Inductively coupled power transfer (ICPT) for electric vehicle charging – A review

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A B S T R A C T

The deficiency in the availability of petroleum products has given rise to the incorporation of electric vehicles (EVs) globally as a substitute for the conventional transportation system. Significant research has been pursued over last two decades in the development of efficient EV charging methods. A preliminary review of few methods developed for wireless charging revealed that ICPT is a promising and convenient method for the wireless charging of EVs. This paper includes the equivalent circuit analysis and characteristics of the ICPT system and focuses on the research progress in respect of the designs for the charging coil, leakage inductance compensation topologies, power level enhancement and misalignment toleration. The improvement in these factors has been essential for the implementation of EV charging. A brief discussion over design process and control of ICPT system has been added. Conclusions have been made on the basis of the information extracted from the literature and some future recommendations are provided.

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1. Introduction

Petroleum products, including compressed natural gas and liquefied petroleum gas, have remained the main resources of the energy demand–supply cycle for transportation [1]. The gradual increase in energy demand has created a scarcity of these naturally available resources. Moreover, carbon dioxide emission contributing global warming and high fuel prices have compelled scientists and researchers to find a sustainable alternate solution to these depleting natural energy reserves [2–4]. Substantial research and development resources are being devoted towards alternate energy technologies [5–7].

The incorporation of electric vehicles (EVs) has been considered to be a suitable replacement for the depleting petroleum resources used for automotive applications [8,9]. The concept of EV was developed with the advent of the Hybrid Electric Vehicle (HEV), which later led to the introduction of plug-in hybrid electric vehicles (PHEVs). But the PHEV exhibited several disadvantages such as such the need of connecting cable and plug in charger, galvanic isolation of on-board electronics, the size and weight of the charger, and more importantly safety issues concerning their operation in the rain and snow [10]. In order to incorporate the aforementioned disadvantages in PHEV, pure EV has been developed [11,12]. Electric vehicles (EV) enable smoke free transportation, and offer an effective solution to the adverse environmental impacts of the conventional transportation system [13], and are powered over a large air gap through wireless charging even in bad weather and harsh environmental conditions without utilizing plugs or wires [14]. However the EVs are operated by means of electrical energy, so these are polluting the environment indirectly depending on the source of energy. They operate with low emissions of greenhouse gases [15]. Furthermore, they can be used with smart house systems to supplement the energy storage through bidirectional energy transfer [16]. Although EV is a possible substitute for depleting energy reserves and to overcome the environmental issues, the limited mileage and time needed to recharge, less misalignment toleration and overall cost involved are still limitations. These issues require special consideration for the successful implementation of an electrically driven vehicle system worldwide. The quest for a solution to the aforesaid issues has led researchers to develop the most useful method of wireless charging of EVs. Several methods have been pursued to charge both stationary and moving electric vehicles [17,18]. Static charging of EVs is convenient for the users to utilize at home or office parking [19], while dynamic charging allows powering the moving EVs. Though the static charging of EVs has the advantage of low cost compared to dynamic charging, but these require heavy size batteries so to store more charge [10], while the dynamic charging makes use of several charging coils paved in the roadbed at a spaced distance which allows more vehicles to get charged simultaneously [20]. Thus the dynamic charging has the main advantage of avoiding the need for a high capacity battery and reduces the battery cost. Inductively coupled power transfer (ICPT) has been most successful in consideration for the wireless charging of EV. Due to reasonable electrical isolation between transmitting coil and receiving coil, the ICPT system has ability to operate in grimy conditions. It is highly reliable and requires less maintenance. Extensive research over the span of time, in different technical aspects, has improved the performance of ICPT in terms of charging distance, misalignment toleration, high power and high efficiency [21,22].

This paper reviews the methods developed for the wireless charging of electric vehicles and their deployment as well as the evolution of ICPT performance. It begins with the impact of electric vehicles on energy and the environment and a brief comparison of the different EV charging methods in Sections 2 and 3 respectively. The operational mechanism of the ICPT method is discussed in Section 4. The equivalent circuit analysis and characteristics of the ICPT system are provided in Sections 5 and 6. A discussion on the research progress of ICPT is presented in Section 7. The discussion on design criteria and control algorithm is presented in Sections 8 and 9 respectively. Few recommendations and a conclusion based on the information learnt from the literature are provided in Sections 10 and 11.

2. EV’s impact on energy and environment and their advantages and drawbacks

Transportation causes the consumption of 27% world petroliam energy and 33.7% of greenhouse gas emissions in 2012 [1,8]. To reduce the CO₂ emissions, legislation is being introduced in some countries to limit the emissions from cars and other means. Substantial use of natural resources has created a scarcity thereof, and, in future, the world may face the impact of the dependence on these depleting natural energy resources.

Electricity has proven to be a viable alternative transportation fuel to replace petroleum products, so the electric vehicle has paved the path for reducing the dependence on petroleum energy. The EVs are solely operated by electric power and generates zero emissions of greenhouse gases. This creates substantial changes to reduce the air pollution, thus making the populated surroundings cleaner and gratifying for all livings around. The noise of conventional internal combustion engines is avoided through adoption of EV and the metropolises becomes noiseless [23].

With the development of wireless charging of EVs, the users do not need any wires to charge them safely. With automatic charging, the users simply need to park the EV over the plugless charging pad. Through the development in technology, the dynamic charging of electric vehicles has been introduced, which enables the charging of moving vehicles on the roadway. Regular stops on the roadway offer charging points to avoid disrupting the timetable of users. The charging system can operate reliably even in the most adverse weather conditions of snow and rain. Particularly, the electric vehicles can be connected to the smart grid of the future. The batteries of EVs have the potential to benefit both consumers and the overall electrical grid [24] and by feeding electricity back to the grid during peak demand it helps to keep the overall electricity cost stable. In addition, the charged vehicle could also potentially serve as an emergency supply for home or business in case of power outage.

There is risk of safety during accidents in case of human or animal presence under the car or bus. Thus, there is a major concern of electromagnetic field exposure in wireless charging of electric vehicles. The EMI exposure has to be under limited range as prescribed safety regulatory authorities during normal as well as abnormal operation.

The main drawback of EV is requirement of a battery of high energy density. It corresponds to frequent mileage of electric vehicle. More the mileage, larger the battery pack will be used. Lead acid battery is mostly used, which is very expensive. Escalating demand of EVs will result in the deficit of energy gradually introducing load management issues in grids.

The provoked concern of environment pollution and energy issues will rapidly ensure the feasibility of EVs for common commercialization by manufacturing light weight high energy density batteries, technical advancements to overcome misalignment, low efficiency during dynamic behavior of the power transfer system.

3. EV battery charging technologies

Different EV battery charging methods have been developed in the quest to achieve high efficiency, large power transfer and other attributes. The deployed methods have approached the different
capabilities in terms of power level, air gap and efficiency. These methods are discussed in this section.

3.1. Microwave power transfer (MPT)

This technology enables the transmission of power and information by using radio waves whose wavelength range falls into the category of microwaves. The operation of MPT involves components including a microwave generator, transmitting antenna and receiving antenna (also termed as rectenna). The block diagram shows the mechanism of MPT. Initially, the power supplied from the 50 Hz grid is converted into DC, which is fed into a microwave generator. There are resonating cavities in the microwave generator through which the current passes and produces microwave electromagnetic radiation. The rectenna receives the microwave energy and converts it back to DC. The received DC is utilized as per the requirements of the application.

Kyoto University has been working on the implementation of the MPT for the charging of EV for some years. In 2000, Kyoto University developed a MPT system for EV charging and achieved an efficiency of 76% [25]. A 10 kW rectenna array capable of receiving 3.2 kW/m² at a circa distance of 4 m with efficiency of 84% has been developed by the Volvo Technologies Japan and the Nihon Dengyo Kosaku companies [26]. Although the MPT has the advantage of transferring power over longer distances, it has the disadvantage of increased cost and antenna size. In addition, high power transmission using microwaves is not considered safe for humans as it does not comply with the radio wave regulation for high power. To overcome the disadvantage of the cost and antenna size, a new technique “Microwave Building” was introduced in [27]. In this technique, a waveguide is used, which provides a path for microwaves and does not allow the diffusion of microwaves. Therefore, the size of antenna and cost are reduced to a great extent and the technique is considered safe. However, to date, low power has been transferred using this technique.

3.2. Inductive power transfer

The charging of plugin electric vehicles has always a safety risk of the direct contact of metal-to-metal. To avoid this concern, the designs of electric vehicle charging systems were developed based on inductive power transfer (IPT) [28]. The IPT works on electromagnetic induction phenomena to transfer power through an air cored transformer with closely spaced primary and secondary coils [2,14,29]. The coils seem to be connected physically to each other but are isolated electrically, as shown in Fig. 1(a). The extended picture in Fig. 1(b) shows a sealed charging pad. The charger is inserted into the vehicle like fueling a conventional vehicle. The schematic diagram of IPT is shown in Fig. 2.

Inductive power transfer has been successfully implemented for EV battery charging. This method showed promising high power transfer with a smaller air gap, however, when the air gap between the primary and secondary coils is increased the performance decreases drastically due to leakage inductance [29].

3.3. Inductively coupled power transfer

The inductive power transfer offers low efficiency when the air gap is increased between charging coils and also involves wired chargers, while the designs for full wireless charging systems have been developed to overcome the deficiencies of IPT and make the charging system convenient for the users. The inductively coupled power transfer (ICPT) employs capacitors connected to both the primary and secondary coils to compensate the leakage flux due to the increased air gap, as shown in Fig. 3. Both the LC circuits work on resonance phenomena to enable effective energy transfer at resonant frequency [31].

The inductively coupled power transfer (ICPT) method is known worldwide for its high power transfer in many applications, mainly in electric vehicles [5,31]. It provides a rapid charging process, and optimized power transmission by frequency variation.
and control over the loss due to low magnetic coupling. The ICPT has been used for both stationary and moving electric vehicles [21]. If the vehicle being charged is stationary, it is said to be “charging of the battery electric vehicle (BEV)” or “static charging”, while, if the vehicle is moving, some names given to it are dynamic charging and online electric vehicle (OLEV). In the OLEV set-up, the primary coil is placed in the pavement at spaced locations, thereby establishing a charging roadbed that allows power transfer at several spaced locations throughout the roadbed. Although it involves high capital cost for infrastructure installation, its feature of frequent charging can elude the need for high capacity batteries. The online electric vehicle (OLEV) uses relatively low resonant frequency as the system is installed for the charging of moving electric vehicles in an open public area. Therefore, it is necessary to maintain safety regulations prescribed by safety regulation organizations, such as the International Committee on Electromagnetic Safety (ICES), and the International Commission on Non-ionizing Radiation Protection (ICNIRP) to avoid the exposure by humans to the electromagnetic field (EMF).

Many authors have termed this technology as the inductively coupled power transfer (ICPT), while Kurs et al. [32], and Karalis et al. [33] termed this method as the strong magnetic coupled power transfer. Nevertheless, both of these indicate same characteristics [13,34]. Takanashi et al. [35] split IPT based on the use of the magnetic core and operating frequency into the inductively coupled power transfer (ICPT) method [31] and the magnetic resonant power transfer method [32,33]. According to [35], the ICPT works on a frequency of less than 200 kHz and employs a ferrite core, while the magnetic resonance power transfer works on a frequency higher than 1 MHz and does not utilize a ferrite core.

The literature suggests that the ICPT is a comparatively efficient, optimum and light charging system through which power can be transferred from one part to another part of the system with no physical contacts, particularly in the electric vehicle application, even in extreme weather conditions [13]. Inductive power transfer (ICPT) has been attracting the interest of manufacturers in the last few years [36]. Cellular phone charging through ICPT is an application that has already been commercialized. The common commercialization of this technology is likely to be unveiled soon and may modernize the automotive industry.

The achievements in research of ICPT technology are tabulated in Table 1:

A comparison of charging methods with respect to the parameters including efficiency, frequency, cost, power level and distance is shown in Table 2.

From developed methods of electric vehicle charging, the ICPT method has enabled the high power transfer.

### 4. Operating principle for ICPT system

In the ICPT system, unlike the transformers in which the primary and secondary windings are wound on a magnetic core to avoid the leakage of inductance, and to produce a good coupling, the windings

---

**Table 1**

ICPT applied projects.

<table>
<thead>
<tr>
<th>Manufacturer/institute</th>
<th>Power rating</th>
<th>Efficiency (%)</th>
<th>Air gap (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007 [32]</td>
<td>60 W</td>
<td>40</td>
<td>200</td>
</tr>
<tr>
<td>2011 [37]</td>
<td>1 kW</td>
<td>88</td>
<td>30</td>
</tr>
<tr>
<td>2011 [38]</td>
<td>3.3 kW</td>
<td>84–90</td>
<td>10</td>
</tr>
<tr>
<td>2011 [39]</td>
<td>60 kW</td>
<td>92</td>
<td>40</td>
</tr>
<tr>
<td>2012 [40]</td>
<td>3.3 kW</td>
<td>90</td>
<td>18</td>
</tr>
<tr>
<td>2012 [26]</td>
<td>30 kW</td>
<td>92</td>
<td>14</td>
</tr>
<tr>
<td>2013 [41]</td>
<td>180 kW</td>
<td>85</td>
<td>10</td>
</tr>
<tr>
<td>2014 [42]</td>
<td>300–600 kW</td>
<td>83</td>
<td>3</td>
</tr>
</tbody>
</table>

**Table 2**

Comparison of various EV battery charging methods.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Efficiency</th>
<th>Frequency</th>
<th>Power level</th>
<th>Distance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave power transfer</td>
<td>Medium</td>
<td>1–30 GHz</td>
<td>Low/medium</td>
<td>Long</td>
<td>High</td>
</tr>
<tr>
<td>Inductive power transfer (Uncompensated)</td>
<td>High</td>
<td>15–100 kHz</td>
<td>High</td>
<td>Very low</td>
<td>High</td>
</tr>
<tr>
<td>Inductive coupled power transfer</td>
<td>Medium</td>
<td>20–200 kHz</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>

---

**Fig. 3.** ICPT circuit.

**Fig. 4.** Components of wireless power transfer for EV charging.
are not linked through a common magnetic core but separated over a large air gap. The inductively coupled power transfer for the EV charging system is depicted in Fig. 4, which consists of a utility supply, high-frequency inverter, primary and secondary resonant circuits and EV load [22]. The primary coil in Fig. 4 is a charging pad that is fixed in the ground. The EV is parked above the charging pad and a high-frequency AC voltage is applied to the charging pad. The rate of current flow creates a time variant magnetic field around the primary coil. Subsequently, by Ampere’s Law and Faraday’s law, being in the vicinity of a variant magnetic field, a voltage is induced at the terminals of the secondary coil, as shown in Fig. 5 [43]. The electrical load of EV is connected to the secondary coil, which completes the circuit and enables the power transfer.

As the primary and secondary coils are separated by a large air gap that results in low mutual inductance and the voltage across the mutual inductance becomes less [31], which creates a delay between the current and voltage and thus the reactive power is produced. To overcome the low power factor due to the reactive power [44], capacitance is added to both the primary and secondary side of inductive coupled power system (ICPT) to achieve the resonance phenomenon. This strengthens the coupling between the loosely coupled coils. The schematic diagram of the series-series compensated circuit topology is as shown in Fig. 6. This enhances the high power transfer when both the primary and secondary circuits are operated at the same resonant frequency [20,31].

The power output of an ICPT system ($P_{out}$) can be analyzed by using two observations in the ICPT system [46]:

Open-circuit test

$$V_{OC} = j \omega M I_1$$ (1)

Short-circuit test

$$I_{SC} = \frac{MI_1}{L_2}$$ (2)

Then power can be calculated as the product of open circuit test voltage and short circuit test current:

$$P = V_{OC} I_{SC} = j \omega M I_1 \times \frac{MI_1}{L_2} = \frac{j \omega M^2 I_1^2}{L_2}$$ (3)

$$P = S_u \times Q = \frac{j \omega M^2 I_1^2}{L_2} \times Q_2$$ (4)

$$P = \frac{j \omega M^2 I_1^2}{L_2} \times \frac{\omega L_2}{R_L}$$; Since $Q_2 = \frac{\omega L_2}{R_L}$ (5)

Therefore, the power transferred at the secondary coil can be calculated using the following equation:

$$P = \frac{\omega^2 M^2 I_1^2}{L_2} R_L$$ (6)

where $\omega$ is the angular frequency of the transmitting coil, $I_1$ is the current through transmitting coil, $M$ is the mutual inductance between two coils and $R_L$ is the load resistance.

5. Equivalent circuit analysis of ICPT

Although the inductively coupled power system has many configurations to compensate for the effect of leakage flux, a series-series resonant structure of the ICPT system is selected for analysis because of its simplicity and moreover it reduces the parameters that are involved in the optimization of efficiency of the ICPT system. An ICPT system with a series resonant capacitor is shown in Fig. 7. $L_p$, $L_s$ are the self-inductances of the primary and secondary side and $M$ is mutual inductance. $C_p$, $C_s$ are the capacitances of the primary and secondary side capacitors. $R_1$, $R_2$ are the resistances of the primary and secondary side and $R_L$ is the load resistance. Fig. 8 shows the T-type of equivalent circuit of the ICPT system circuit shown in Fig. 7.

The coupling coefficient ($K$), that defines the extent of coupling of the primary and secondary coil, is given by:

$$k = \frac{M}{\sqrt{L_p L_s}}$$ (7)
The total impedance of the equivalent circuit for given parameters may be calculated as:

\[ Z_{SS} = \left( R_1 + j \left( L_1 \alpha - \frac{1}{C_1 \alpha} \right) \right) + \left( \frac{\omega^2 M^2}{R_2 + j (\omega L_2 - \frac{1}{C_2 \omega}) + R_L} \right) \]  
(8)

The current absorbed from the supply is given by:

\[ I_1 = \frac{V_s}{Z_{SS}} \]  
(9)

\[ I_1 = \frac{V_s}{R_1 + \left( \frac{12 \pi \alpha f R^2}{R_1 + R_L} \right)} \]  
(10)

Now the circuit is operating at a resonant frequency \( f_r \) and the LC components cancel out their reactance and \( I_1 \) is given by:

\[ I_1 = \frac{V_s}{R_1 + \left( \frac{12 \pi \alpha f R^2}{R_1 + R_L} \right)} \]  
(11)

The input power can be calculated as:

\[ P_{IN} = \frac{V_s^2}{R_1 + \left( \frac{12 \pi \alpha f R^2}{R_1 + R_L} \right)} \]  
(12)

Or:

\[ P_{IN} = \frac{V_s^2 (R_2 + R_L)}{R_1 R_2 + R_1 R_L + (2 \pi f)^2 M^2} \]  
(13)

Likewise, the output power can be obtained as below:

\[ P_{OUT} = \frac{V_s^2 (2 \pi f)^2 M^2 R_L}{(R_1 R_2 + R_1 R_L + (2 \pi f)^2 M^2)^2} \]  
(14)

And the efficiency of the system can be represented by the following equation:

\[ \eta = \frac{P_{OUT}}{P_{IN}} \]  
(15)

Or

\[ \eta = \frac{R_L}{R_1 + R_1 \left( \frac{R_2 + R_L}{(2 \pi f M)^2} \right)^2 + R_2} \]  
(16)

The maximum load resistance for optimized efficiency can be obtained by:

\[ R_L = 1 + \sqrt{\frac{(2 \pi f)^2 M^2}{R_1 R_2}} \]  
(17)

And, thus, the maximum efficiency can be obtained as:

\[ \eta_{\text{max}} = \frac{(2 \pi f)^2 M^2}{\left( \sqrt{R_1 R_2 + (2 \pi f)^2 M^2} + \sqrt{(R_1 R_2)^2} \right)^2} \]  
(18)

6. Characteristics of ICPT system

6.1. Impact of coupling coefficient and frequency on the efficiency of the ICPT system

The coupling coefficient between the primary and secondary can be calculated from Eq. (1). If no coupling exists between the primary and secondary, then \( M = 0 \), and, thus \( k = 0 \). The general transformers with cores and no air gap have the highest coupling coefficient. The coupled coils have \( k \geq 0.5 \), they are termed as tightly coupled and those having \( k \leq 0.5 \) are called loosely coupled. The value of \( M \) and thereby \( k \) depends on the physical dimensions and the number of turns of each coil, their relative position to one another and the magnetic properties of the core on which they are wound. There is also a probable decrease in the coupling coefficient due to misalignment between the transmitting and pick-up coils in both the static and dynamic charging of EVs. Fig. 9 depicts the variation of coupling coefficient and mutual inductance as a function of variable distance.

Eq. (16) can be simplified to determine the dependence of the efficiency of the ICPT system on the coupling coefficient. The relationship between the coupling coefficient \( (k) \) and power
transferred can be represented by Eq. (19):

\[
\eta = \frac{R_k k^2 (2\pi f_c)^2 L_1 L_2}{(R_1 + R_2)(R_1 R_2 + R_1 + k^2 (2\pi f_c)^2 L_1 L_2)}
\]  

(19)

Fig. 10 shows that the efficiency varies directly with the coupling coefficient and frequency. The lower air gaps offer higher efficiency. It is important to select a trade-off between the distance and efficiency for high power transfer, keeping in view the necessity of application.

The power transferred can be determined by Eq. (1). Fig. 11 shows the maximum power transferred for different load resistances at certain bandwidth of optimum resonant frequencies. At these frequencies, the LC components cancel out their reactance at certain bandwidth of optimum resonant frequencies. At other frequencies, the LC components cancel out their reactance at all other frequencies except the range of bandwidth.

6.2. Impact of quality factor (Q) of coils on the efficiency of ICPT system

The quality factor quantifies how much the coil is purely inductive. It signifies its ability to produce a large magnetic field. Normally, the ICPT system is designed to operate at a fixed frequency; however, sometimes, due to a change in parameters, i.e. capacitance or load, the air gap causes the change in system frequency, so the transfer efficiency drops. Therefore, the system does not operate at a zero phase angle frequency.

The native quality factor of primary and secondary coil can be calculated as:

\[
Q_1 = \frac{\omega L_1}{R_1}, \quad Q_2 = \frac{\omega L_2}{R_2}
\]  

(20)

The loaded quality of series and parallel compensated ICPT system are given in Table 3.

A bifurcation phenomenon occurs when a system has more than one zero phase angle frequency [47]. Fig. 12 shows the efficiency characteristics during bifurcation phenomenon. It can be seen that there are more than one resonant frequencies where the efficiency becomes high. It has been shown in [47,48] that the bifurcation phenomenon highly depends on the quality factors of the coils. The condition for bifurcation in SS topology is derived in [48] and presented by Eq. (21):

\[
Q_1 > \frac{4Q_2^3}{4Q_2^3 - 1}
\]  

(21)

To avoid the bifurcation phenomenon in the series–series (SS) ICPT system, the quality factor of primary coil should always be greater than the secondary coil and thus the system will operate on a single zero angle frequency.

The impact of quality factor on the amount of power transferred and its efficiency can be observed from the following equations [49]:

\[
P = j\omega L_2 I_1 \times \frac{M^2}{L_2 L_1 Q_2}
\]  

(22)

\[
P = V_1 \times I_1 \times k^2 \times Q_2
\]  

(23)

To determine the maximum efficiency of the ICPT system, an equation based on the coupling coefficient and Q factor is developed in [35]:

\[
\eta_{\text{max}} = \frac{1}{1 + \frac{1}{L_2 M^2 k^2 Q_2}}
\]  

(24)

Fig. 13 shows the results plotted between \(\eta_{\text{max}}\) and \(kQ\):

\[
f_{r} = \frac{4Q_2^3}{4Q_2^3 - 1}
\]

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\[
P = j\omega L_2 I_1 \times \frac{M^2}{L_2 L_1 Q_2}
\]  

(22)

\[
P = V_1 \times I_1 \times k^2 \times Q_2
\]  

(23)

To determine the maximum efficiency of the ICPT system, an equation based on the coupling coefficient and Q factor is developed in [35]:

\[
\eta_{\text{max}} = \frac{1}{1 + \frac{1}{L_2 M^2 k^2 Q_2}}
\]  

(24)

Fig. 13 shows the results plotted between \(\eta_{\text{max}}\) and \(kQ\):

\[
\frac{P}{V_1 I_1} = \frac{M^2}{L_1 L_2 Q_2}
\]

in [48] and presented by Eq. (21):

\[
Q_1 > \frac{4Q_2^3}{4Q_2^3 - 1}
\]  

(21)

7. Development of ICPT system

7.1. Compensation technologies

The increase in air gap between two inductive coils increases the leakage inductance and magnetizing current, and, accordingly, the coupling between them weakens. The circuit is operated at a resonant frequency to compensate the leakage inductance and to strengthen the coupling between the resonant coils [50]. It has been analyzed that the primary coil compensation can minimize the apparent power rating of the power supply of the ICPT system, while the secondary coil compensation can increase the capability of the pick-up coil [31]. This is achieved by operating the system at the zero phase angle frequency, i.e. the angle between the current and voltage is always kept at zero. The arrangement of the capacitor connections for compensation on both sides either in series or parallel makes four topologies – series-series (SS), series-parallel (SP), parallel-series (PS) and parallel-parallel (PP) – as shown in Fig. 14. All these four basic topologies have different merits and demerits that are presented in Table 4. The selection of...
the topologies depends upon their suitability for specific applications satisfying the respective requirements, as SS and SP topologies can transfer higher power than the rated, but these offer an uncertain behavior to the supply [50], and the PS and the PP compensated ICPT systems are safe for the supply in the absence of secondary winding but these are unable to transfer the rated power if the coils are somewhat misaligned. The behavior of SS and SP topologies when the secondary is absent is shown in Fig. 15; the current rises due to decrease in impedance with increase in misalignment. The $I_2$ is load current and $I_{2r}$ is rated load current. However in PS, PP the current decreases as the total impedance increases due to misalignment as shown in Fig. 16. They require additional series inductor to control the inverter output current flowing through primary parallel resonant circuit, however, the size and cost of converter is increased. In [51], a series-parallel LCL pick-up design was presented that offered uninterrupted controlled power and smooth power transitions during switching states but it reflected reactive power back onto the source [52]. Moreover, the SP topology depends upon the coupling coefficient and requires a high-value of capacitance for stronger magnetic coupling [53]. According to [31,54], the SS topology is considered as the most suitable for EV charging because the primary and secondary capacitances are unimpeded from both the magnetic coupling coefficient and the load. It may

Table 4
Characteristics of compensation topologies.

<table>
<thead>
<tr>
<th>Topology</th>
<th>Acts as</th>
<th>Independent of changes in</th>
<th>Power factor at small distance</th>
<th>Power factor at small distance</th>
<th>Total impedance at resonant state</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series-series (SS)</td>
<td>Voltage source</td>
<td>C2</td>
<td>Low</td>
<td>Very high</td>
<td>Low</td>
<td>Very high</td>
</tr>
<tr>
<td>Series-parallel (SP)</td>
<td>Current source</td>
<td>C2</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Parallel-series (PS)</td>
<td>Voltage source</td>
<td>C1</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Parallel-parallel (PP)</td>
<td>Current source</td>
<td>C1</td>
<td>Very high</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Fig. 14. Compensation topologies (a) SS, (b) SP, (c) PS, (d) PP.

Fig. 15. The behavior of SS, SP topologies in absence of secondary [50].

Fig. 16. The behavior of PS, PP topologies in absence of secondary [50].
also act as a constant current and voltage source that is desirable for battery charging.

Besides these four conventional compensation topologies, other meritorious designs are proposed [21,31,48,55]. In [31] a design based on a primary compensated circuit was presented that minimized the effects of frequency shifts to avoid a low coupling coefficient. In [54], parallel–parallel–series (PPS) topology has been implemented that offered higher efficiency than PP topology for same distance of 50 mm and load of 1 Ω. The power factor of inverter in PPS topology has higher power factor than PP, however for smaller misalignment the PP topology has good performance than PPS. Vila et al. [50] presented the SPS design, which offered better performance for 2 kW prototype in terms of misalignment toleration and efficiency as compared to the basic compensation topologies for the load of 1.25 Ω. The selection of PPS and SPS topologies may done according to application requirement as SPS would not fit where less misalignment is expected but PPS can be useful. The Sakamoto et al. [56] presented an inductive coupler design that is capable of providing high self-inductance and less leakage inductance resulting in 8.3 kW of power transferred at an air gap of 3 mm with more than 97% efficiency.

7.2. Charging distance

The large air gap has been the main consideration in the development of EV charging, as a reasonable ground clearance is required between the EV chassis and the charging pad fixed in the ground. An air gap of a few hundred millimeters is considered necessary for EV application [57] and the value of $k$ in the EV charging ICPT systems has been observed to be between 0.3 and 0.6 [31].

In the quest to achieve efficient, optimum and high power transfer, research has been carried out on various transformers with a core and without a core (air core). Many designs have been proposed using an air core [20] and ferrite core [43]. Ferrite cores have been preferred because of their improved coupling coefficient and lower cost compared to others [14]. Table 5 shows a comparison between ICPT EV charging systems employing a ferrite core and an air core. This comparison reveals that the coupling coefficient in the ICPT systems using a core is higher than in the air core systems.

Extensive research studies have been conducted and published over time concerning the optimization of the charging pad by employing different core shapes. Initially, U cores, E cores and pot cores were examined but these were incompatible with EV application due to their greater thickness. The single-sided winding with a circular core shape, as shown in Fig. 17, was considered and used in the EV charging applications for long spans of time [31,61]. Mecke and Rathge [57] used circular coils of 400 mm diameter to transfer 1 kW power with an air gap of 300 mm. They achieved an overall power transfer system efficiency of more than 80% but misalignment was not focused upon. In [62], a 2 kW 700-mm-diameter circular power pad with a 200 mm air gap was proposed. The single-sided circular core offered both a low leakage electric field and electromagnetic radiation, which are desirable in EV charging. Less leakage of an electric field is preferable due to the surrounding metallic structures in the EV as the pick-up coil is embedded in the EV chassis. The circular pads exhibited limited coupling and offered poor tolerance to horizontal offset. In [62], it was shown that the pick-up coil should be aligned with the transmitting coil for the charging of the EV using circular coils, however, when the misalignment attained an offset of around ± 40%, the output power fell to zero. Budhia et al. [19] proposed a meritorious solution to overcome the limitations revealed by the circular pad. They introduced and optimized a new polarized coupler called a Double D Quadrature (DDQ), as shown in Fig. 18.

<table>
<thead>
<tr>
<th>Table 5</th>
<th>ICPT systems using ferrite core.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrite cored ICPT systems</td>
<td>Air cored ICPT systems</td>
</tr>
<tr>
<td>Ref no.</td>
<td>Charging distance (mm)</td>
</tr>
<tr>
<td>[11] 70</td>
<td>0.35</td>
</tr>
<tr>
<td>[58] 80</td>
<td>0.25</td>
</tr>
<tr>
<td>[59] 6</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Fig. 17. Single-sided circular charging pad [13].

Fig. 18. Double-D quadrature magnetic couple design [13].

Fig. 19. Rectangular H-shaped core [63].
The DDQ produced a flux path height twice that of a circular pad together with having a single-sided flux path completely inter-operable with the traditional circular pads. According to [63] and [64], the double-sided windings with rectangular core shape, as shown in Fig. 19, have also been considered for EV charging systems. The double-sided rectangular H-shaped core type was compact and lightweight but resulted in a low coupling coefficient due to its leakage flux at the back of the core, however, this leakage flux could be shielded by the aluminum sheet.

As there is an escalation in both the static and dynamic charging of EVs, accordingly, such power pads should be developed that can handle both [19]. In the design of power pads, the winding width should be sufficient enough to prevent the decrease in k. To decide upon the optimum winding width, Takanashi et al. [35] determined the effect of the winding width (w) and magnetic air gap (g) on the efficiency. It has been analyzed that a larger w/g ratio could observe maximum efficiency at a w/g ratio of 1.4. However, the large size of the secondary coil cannot fit on an EV chassis. Thus, it is required to keep in view the geometry of the secondary coil while designing for an EV chassis. According to [62], an increase in coil diameter with centered ferrite core can increase the self-inductance in a greater proportion than the mutual inductance that reduced the coupling coefficient. Generally, the magnetic coupling decays at 1/r², r being the distance from center loop, thus it seems that the size of magnetic charging pad can be increased but there are some limitations due to cost [65].

7.3. Power level

The power level for the ICPT system accommodates several important aspects including charging time, location, and cost [66]. The suitability of ICPT in different applications, charging time and the cost significantly depends upon the selection of the power level. A high power level is desirable when more vehicles are being charged from a single charging track. The static charging of EV prefers power levels of 2–7 kW with an operational air gap of 100–250 mm.

Different codes and standards suggest different criteria for the suitability of the power level selected for EV charging. The Society of Automotive Engineers (SAE) J1772 code describes the power level according to three categories that define different amounts of energy transfer requiring different infrastructure. The power level may also be classified according to on-board (the charger located inside the EV) and off-board charging [67]. The charging levels prescribed in SAE J1772 are summarized in Table 6.

Different OEMs (Original Equipment Manufacturers) manufacture production with different specifications that do not follow a single standard worldwide. Recently, the SAE international J2954 task force for the wireless power transfer (WPT) of light duty electric and plug-in electric vehicles [68] has proposed a specific frequency and power level for the interoperability of EV charging before commercialization. The proposed frequency that may be used for charging light electric vehicles is 85 kHz, which lies within an internationally available 81.38–90 kHz frequency band. The power levels prescribed by this code are presented in Table 6.

7.4. Misalignment tolerance

Misalignment is the displacement of the pick-up coil with respect to the transmitting coil and leads to a decline in both the efficiency and power transfer of the ICPT system. The ICPT system for EV charging requires maximum alignment between the coils to avoid inefficient power transfer due to driver mistake while parking the vehicle in the desired position [62]. The car weight may slightly change the air gap between the EV chassis and the ground and thereby coupling, consequently it would affect the power transfer efficiency [64]. The ICPT charging system with perfect alignment will reduce the leakage flux, and, as a result, it reduces the electromagnetic interference emission from the system; however, an ICPT system that could offer good tolerance for misalignment to give maximum freedom to the driver, is desirable [31].

Misalignment may be classified as lateral or longitudinal, in which the lateral misalignment can occur when coils are horizontally misaligned and longitudinal misalignment can occur when the coils are irregular with respect to their length [70]. Both types of misalignment may reduce the mutual inductance, and can cause the ICPT system to operate on a frequency other than what was designed with a low coupling coefficient k. When the secondary coil of a single-sided winding transformer with circular core is displaced 40% from the transmitter coil, the coupling coefficient becomes zero, as can be observed from Fig. 20. In [43], a polarized flux pipe was presented that offered better tolerance to misalignment than the circular pad and met the tolerance requirements for an EV. In [19], a Double D Quadrature (DDQ) coil design was presented, which offered far greater tolerance than a circular coil and was also compatible with circular coils. It may be observed that when the double-sided windings are misaligned to a certain position, as shown in Fig. 21, they still have good coupling because the flux linkage path is extended compared to the circular coils, as shown in Fig. 20 [64]. The ICPT systems can have a variable coupling coefficient, thus a perfect frequency control that keeps the ICPT circuit to remain in the state of resonance or coil geometry optimization that can offer high efficiency with a reasonable misalignment between coils may be employed, however, the system becomes either complex in terms of frequency control or costly due to the geometry of the coils [62,71].

<table>
<thead>
<tr>
<th>Power level type</th>
<th>Charger location</th>
<th>Typical use</th>
<th>Energy supply interface</th>
<th>Expected power level</th>
<th>Charging time</th>
<th>Vehicle technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 (Opportunity) 120 Vac (US)</td>
<td>On-board 1-phase</td>
<td>Charging at home or office</td>
<td>Convenience outlet</td>
<td>1.4 kW (12 A)</td>
<td>4–11 h</td>
<td>PHEVs (5–15 kWh)</td>
</tr>
<tr>
<td>230 Vac (EU)</td>
<td>On-board 1-or 3-phase</td>
<td>Charging at private or public outlets</td>
<td>Dedicated EVSE</td>
<td>4 kW (17 A)</td>
<td>1–4 h</td>
<td>PHEVs (5–15 kWh)</td>
</tr>
<tr>
<td>Level 2 (Primary) 240 Vac (US) 400 Vac (EU)</td>
<td>Off board 3-phase</td>
<td>analogous to a filling station</td>
<td>Dedicated EVSE</td>
<td>50 kW 100 kW</td>
<td>0.4–1 h</td>
<td>EVs (20–50 kW)</td>
</tr>
<tr>
<td>Level 3 (Fast) (280 V-600 Vac or Vdc)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6

Power levels defined by code: J1772 [69].
overcome the low coupling coefficient of the output of the inverter and that of the transmitter coil to and thereby permitted power transfer at a reasonably larger air gap. The variation in coupling was proposed and validated experimentally, which resulted in recoverable potency of the circuit to counter the variation in coupling. A meritorious study was conducted on the misalignment performance enhancement of ICPT by selecting a suitable SPS compensation topology, shown in Fig. 22, that realized the rated power transfer. The ICPT compensation circuits play a significant role in misalignment tolerance. Throngnumchai et al. [54] pointed out that basic compensation circuit topologies SS, SP, PS and PP are not suitable for ICPT systems considering the need for low sensitivity to the misalignment requirements of EVs, high power level and larger air gap. A meritorious study was conducted on the misalignment performance enhancement of ICPT by selecting a suitable SPS compensation topology, shown in Fig. 22, that realized the rated power transfer with the high misalignment of the pick-up coil without any complex control [62]. In [31], another circuit topology PPS, shown in Fig. 23, was proposed and validated experimentally, which resulted in recoverable potency of the circuit to counter the variation in coupling and thereby permitted power transfer at a reasonably larger air gap. The circuit topology presented was able to enhance the power factor of the output of the inverter and that of the transmitter coil to overcome the low coupling coefficient.

8. Design criteria of ICPT system

The development of ICPT design is done systematically using iterative process or experimental analysis. The principal condition for maximum power in ICPT system is resonant frequency operation. Thus the design of ICPT system primarily corresponds to the parameters that are necessary for resonant operation. These parameters are winding inductances ($L_P$, $L_s$), their respective capacitances ($C_P$, $C_s$) that are connected with them and resonant frequency ($f_o$). Following is resonant condition for inductive power transfer.

$$\omega_0 = \frac{1}{\sqrt{L_p C_P}} = \frac{1}{\sqrt{L_s C_s}}$$

(25)

Or

$$f_o = \frac{1}{2\pi \sqrt{L_p C_P}} = \frac{1}{2\pi \sqrt{L_s C_s}}$$. Since $\omega_0 = 2\pi f_o$.

(26)

Considering the overall ICPT system, design process involves the amount of power to be transferred, load resistance, desired load voltage. Based upon the amount of power, the frequency, inductances, capacitances are selected. The inductance of windings depends on number of turns and dimensions of coils and may be varied as per requirement. A meritorious study on design process has been presented in [21] that provides a flow diagram of ICPT design process depicted in Fig. 24. This design flow process can be applied for low to high power level ICPT system. According to this flow diagram the design process initiates with initial geometry, number of turns, cross sectional area and current density of coils and then an iterative process is applied until the fulfillment of required power level with permissible maximum frequency, geometry of coil. From Eq. (6), it clear that the resonant operating frequency is related to the amount of power to be transferred; higher the power to be transferred, higher will be the operating frequency. But higher frequencies are limited due to switching speed of inverter. To ensure high efficiency in ICPT system, the coupling coefficient and quality factors of coils should be high. The coupling coefficient may be improved by various magnetic shapes such as combination of ferrite core and litz wire. The coils of high Q-factor enable protection from electromagnetic interference [72].

Generally ICPT systems are designed for either fixed frequency operation or variable frequency operation. In variable frequency operation, the ICPT systems are designed in such a way that their input VA should be greater than secondary VA to avoid point of bifurcation and power loss [49].

Nowadays new trends in magnetic coupler designs and electronic are being introduced [46,73].

9. Control algorithms

The variation in air gap and alignment causes the change in load resistance and magnetic coupling between primary and secondary coil. There can be a deviation in frequency of inverter and load can vary over a considerable range. Uncertain characteristics can be expected due to all these issues. The output voltage of secondary coil may vary excessively from designed value. To avoid undesirable characteristics under various
operating conditions and to maintain a normal operation of power transfer, a proper control is essential. It will prevent from output voltage fluctuation, where a constant supply is important. The control strategy may be applied to different parts of ICPT; individually for primary coil power supply control and secondary coil power control or synchronised control of primary and secondary coils. The control of secondary coil is more common in order to get stabilized voltage.

The circuit of inductively coupled power transformer is shown in Fig. 6. A high frequency inverter is necessary to operate the resonant circuit and produce high frequency supply for primary coil. The operating frequency of inverter switches has to match with the designed frequency of coils but fixed frequency control cannot manage variation of circuit parameters, and as a result the switches practice high voltage or current stress, and high energy loss in the form of heat. Thus variable frequency control has been developed to

Fig. 24. Flow diagram of ICPT design [21].

Fig. 25. Control block diagram of ICPT Coil Supply.
ensure circuit resonance [74]. Proportional–integral (PI) controllers have been implemented to control the input and output current through DSP, FPGA and other devices [2,18,53,58,75]. Atypical control block diagram of input current is shown in Fig. 25. Promoting the concept of bidirectional power transfer for V2G (vehicle-to-grid) system and V2H (vehicle-to-home), some coordinated controller including single-ended quasi resonant high frequency inverter, directional tuning control and synchronised PWM with high frequency communication system have been implemented [76–78].

10. Future recommendations

Although EVs have huge potential to switch conventional transport into modern electric transport, they are not commonly adopted yet due to various technical and commercial obstacles. A positive approach to these obstacles is expected in the near future to replace conventional vehicles with EVs.

• Besides ferrite cores, the research may be extended to a unique core material and design that provides high magnetic field strength and low core losses to allow users to charge freely regardless of the misalignment issue within permissible limits.
• During the optimization process to avoid the copper losses, the current ratings can be kept at possible low values.
• The challenge for future EVs would be the long mileage. The long mileage by an EV mainly requires a high-energy density battery that could be charged within a few minutes and last for several hundred miles. Consideration of the use of graphene material for batteries and super-capacitors may enhance the mileage issue. Then a single charging of EV may provide longer mileage.

11. Conclusion

This paper has provided a brief review and comparison of the different EV charging methods and their deployment. The equivalent circuit analysis and characteristics of the ICPT system were presented. The progress of the ICPT method for various factors and benefits from them were reviewed. The implementation of ICPT was found to be contingent upon the leakage flux compensation topology, charging distance and proper alignment. A trade-off between distance, charging pad size and efficiency is necessary for EV charging application. Advanced flux leakage compensating topologies SPS and PPS topologies offer efficient power transfer over large air gaps and better misalignment toleration as compared to basic conventional topologies. Power levels 1 and 2 are designed for slow and moderate charging at home and public parking, respectively, however, power level 3 provides off board quick charging. Rectangular and DDQ coils offer good coupling and high misalignment consideration. Design criteria is utmost to develop the overall ICPT system for low to high power level. To cope with the dynamic behavior of ICPT system many controllers have been developed to maintain input and output parameters. Future recommendations supporting the implementation of this technology are included.

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