not always maximum at the resonance frequency [29]. The transmitted power, P_{out}, is a function of the following: the quality factor of the receiver coil, Q_2, its inductance, L_2, operating frequency, ω, square of mutual inductance and input current, I_1. The power delivered to the receiver is given by equation (3).

$$P_{out} = \omega I_1^2 \frac{M^2}{L_2} Q_2 \tag{3}$$

The maximum power can be delivered to a load battery from the receiver circuit when their impedances are matched, this can be achieved by adding a matching network between them [26]. The level of received power specifies the battery charging time and cost [30]. The power level range of EVs charging is shown in Table 1.

3.4. Misalignment tolerance

Misalignment is the deviation of a receiver module with respect to a transmitter module. As the misalignment increases, the leakage flux increases and mutual inductance decreases; as a consequence, less power will be captured by the receiver coil and the overall system efficiency will be declined.

Due to its importance to overall system efficiency, a robotic arm mounted on the vehicle has been proposed to enhance the misalignment tolerance [31].

The effect of coil shapes and flux distribution on misalignment tolerance have been studied by many researchers. It has been observed that the flux pipes of double-sided coils have more misalignment tolerance than the single-sided circular coils [32].

Budhia, M et al. were designed a *double-D (*DD) coil, which was compatible with circular coils, and provided more misalignment tolerance than the circular coils [30].

3.5. Operating frequency

Almost all system parameters are affected by frequency; therefore, system development can be achieved by controlling the operating frequency. The transmission power level and efficiency can be improved in terms of Q_2.

For EVs inductive charging applications, the usually used operating frequency range is (10-200 kHz) [16].

The chosen resonant frequency depends on the distance between inductively coupled coils and the size of the coils. The targeted system quality factor, Q, of the resonant circuit leads to high transmission power efficiency η_{max}, as given by equation (4) [16].

$$\eta_{max} \approx 1 - \frac{1}{kQ} \tag{4}$$

The effect of parasitic capacitance on resonance frequency can be neglected, due to small capacitance value (a few pF) [26].

The operating frequency is preferred to be independent, because of any variation of actual ideal alignment, or air-gap length, resulting in a change of M and k [16].

The relation of Q is depending whether a compensation capacitor connected in series or parallel with a coil. The Q relations are given by equations (5) and (6).

$$Q_{series} = \frac{\omega L}{R} = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{5}$$

$$Q_{parallel} = \frac{R}{\omega l} = R\sqrt{\frac{C}{L}} \tag{6}$$

To get high-quality factor, thicker wires of high quality are used to build the coils.

However, lowering the capacitance can result in high frequency, which increases the skin effect. A single layer coils are preferred than multi-layer coil because the parasitic capacitance raises up the overall capacitance and leads to dropping Q [17].

The simulation results showed that when the variation of misalignment is up to 30 %, and of air-gap is up to 20%, the system efficiency, and transmitted power can be kept near their rated values if the system frequency is well-controlled [18].

3.6. Quality factor

An increasing the coil's self-inductance, or operating frequency, and decreasing AC resistance, has as result a high value of *Q* factor [29]. The electromagnetic interference can be minimized with high Q [33]. The factor Q is given by equation (7) [26], where ω is the angular frequency, *W* is coil stored energy, and P_{loss} is the power loss in the inductor.

$$Q = \frac{\omega \cdot W}{P_{loss}} \tag{7}$$

The quality factor for single-sided flux distribution is lower than that of double-sided [25]. Therefore, when the ferrite is added to guide magnetic flux and reducing the leakage inductance, the quality factor is negatively affected.

4. Configurations of charge pad

There are many types of coil configurations and cores. The question is which coil geometry and core shape are optimal to be used [34].

Based on the polarity of flux distribution, that is generated by inductively coupled coils, the structures of an EV charging pads can be classified into: unipolar pad (non-polarized), polarized pad, and Double D pad (DDP) [35, 36].

A symmetrical flux distribution is generated around a unipolar pad centre; therefore, it can be coupled optimally with a similar receiver pad. Polarized pads generate asymmetrical flux distribution, where the flux dominates in only one direction. Hence, they can be coupled optimally only with similar receiver pads, if the receiver pad approaches it, in a particular direction [37].

4.1. Circular pad (CP)

The CP with ferrite bars is shown in Figure 3 [38].

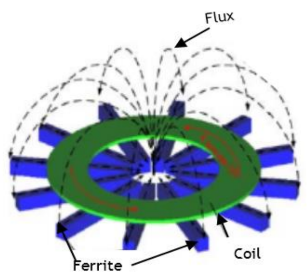

Figure 3. Circular pad (CP)

The CP has symmetric double-sided flux distribution. The fundamental flux path height, P_z, is proportional to about one-quarter of the pad diameter, P_d, as given in equation (8) [39, 40]. This means the pad diameter must be as much as four times the air-gap length, making it impractical for systems with large air-gaps [37]. Therefore, this type of pad is suitable only for stationary charging.

$$\triangle\ P_z \alpha \frac{1}{4} P_d \quad (8)$$

In [35], have been shown that the optimum coil diameter of CP is about 57% of the pad diameter, with an aluminium ring included. For a prototype of a circular planar structure with ferrite spokes used, the design has a transmitted power of 2 kW through an air-gap of 200 mm. The design consists of two identical charge pads, with a diameter of 700 mm, with ferrite spokes placed in a radial disposition. A single-sided coil winding has been used for each of the power pads. The pad has 130 mm of horizontal tolerance.

4.2. Flux-Pipe pad (FPP)

FPP sometimes called solenoidal, is shown in Figure 4 [38], it consists of one or two coils wrap around a rectangular core [39, 36].

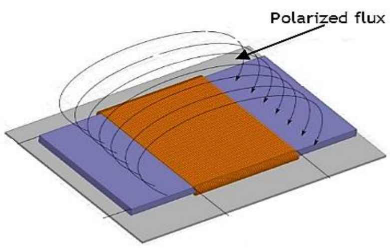

Figure 4. Flux-Pipe pad (FPP)

The FFP has double-sided polarized flux and higher field than non-polarized pad without adding an aluminium plate or a shield. The flux pipe results in a fundamental flux path height, that it is proportional to half of the pad length, as given in equation (9). This means that the pad diameter must be twice the air-gap length. [37]

$$\triangle\ P_z \alpha \frac{1}{2} P_d \quad (9)$$

An identical inductively coupled FPPs structure used by Chigira M. et al. have the coil winding rolled around a rectangular ferrite core; this structure is called H-shape core transformer, or rectangular H-shape core. With this design, a 1.5 kW of power transferred through 70 mm of air-gap, a 95 % of efficiency, and lateral misalignment tolerance of ±150 mm, where be obtained.

A 3 kW of power level, which can decrease the charging time to half compared with 1.5 kW, has been tested. Finally, the core has sliced in order to reduce all system weight; the results showed that the slicing structure could transfer the power efficiently. The performance exhibited by this structure is very good due to its lightweight (3.9 kg), small size (240×300×40mm), high efficiency, and good misalignment tolerance [32].

An experiment carried out by Takanashi H. et al. for a FPP with a H-shape core transformer, that has a 5.5 kg of weight, and size of (320 mm × 300 mm × 40 mm) achieved an efficiency of 90 % when 3 kW of power was transferred through an air-gap of 200 mm; For this structure, a ±200 mm of lateral tolerance misalignment was permitted; it was observed that maximum efficiency could be achieved, when the ratio of winding width to air-gap is 1.4 [36].

4.3. Double-D pad (DDP)

DDP of square coils is shown in Figure 5 [38], this is a single-sided polarized solenoid pad; this design merges advantages of both circular and flux pipe pads.

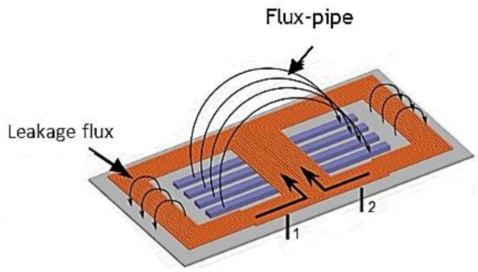

Figure 5. Double-D pad (DDP) of square coils

The DDP consists of two coils, magnetically in series and electrically in parallel to get low inductance. The coils also could be connected electrically in series using the same Litz wire. The DDP structure has a flux pipe in the centre, which usually made as long as possible; the remaining length of the coil has been minimized, in order to save copper, lowering the AC resistive losses, and controlling the flux height [41]. The flux height is directly proportional to the half-length of the pad [25].

4.4. Double-D quadrature pad (DDQP)

DDQP is shown in Figure 6 [37].

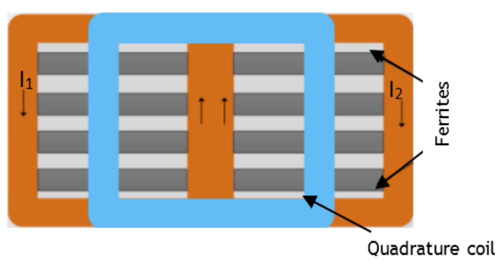

Figure 6. Double-D quadrature pad (DDQP)

The DDQP structure is same as DDP, but has an additional quadrature coil, to enhance vertical misalignment tolerance. The flux height produced by DDQP structure is twice that those produced by CP structure [37].

4.5. Rectangular and square pads (SP)

In this design, the coils have almost the same structure, but they differ hugely in performance; they form a double-sided polarized flux distribution [37].

This structure produces a higher flux path than the circular pad. When the coils are polarized, single-sided distribution flux is produced; this design has the highest magnetic coupling among all the other pad shapes. A drawback of configuration that it is require more Litz wires to make a rectangular/square coil of the same area as that of a circular coil [26].

An analytic model built and validated experimental, to study and compare the performance of square pad with circular planar spiral pad, it was proved that square pad is the better choice for EV inductive charging [42].

For a rectangular magnetic coupler with an oval-shaped coil, designed to transfer the power of 5 kW, has been obtained a coupling coefficient of as many as 0.46 [34].

4.6. Bipolar pad (BPP)

BPP, shown in Figure 7 [27], has a construction identical to DDP, except that the two coils here are overlapped [41].

It has proved that BPP provided an increase of misalignment tolerances [43].

4.7. Tripolar pad (TPP)

This pad, recently proposed, consists of three independent coils, partially overlapping, and mutually decoupled, as shown in Figure 7 [44].

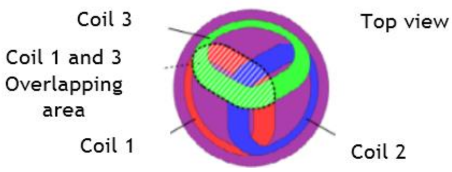

Figure 7. Tripolar pad (TPP)

Each coil can be traversed by currents with different magnitudes and frequency, with minimal impact on adjacent coils. Magnetic coupling has been studied, when TPP was used as a transmitter, and the CP and the BPP were used as a receiver individually; the results showed an increase of *k* when individual coils of TTP traversed by currents with different magnitudes and phases [44].

5. Inductive coupler modelling

The modelling methodologies help to determine element parameters, such as voltages and currents across the coils. This can aid the selection of design parameters and the determination of the system performance indices [29].

There are two electrical equivalent circuits to model the inductive coupler; transformer model and voltage dependent source model are shown in Figure 8 and Figure 9, respectively.

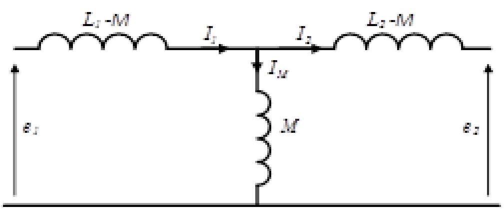

Figure 8. Transformer model

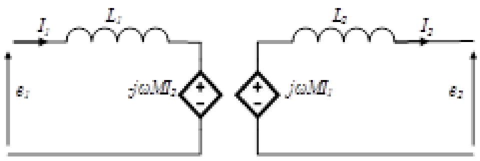

Figure 9. Voltage dependent source model

The transmitter current induces in the receiver coil an open circuit voltage, V_{oc} given by Eq. (10).

The possible short circuit current, I_{sc}, is given by Eq. (11) [45];

$$V_{oc} = j\omega M I_1 \tag{10}$$

$$I_{sc} = \frac{M I_1}{L_2} \tag{11}$$

The maximum rating power, S_{su}, at a receiver coil is given by equation (12) [27].

$$S_{su} = V_{oc} I_{sc} = \omega I_1^2 \frac{M^2}{L_2} \tag{12}$$

A maximum power that can be drawn from the receiver without compensation is $S_{max} = S_{su}/2$, which is low [27].

However, when a compensated topology is used, the output power can be expressed as in equation (13) [46, 47].

$$P_{out} = S_{su} \cdot Q_2 = V_{in} I_1 k^2 Q_2 = \omega I_1^2 \frac{M^2}{L_2} Q_2 \tag{13}$$

6. Compensation topologies

Leakage inductance, magnetizing current and input VA rating, are drastically increased as the air-gap between transmitter coil and receiver coil increased, and consequently, all system efficiency declines [16, 33, 48].

To minimize the air-gap between transmitter and receiver coils as much as possible, it was suggested to use the static charging in-wheel [49].

However, the impedance of a coil inductance can be totally compensated by connecting an equivalent capacitor in series or parallel with the coil; in such case, the operating frequency is called the resonant frequency [9].

The resonance circuit at the transmitter side ensures zero inductive impedance (or reactive power), unity power factor, less VA ratings (low inverter cost), and maximum power transfer at a high value of the coefficient k. In this design, high efficiency and maximum power delivered to the battery are ensured by resonance with the receiver side [47, 48].

Inverter switching frequency should be identical to the resonant frequency of single frequency system, while at multi-frequency system, it should be lower than the resonant frequency [37].

The compensations topologies can be classified according to the capacitor connection with a transmitter and receiver coil, respectively. There are four basic topologies: series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP).

The SS and SP topologies provide more than the rated power to the load, but uncertain action to the power supply may happen in absence of the load [50]. The PS and PP topologies are safe for the power supply but deliver less power to the load [16].

In parallel compensation, the capacitance value depends on the factor k, which is continuously variable for both static and dynamic charging, therefore, SS compensation is preferred [29]. Kissin M. et al., have built a prototype of 5 kW in which the SS compensation was used. The results showed that the power transfer capability and efficiency are significantly affected by the air-gap, and misalignment [18]. With an SP compensation, the system has achieved an efficiency of 90 % [51]

Due to presented challenges, and load requirements, some other compensation topologies have proposed by other researchers to combine advantage features of the basic topologies.

The SPS topology has been proposed; this topology has a capacitor connected in series followed by another one connected in parallel with the transmitter coil, and a capacitor connected in series with the receiver coil [33]. This topology combines the features of SS and PS topologies. It was used for an IPT system prototype to transfer 2 kW of power through an air-gap of 150 mm; it provided rated power transfer at a misalignment up to ± 25 % [50].

Also, the PPS topology has been introduced; this topology has a capacitor connected in parallel with the transmitter coil, while the receiver coil connected with a capacitor in parallel followed by another one in series. This topology was able to enhance the power factor of the transmitter coil, and the premised misalignment was improved by means of coupling coefficient enhancement [16].

Other researchers have suggested adding an inductor, as well as a capacitor to the compensation circuit, to get more features which meet the load requirements.

An LCL topology has been introduced; this topology has an inductor connected in series and a capacitor connected in parallel with the transmitter coil or with the receiver coil, or with both [52]. The feature of this topology is that the circuit behaves as a current source, i.e. the input current is independent of load current.

However, this topology reflects reactive power back into the source [16]. To reduce the weight and size of the LCL topology, an LCC topology was proposed; this topology has an inductor connected in series, a capacitor connected in parallel, and another capacitor connected in series with the transmitter coil [53, 33].

A zero-current switching (ZCS) can be produced. This topology provides, fewer losses, good performances, and high efficiency have been obtained. To control a bi-directional power flow, a CLCL model has been proposed [54].

7. Charging methodologies

Based on the state of an electric vehicle, whether it is stationary or moving, there are two EV charging methodologies;

7.1. Stationary charging

An EV van charged during parking time. This type of charging requires high power density batteries, to store more charges; this results in increased cost of the EV [12].

A single circular inductively coupled coils design, at transmitter and receiver sides, has been used to charge a stationary EV from Golf Company, with a power of 20 kW, and an air-gap of 50 mm. The obtained efficiency was about 90 %. The same design used a power of 60 kW to charge an urban bus with an air-gap of 30 mm.

A commercial product has been realized that consists of one transmitter coil and multi-receiver coils. This technology can transmit a power of 3.3 kW through an air-gap of 180 mm with a 90 % efficiency [55].

WiTricity Corporation has developed a WiT-3300 kit (500*500 mm), for inductive stationary charging. This kit is capable of transferring a power of 3.3 kW with 90 % of efficiency, through an air-gap of 180 mm [55]. A circular pad has been designed which it is capable of achieving 5 kW of power transfer for stationary inductive charging, through an air-gap of 150 mm, with an efficiency of 90 % [35]. A prototype with 2 kW of power has demonstrated that is capable for dynamic/stationary charging of an EV through an air-gap of 75 mm, with an efficiency of 91 % [56].

As mentioned earlier, one of the major EV problems is the mileage per charge. For the EV with the battery energy capacity of 16 kWh, the mileage is approximately 154 km [11]. The dynamic charging can improve the EV mileage due to the fact that the charging is happening during car movement, bus stops, traffic corridors intersections etc., but infrastructure cost is higher than in the case of stationary charging.

7.2. Dynamic charging

Dynamic charging, or online electric vehicle (OLEV), was developed by the Korean advanced institute of science and technology (KAIST). OLEV means an EV can be charged during its moving [57].

This technology can reduce the battery capacity required on-board by 20 %, due to frequent charging. Therefore, the size and weight of the EV are reduced [58]. This technology uses a relatively low resonant frequency because the system is in an open public area. In addition to, metal objects on the road may cause some difficulties [13].

The dynamic inductive charging has a less magnetic coupling, a more lateral misalignment tolerance, and a lower efficiency than the stationary charging. Therefore, it was proposed to use the lumped pad system type (multi-segmented coils array) instead of the single-track system [59]. The proposed system consists of multi-coils, operated at the same frequency, in transmitter or receiver, or on both sides, in order to cover more area as much as possible, with more misalignment tolerance. It was mentioned by Vilathgamuwa D. et al., that the spatial distance between the lumped pads coils should be chosen carefully, to avoid negative mutual inductance between the inductively coupled coils [29].

Three possible solutions were suggested by Kissin M. et al., to minimize this issue [60]. The best proposed solution uses different frequencies for each coil in the multi-coils system [61]. However, fixed or variable frequencies can be used in the operation of the IPT systems.

To avoid the point of bifurcation, and power loss during variable frequency operation, the input VA rating of the inductive coupler should be greater than its receiver [32]. It was proved, that the system performance of dual-frequency outperforms the single frequency system [61].

A single frequency system, with a single transmitter track, uses a single transmitter coil in paved roadbed; this allows one EV charged at a time. This technology provides a relatively low constant coupling coefficient due to the small area which is covered by the transmitter pad but, in return, it is easy to control. Because more pads are required to charge more vehicles, the result is high infrastructure cost [16]. A power pulsations problem arises at the receiver when the single-track system is used and, in this case, the battery lifetime is affected. The use of a long track transmitter is one of the expensive possible solutions. Multi-segmented coils array at transmitter or receiver, or on both sides, can be used as another solution to minimize pulsation as much as possible and to provide many other features, such as coupling enhancement, and less field exposure [62]. The drawback of this solution is that when the number of coils increases, the system cost increases [29].

An experiment was carried out, to transfer a power of 15 kW continuously to a moving EV. The transmitter side consisted of a single-track system, while the receiver side used a multi-coils system. A ± 200 mm of misalignment tolerance was obtained [46]. Oakridge National Lab has demonstrated that with a segmented coil array for the inductive charging system, using coils of 330 mm diameter, a power of 2 kW can be transmitted over 100 mm, with about 85 % efficiency. However, the efficiency of their design tends to drop significantly with misalignment [24].

In the process of dynamic inductive charging, when a high-power density is transmitted through a large air-gap, a reactive voltage of about a few kV is generated in the receiver side. This value is difficult to insulate, even if it is compensated.

However, instead of using a single capacitor connected at one point, many capacitors connected among winding cables can be used, in order to compensate the reactive voltage.

An OLEV system was implemented with 5 pick-up coils (each of 20 kW) to receive a power of 100 kW; by using capacitors connected among the winding, the peak reactive voltage was reduced from 10 kV to 2 kV; the system efficiency was 80 % through an air-gap of 260 mm [9].

A demonstrative inductive charging system for a bus, using the SMFIR technology, realized with E-magnetic cores, was capable to transmit a power of 100 kW through an air-gap of 200 mm, with a 75 % efficiency [21].

8. Interoperability

Interoperability is an essential requirement for the commercial inductive charging. A receiver can enhance interoperability with different transmitters by utilizing a multi-coils system with different frequencies.

An interoperability of charge pads means that receiver topology can be charged with different transmitter topologies, with high efficiency. An interoperability standard J2954 has been released by SAE. This standard specifies a frequency of transmission as being 85 kHz [63].

An interoperability performance comparison has been studied between BPP, or DDQP, as receivers, and DDP or CP as transmitters. The results showed that BPP receiver performance almost matches DDQP, but a less amount of copper was used by BPP [41]. Another study has carried out, to make a performance comparison between DDP, DDQP or BPP as a transmitter, and DDP or CP as a receiver. The results showed for transmitter interoperability that DDP is a poor selection, DDPQ is a good choice, with leakage inductance improvement, and BPP achieves good performance, with an improvement of a material usage efficiency [38].

To enhance interoperability, misalignment tolerance, and to reduce pulsation at receiver during dynamic charging, a prototype of 15 kW, which consists of three transmitter DDPs, and a BPP at the receiver side, has been built. The measurements have proved as ± 200 mm of lateral misalignment tolerance can be obtained [46].

9. Power electronics components

To transmit power efficiently from the transmitter side to the receiver side, the voltage level, frequency, and signal type are required to be converted from stage to stage. So, power electronics components are required to make these conversions. The major concern regarding the use of power electronics devices is harmonics injection into utility grid; this can increase the stress of low-voltage alternating current on the electric public network.

In order to meet the requirements of international standards and get high system efficiency, power electronic devices, such as synchronous rectifiers, filters, and power factor correction (PFC) have been added into the system, as shown in Figure 1 [11].

At the transmitter side, a half/full bridge rectifier is required for AC/DC conversion, followed by large enough capacitor to obtain mostly pure DC output voltage. For bi-directional power flow, another inverter can be used, that is capable of works in the rectifier mode with good control between the transmitter and the receiver sides [64].

A DC/AC stage can be implemented by using a half/full bridge inverter, a three-level neutral point clamped (3L-NPC), or a full bridge inverter (IGBT or MOSFET). A study carried out showed that the best choice is the full bridge inverter in terms of losses, size, and total harmonic distortion [65]. The operations of MOSFET and IGBT can be controlled through phase shift, pulse width modulation (PWM) or discrete pulse modulation (DPM). The advantage of the phase shift control in comparison with PWM consists in its ability to add a degree for the switching losses control as well as low switching loss [66].

A constant voltage can be obtained by controlling the inverter. However, constant current control is preferred, because the current source is naturally resonant converter dealing with changes in the load resistance or multi pick-up charging [39]. The voltage and current requirement of an individual inverter can be reduced when a multi-level inverter is used [67].

To supply the EV batteries with constant voltage, regardless power transfer level, which is affected by many parameters, regulators have to be used. Regulators are DC/DC converters, which control the current and voltage of the battery. Regulators can be classified into: buck, boost, and buck-boost [9, 7, 68]. A regulator could be connected with the transmitter side (post-converter) to get a closed loop system, or with the receiver side (post-rectifier) to get an open loop system. It is preferred to connect it with the transmitter side, because the area and the size are limited on an EV [64, 69].

Switching losses and conduction losses arise during electronic component operation. Converter-switching losses can be minimized when it operates at the resonant frequency, zero voltage switching (ZVS), or zero current switching (ZCS) [70]. However, the inverter frequency and the output voltage of the regulator must be controlled. Many controllers can be used to control system frequency and operation of the regulator, such as PID, FPGA, and DSP etc. [68]. Dual PI controllers have been used to control the input currents of the two boost converter, and one PI controller to regulate the output voltage of the regulator. PWM method has been used to control a two-segment IGBT inverter; more than 96% of inverter efficiency was be measured when the output power was 116 kW [9].

10. Conclusion

This paper reviewed the battery inductive charging technology.

Many coil configurations and charge pad designs have been proposed to improve an IPT system performance in terms of, the coupling coefficient between inductively coupled coils, and misalignment tolerance.

As the air-gap between the transmitter and receiver coils increases, the leakage flux also increases, then the overall system efficiency is affected.

To get maximum power transfer through an inductive coupler with minimum losses, the coils should be work at resonance condition, many compensation topologies have been proposed to make an IPT system work at resonance.

The resonance condition may be disrupted due to change in air-gap that the system has been designed to work at it, or due to misalignment tolerance, so, some works of literature proposed to use a controller to change the resonance frequency due to practical conditions to keep a system work in resonance. To supply batteries package with a constant power level a voltage regulator can be used.

To make the EVs more practical: in terms of increasing the mileage, the dynamic charging has been proposed; and in terms of commercial purpose, the interoperability between different charge pads have been researched and could be improved.

In spite of its huge challenges and limitations, the IPT technology proves its eligibility to transfer power efficiently with reasonable air-gap.

11. References

[1] Ciceo, S., Mollet, Y., Sarrazin, M., Van Der Auweraer, H., Marțiș C.S., “Model-Based Design and Testing for the Energy. Consumption Analysis of the Electric Vehicles”, in *Electrotehnica, Electronica, Automatica (EEA)*, 2016, vol. 64, no. 4, pp. 46-51, ISSN 1582-5175.

[2] Hasanzadeh, S., Vaez-Zadeh, S., Isfahani, A.H., “Optimization of a contactless power transfer system for electric vehicles”, in: IEEE Transactions on Vehicular Technology, 2012, vol. 61, no. 8, pp. 3566-3573, ISSN 1939-9359.

[3] Trigg, T., Telleen, P., Boyd, R., Cuenot, F., D’Ambrosio, D., Gaghen, R., Gagné, J.F., Hardcastle, A., Houssin, D., Jones, A.R. and Kaneko, H., “Global EV outlook: understanding the electric vehicle landscape to 2020”, Int. Energy Agency, pp.1-40. 2013.

[4] Imura, T., Yasuda, T., Oshima, K., Nayuki, T., Sato, M., Oshima, A., “Wireless power transfer for electric vehicle at the kilohertz band”, in: IEEJ Transactions on Electrical and Electronic Engineering, 2016, vol. 11, no. S2, pp. S91-S99, ISSN 1931-4981.

[5] Yilmaz, M., Krein, P.T., "Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles," in: *IEEE Transactions on Power Electronics*, 2013, vol. 28, no.5, pp.2151-2169, ISSN 1941-0107.

[6] Liu, C., Hu, A.P., Budhia, M., “A generalized coupling model for capacitive power transfer systems”, in: *IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society*, 2010, pp. 274-279, ISSN 1553-572X.

[7] Kishan, D., Nayak, P.S., “Wireless power transfer technologies for electric vehicle battery charging—A state of the art” in: *International Conference on Signal Processing, Communication, Power and Embedded System (SCOPES)*, 2016, pp. 2069-2073.

[8] AL-SAADI M., AL-GIZI A., AHMED S., AL-CHLAIHAWI S., CRĂCIUNESCU A., “Analysis of Charge Plate Configurations in Unipolar Capacitive Power Transfer System for the Electric Vehicles Batteries Charging”, in: *12th International Conference Interdisciplinarity in Engineering*, Târgu-Mureș, România, 2018.

[9] Shin, J., Shin, S., Kim, Y., Ahn, S., Lee, S., Jung, G., Jeon, S.J., Cho, D.H., “Design and implementation of shaped magnetic-resonance-based wireless power transfer system for roadway-powered moving electric vehicles”, in: *IEEE Transactions on Industrial Electronics*, 2014, vol. 61, no. 3, pp.1179-1192, ISSN 1557-9948.

[10] Karnez, E., Çetin, M., "World's largest Science, Technology & Medicine Open Access book publisher", (2017).

[11] Sabki, S.A., Tan, N.M., “Wireless power transfer for electric vehicle”, in: *IEEE 8th International Power Engineering and Optimization Conference (PEOCO)*, 2014, pp. 41-46.

[12] Kutkut, N.H., Klontz, K.W., “Design considerations for power converters supplying the SAE J-1773 electric vehicle inductive coupler”, in: *IEEE Twelfth Annual Applied Power Electronics Conference and Exposition*, 1997, Vol. 2, no. pp. 841-847.

[13] Williamson, S.S., Rathore, A.K., Musavi, F., “Industrial electronics for electric transportation: Current state-of-the-art and future challenges”, in: *IEEE Transactions on Industrial Electronics*, 2015, vol. 62, no. 5, pp. 3021-32, ISSN 1557-9948.

[14] Gil, A., Taiber, J., “A literature review in dynamic wireless power transfer for electric vehicles: Technology and infrastructure integration challenges”, in: *Sustainable automotive technologies*, 2013, pp. 289-298, Springer, Cham.

[15] Shaukat, N., Khan, B., Ali, S.M., Mehmood, C.A., Khan, J., Farid, U., Majid, M., Anwar, S.M., Jawad, M., Ullah, Z., "A survey on electric vehicle transportation within smart grid system", in: Renewable and Sustainable Energy Reviews, 2017.

[16] Kalwar, K.A., Aamir, M., Mekhilef, S., “Inductively coupled power transfer (ICPT) for electric vehicle charging–A review”, in: *Renewable and Sustainable Energy Reviews*, 2015, vol. 47, pp. 462-475, ISSN 1364-0321.

[17] El Rayes, M.M., Nagib, G., Abdelaal, W.G., “A Review on Wireless Power Transfer”, in: *International Journal of Engineering Trends and Technology (IJETT)*, 2016, vol. 40, no. 5, pp. 272-280, ISSN: 2231-5381.

[18] Villa, J.L., Sallán, J., Llombart, A., Sanz, J.F., “Design of a high frequency inductively coupled power transfer system for electric vehicle battery charge”, in: *Applied Energy*, 2009, vol. 86, no. 3, pp. 355-363, ISSN 0306-2619.

[19] Miskiewicz, R., Moradewicz, A., “Contactless power interface for plug-in electric vehicles in V2G systems”, in: *Bulletin of the Polish Academy of Sciencess*, 2011, vol. 59, no.4, pp. 561-568.

[20] Cheon, S., Kim, Y.H., Kang, S.Y., Lee, M.L., Lee, J.M., Zyung, T., “Circuit-model-based analysis of a wireless energy-transfer system via coupled magnetic resonances”, in: *IEEE Transactions on Industrial Electronics*, 2011, vol. 58, no. 7, pp. 2906-2914, ISSN 1557-9948.

[21] Cho, D.H., Suh, N.P., Yoon, U., Jung, G., “Shaped Magnetic Field in Resonance Technology and its Application to Transportation System”, in: ASME International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers, 2015, pp. V015T19A010-V015T19A010.

[22] Su, Y.P., Liu, X., Hui, S.R., “Mutual inductance calculation of movable planar coils on parallel surfaces”, in: *IEEE Transactions on Power Electronics*, 2009, vol. 24, no. 4, pp.1115-1123, ISSN 1941-0107.

[23] Acero, J., Carretero, C., Lope, I., Alonso, R., Lucia, Ó., Burdio, J.M., “Analysis of the mutual inductance of planar-lumped inductive power transfer systems”, in: *IEEE Transactions on Industrial Electronics*, 2013, vol. 60, no. 1, pp. 410-420, ISSN 1557-9948.

[24] Onar, O.C., Miller, J.M., Campbell, S.L., Coomer, C., White, C.P., Seiber, L.E., “A novel wireless power transfer for in-motion EV/PHEV charging”, in: *Applied Power Electronics Conference and Exposition (APEC), Twenty-Eighth Annual IEEE*, 2013, pp. 3073-3080, ISSN 1048-2334.

[25] Ibrahim, M., “*Wireless Inductive Charging for Electrical Vehicules: Electromagnetic Modelling and Interoperability Analysis”*, Doctoral dissertation, Paris, 2014.

[26] Chatterjee, S., Iyer, A., Bharatiraja, C., Vaghasia, I., Rajesh, V., “Design Optimisation for an Efficient Wireless Power Transfer System for Electric Vehicles”, in: *Energy Procedia*, 2017, vol. 117, pp. 1015-1023.

[27] Ongayo, D., Hanif, M., "Comparison of circular and rectangular coil transformer parameters for wireless Power Transfer based on Finite Element Analysis", in: *Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC), IEEE 13th Brazilian,* 2015, pp. 1-6.

[28] Zheng, C., Lai, J.S., Chen, R., Faraci, W.E., Zahid, Z.U., Gu, B., Zhang, L., Lisi, G., Anderson, D., "High-efficiency contactless power transfer system for electric vehicle battery charging application", in: *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2015, vo. 3, no. 1, pp. 65-74, ISSN 2168-6785.

[29] Vilathgamuwa, D.M., Sampath, J.P., "Plug in Electric Vehicles in Smart Grids", in: Springer press, Singapore, 2015, pp. 33-60.

[30] Budhia, M., Covic, G.A., Boys, J.T., Huang, C.Y., "Development and evaluation of single sided flux couplers for contactless electric vehicle charging", in: *IEEE Transactions on Industrial Informatics,* 2011, vol. 8, no. 3, pp. 614-621, ISSN 1941-0050.

[31] Barzegaran, M.R., Zargarzadeh, H., Mohammed, O.A., "Wireless power transfer for electric vehicle using an adaptive robot", in*: IEEE Transactions on Magnetics*, 2017, vol. 53, no. 6, pp. 1-4, ISSN 1941-0069.

[32] Chigira, M., Nagatsuka, Y., Kaneko, Y., Abe, S., Yasuda, T., Suzuki, A., "Small-size light-weight transformer with new core structure for contactless electric vehicle power transfer system", in: *Energy Conversion Congress and Exposition (ECCE), IEEE*, 2011, pp. 260-266, ISSN 2329-3748.

[33] AL-SAADI M., IBRAHIM A., AL-OMARI A., AL-GIZI A., CRACIUNESCU A., "Analysis and Comparison of Resonance Topologies in 6.6kW Wireless Inductive Charging for Electric Vehicles Batteries", in: *12th International Conference Interdisciplinarity in Engineering*, Tîrgu-Mureș, România, 2018.

[34] Petersen, M., Fuchs, F.W., "Development of a 5 kW Inductive Power Transfer System Including Control Strategy for Electric Vehicles"", in: *PCIM Europe, International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 2014, pp.1-8.

[35] Budhia, M., Covic, G.A., Boys, J.T., "Design and optimization of circular magnetic structures for lumped inductive power transfer systems", in: *IEEE Transactions on Power Electronics*, 2011, vol. 26, no. 11, pp. 3096-3108, ISSN 1941-0107.

[36] Takanashi, H., Sato, Y., Kaneko, Y., Abe, S., Yasuda, T. A., "large air gap 3 kW wireless power transfer system for electric vehicles", in: *Energy Conversion Congress and Exposition (ECCE), IEEE,* 2012, pp. 269-274, ISSN 2329-3748.

[37] Prazeres, J.R., "An Investigation of the Design and Development of a Multi Frequency Inductive Power Transfer System", in: Delft University of Technology, Doctoral dissertation, Netherlands, 2014.

[38] Zaheer, A., Hao, H., Covic, G.A., Kacprzak, D., "Investigation of multiple decoupled coil primary pad topologies in lumped IPT systems for interoperable electric vehicle charging", in: *IEEE*, 2015, vol. 30, no. 4, pp. 1937-1955, ISSN 1941-0107.

[39] Covic, G.A., Boys, J. T., "Inductive Power Transfer", in: *IEEE*, vol. 101, no. 6, pp. 1276-1298, 2013.

[40] Budhia, M., Covic, G., Boys, J., "A new IPT magnetic coupler for electric vehicle charging systems", in: *IECON 36th Annual Conference on IEEE Industrial Electronics Society*, 2010, pp. 2487-2492. ISSN 1553-572X.

[41] Zaheer, A., Kacprzak, D., Covic, G.A., "A bipolar receiver pad in a lumped IPT system for electric vehicle charging applications", in: *Energy Conversion Congress and Exposition (ECCE), IEEE*, 2012, pp. 283-290, ISSN 2329-3748.

[42] Luo, Z., Wei, X., "Analysis of Square and Circular Planar Spiral Coils in Wireless Power Transfer System for Electric Vehicles", in: *IEEE Transactions on Industrial Electronics*, 2018, vol. 65, no. 1, pp. 331-341, ISSN 1557-9948.

[43] Choi, S.Y., Lee, S.W., Lee, E.S., Jeong, S.Y., Gu, B.W., Rim, C.T., "Self-decoupled dual pick-up coils with large lateral tolerance for roadway powered electric vehicles", in: *Power Electronics Conference (IPEC-Hiroshima 2014-ECCE-ASIA), International*, 2014, pp. 1103-1108. ISSN 2150-6086.

[44] Kim, S., Covic, G.A., Boys, J.T., "Tripolar pad for inductive power transfer systems for EV charging", in: *IEEE Transactions on Power Electronics*, 2017, vol. 32, no. 7, pp. 5045-5057, ISSN 1941-0107.

[45] Covic, G.A., Boys. J.T., "Modern trends in inductive power transfer for transportation applications", in: *IEEE Journal of Emerging and Selected topics in power electronics*, 2013 vol. 1, no. 1, pp. 28-41, ISSN 2168-6785.

[46] Zaheer, A., Neath, M., Beh, H.Z., Covic, G.A., "A dynamic EV charging system for slow moving traffic applications", in: *IEEE transactions on transportation electrification*, 2017, vol. 3, no. 2, pp. 354-369, ISSN 2332-7782.

[47] Wang, C.S., Covic, G.A., Stielau, O.H., "Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer systems", in: *IEEE transactions on industrial electronics*, 2004, vol. 51, no. 1, pp. 148-157, ISSN 1557-9948.

[48] Fang, X., Hu, H., Shen, Z.J., Batarseh, I., "Operation mode analysis and peak gain approximation of the LLC resonant converter", in: *IEEE transactions on power electronics,* 2012, vol. 27, no. 4, pp. 1985-1995, ISSN 1941-0107.

[49] Panchal, C., Lu, J. and Stegen, S., "Static In-wheel Wireless Charging Systems for Electric Vehicles", in: INTERNATIONAL JOURNAL OF SCIENTIFIC & TECHNOLOGY RESEARCH, 2017, vol. 6, no. 9, pp. 280-284, ISSN 2277-8616.

[50] Villa, J.L., Sallan, J., Osorio, J.F., Llombart, A., "High-misalignment tolerant compensation topology for ICPT systems", in: *IEEE Transactions on Industrial Electronics*, 2012, vol. 59, no. 2, pp. 945-951, ISSN 1557-9948.

[51] Wu, H.H., Gilchrist, A., Sealy, K., Bronson, D., "A 90 percent efficient 5kW inductive charger for EVs", in: *Energy Conversion Congress and Exposition (ECCE), IEEE,* 2012, pp. 275-282. ISSN 2329-3748.

[52] Madawala, U.K., Thrimawithana, D.J., "A bidirectional inductive power interface for electric vehicles in V2G systems", in: *IEEE Transactions on Industrial Electronics*, 2011, vol. 58, no. 10, pp. 4789-9476, ISSN 1557-9948.

[53] Hu, A.P., "Wireless/Contactless Power Supply:-Inductively coupled resonant converter solutions", in: *VDM Publishing, 2009, pp. 139-141.*

[54] Thrimawithana, D.J., Madawala, U.K., "A generalized steady-state model for bidirectional IPT systems" in: *IEEE Transactions on Power Electronics*, 2013, vol. 28, no. 10, pp. 4681-4689, ISSN 1941-0107.

[55] Qiu, C., Chau, K.T., Liu, C., Chan, C.C., "Overview of wireless power transfer for electric vehicle charging", in: *Electric Vehicle Symposium and Exhibition (EVS27), IEEE*, 2013, pp. 1-9.

[56] Miller, J.M., White, C.P., Onar, O.C., Ryan, P.M., "Grid side regulation of wireless power charging of plug-in electric vehicles", in: *Energy Conversion Congress and Exposition (ECCE), IEEE,* 2012, pp. 261-268, ISSN 2329-3748.

[57] Li, S., Mi, C.C., "Wireless power transfer for electric vehicle applications", in: *IEEE journal of emerging and selected topics in power electronics*, 2015, vol. 3, no. 1, pp. 4-17, ISSN 2168-6785.

[58] González-Santini, N.S., Zeng, H., Yu, Y., Peng, F.Z., "Z-source resonant converter with power factor correction for wireless power transfer applications", in: *IEEE Transactions on Power Electronics*, 2016, vol. 31, no. 11, pp. 7691-700, ISSN 1941-0107.

[59] Ahn, S., Suh, N.P., Cho, D.H., "Charging up the road", in: *IEEE Spectrum*, 2013, vol. 50, no. 4, pp. 48-54, ISSN 0018-9235.

[60] Kissin, M.L., Boys, J.T., Covic, G.A., “Interphase mutual inductance in polyphase inductive power transfer systems”, in: *IEEE Transactions on Industrial Electronics*, 2009, vol. 56, no. 7, pp. 2393-2400, ISSN 1557-9948.

[61] Prazeres, J.R., Prasanth, V., Bauer, P., “Multi-coil multi-frequency inductive power transfer”, in: *Transportation Electrification Conference and Expo (ITEC), IEEE*, 2015, pp. 1-8.

[62] Kim, J., Kim, J., Kong, S., Kim, H., Suh, I.S., Suh, N.P., Cho, D.H., Kim, J., Ahn, S., “Coil design and shielding methods for a magnetic resonant wireless power transfer system”, in: *IEEE*, 2013, vol. 101, no. 6, pp. 1332-1342, ISSN 1558-2256.

[63] Bosshard, R., Kolar, J.W., “Inductive power transfer for electric vehicle charging: Technical challenges and trade off”, in: *IEEE*, 2016, vol. 3, no. 3, pp.22-30, ISSN 2329-9215.

[64] Mude, K.N., “Wireless Power Transfer for Electric Vehicle”, in: University of Padova, Italy, Doctoral dissertation.

[65] Meins, J., Buhler, G., Czainski, R., Turki, F., “Contactless inductive power supply,” in: *19th International Conference Magnetically Levitated Systems and Linear Drives*, 2006, pp. 1–9.

[66] Wang, S., Dorrell, D., "Simulation of electric vehicle inductive charging systems", in: *Power Electronics and Drive Systems (PEDS), IEEE 11th International Conference,* 2015, 399 – 404, ISSN 2329-3748.

[67] Mai, Y., Li, R., Yang, M., He, Z., “Cascaded multi-level inverter based IPT systems for high power applications”, in: *Power Electron,* 2015, vol.*15*, no. 6, pp. 1508–1516, ISSN 2093-4718.

[68] Al-Gizi, A., Louzazni, M., Fadel, M.A., Crăciunescu, A., “Critical constant illumination time in comparison of two maximum power point tracking photovoltaic algorithms,”, in: U. P. B. Sci. Bull., Series C, 2018.

[69] AL-SAADI M., AL-QAISI M., AL-BAHRANI L., AL-OMARI A., CRACIUNESCU A., “A Comparative Study of Capacitive Couplers in Wireless Power Transfer”, in: International Symposium on Fundamentals of Electrical Engineering (ISFEE), 2018.

[70] Jiang, C., Chau, K.T., Liu, C., Lee, C.H., “An overview of resonant circuits for wireless power transfer”, in: Energies, 2017, vol. 10, no. 7, pp.1-20.

Funding Sources and/or Acknowledgments

This research was performed within the Doctoral Studies School in University Politehnica of Bucharest, Romania.

Biography

Mohammed AL-SAADI was born in Baghdad (Iraq), in 1991.
He received the B.Sc. degree in electrical engineering and the M.Sc. degree in electronic and communication engineering from Al-Mustansiriyah University, Baghdad, Iraq, in 2012 and 2015, respectively.
He is joined to the University Politehnica of Bucharest (UPB) as a Ph.D. student in 2017, in Bucharest (Romania).
His research interests concern: electric vehicles, renewable and sustainable energy systems, power electronics, electromagnetics, power plants, electric machines, and photodetectors.
e-mail address: mohamedshihab91@gmail.com

Ali Al-Omari was born in Baghdad, Iraq in 1977.
He received M.Sc. degree in electrical engineering from the University of technology (Iraq) in 2002.
In 2018 he awarded Ph.D. degree from the University of Plymouth, UK.
His research interests concern: grid tie converters, SMPS, motor drives, and electric vehicles.
e-mail address: alih_jabbar@yahoo.co.uk

Sarab AL-CHLAIHAWI was born in Najaf, Iraq, in 1973.
She received the B.Sc. degree in electrical engineering and education from the University of Technology (Iraq), in 1995.
In 2012, she received the M.Sc. degree from Department of Electrical and Electronic Engineering, Jawaharlal Nehru technological University, Hyderabad, India.
Her research interests concern: power electronic, electric vehicles, renewable and sustainable energy systems.
e-mail address: sarab.haedar@yahoo.com

Ammar AL-GIZI was born in Baghdad, Iraq, in 1978.
He received the B.Sc. degree in electrical engineering and the M.Sc. degree in electronic and communication engineering from Al-Mustansiriyah University, Baghdad, Iraq, in 1999 and 2003, respectively.
He has been a Ph.D. student in the Faculty of Electrical Engineering, University.
Politehnica” of Bucharest (UPB), Bucharest, Romania.
His research interests concern: intelligent control and evolutionary algorithms in the renewable and sustainable energy systems, power electronics, and electric vehicles.
e-mail address: ammar.ghalib@yahoo.com

Aurelian CRĂCIUNESCU was born in Bucharest, Romania, in 1941.
He received the M.S. degree in electrical engineering from University Politehnica of Bucharest, Romania, in 1963, and the Ph.D. degree in electrical engineering from the same University, in 1973.
His research interests concern: analysis and design of electrical machines, power electronics and drives for traction and propulsion applications, and analysis and design of renewable energy sources.
e-mail address: aurelian.craciunescu@upb.ro