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A Review of an Inductive Power Transfer System for EV Battery Charger

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Abstract

The whole world is looking forward this year to reducing fuel consumption and creating a cleaner environment for future generations. The development of electric vehicles over the years has proved to be the best solution, despite the challenges they face to reduce their performance. This paper discusses the solution of these challenges, which is how to provide a convenient and less complicated way of charging the battery. It is well known that the plug-in charging is not useful due to the lack of protection and complexity, while the Contactless Power Transfer strategy (CPT) has gained a lot of attention because it provides the energy transfer wirelessly. The inductive power transfer (IPT) can be classified as a part of contactless power transfer. This paper focuses on reviewing how the IPT charging system (parts) works and addresses the many problems that this technology faces in order to design a better system that can achieve a convenient and fast charging.

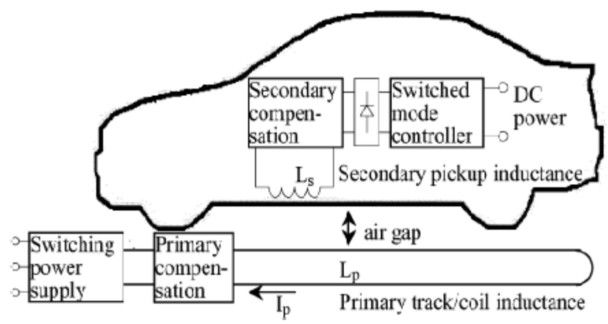
Keywords: Inductive power transfer, Electric vehicle applications, Battery charging.

1. Introduction

In recent years, the world has been convinced that the electric vehicle is the one of best solutions to overcome concerns about the environment, which cover health effects of burning fossil fuel, greenhouse gas emissions, wasting fuel use of oil and so on. However, the drawbacks of EV are not satisfactory to researchers and this forced them to focus on the development of its performance while minimizing its limitations. One of the limits faced by electric vehicles is to provide comfortable and fast charging batteries. Many researchers use the principle of inductive power transfer (IPT) strategy to charge electric cars wirelessly.

The IPT system has been proposed for more than two decades, in order to transfer power from primary (source) to moveable secondary part (load) [1][2]. The theory of inductive power transfer wirelessly is based on the laws of Ampere and Faraday. In relation to that, this strategy depends on the magnetic coupling between two windings. One of the windings is installed in the charging terminal (track coil), while the other is embedded in the vehicle (pick up coil) [3]. Placing the power source or charging station underneath the park is considered the most important to integrate convenient charging in the parking site [4]. It is well known that, the secondary part (on-board) is within the vehicle, and it is important to design the on-board as small as it is possible in order to minimize the space usage of the vehicle. There are many other factors should be taken into account such as fast charging, safety, long cycle life, low maintenance and cost [5].

Figure 1: Typical inductive power transfer system



2. The Performance of IPT System

The primary configuration of an IPT system is shown in Figure 1, which consists of three parts: power source, converter and Track. The supply is used to produce a constant AC current IP, which passes through the track. The converter is used to ensure maximum transmission power. Controller also is needed in the primary side to protect the functions during abnormal situations [6]. The secondary part is mutually coupled with the track, which induces a voltage in pickup coil, based on Ampere's and Faraday's law of *Voc=jwMIP*, and the short circuit current *Isc=MIP/Ls*. In order to regulate the power transfer from the secondary coil to the battery, there is a need to use switched mode controller (rectifier) to obtain regulated DC power [7].

However, the maximum power which can be drawn from the pickup without any compensation only equals to *VocIoc/2*. In order to enhance the power transmission capability, the pickup is compensated with capacitors. The tuned quality factor of the compensation circuit can be defined as the ratio between the real and reactive power [8-9].

3. Optimization on IPT System

In order to design inductive coupler ferrite pot cores, two fundamental structures had been examined (E-core square shaped and planed core round shaped) [10]. The evaluation was based on a conducted performance comparison and the results adopted the plan-core round-shape, which seemed more effective in terms of the capacity and coupling coefficient [11].

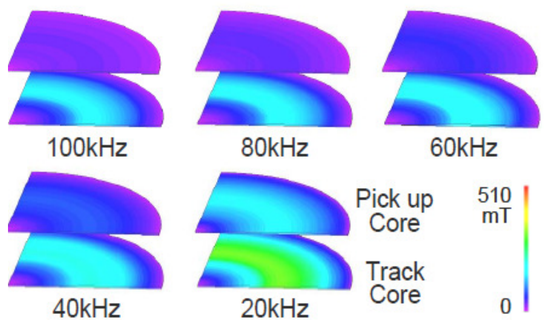
S.H. Lee and R.D. Lorenz [12] designed a coupler that operated at 300mm using ferrous coils. Another 335mm clearance, which was made using copper tubing, is also outlined in [13]. The losses of these prototypes would be very high, because there is no ferromagnetic material to guide the field.

The relationship between the core size and the flux destiny transferred to the secondary had been studied based on the concept of fundamental flux path height in [14]. The core with weight 7kg and 420 mm diameter had the overall efficiency around 85% [3]. Another system with 600mm diameter that achieved an efficiency of 92% was mentioned in [15]. As mentioned previously, the round core would generate a vertical field, so that when the secondary core was positioned and aligned, power transfer would be possible. Because of the nature of the field, the round core did not require either large tolerance to misalignment, or large vertical separations. However, in order to create good coupling coefficients, the diameter needed to be increased with an increase in the air gap [16-17].

The relationship between the drive frequency and flux destiny was also studied. Over a 100 to 10 KHZ range was analyzed, as shown in Fig 2. We were able to confirm that there was no magnetic saturation (510 mT) in the indicated frequency range. A recent study [10] covered the dependency of iron losses, as described by the maximum secondary core flux destiny (Bm), which was calculated by using the equation below, where V2 defines secondary voltage terminal; f= frequency; N=number of secondary coils, and A=cross-section area.

Figure 2: The flux destiny distribution

$$V_2 = 4.44 f\, B_m A$$

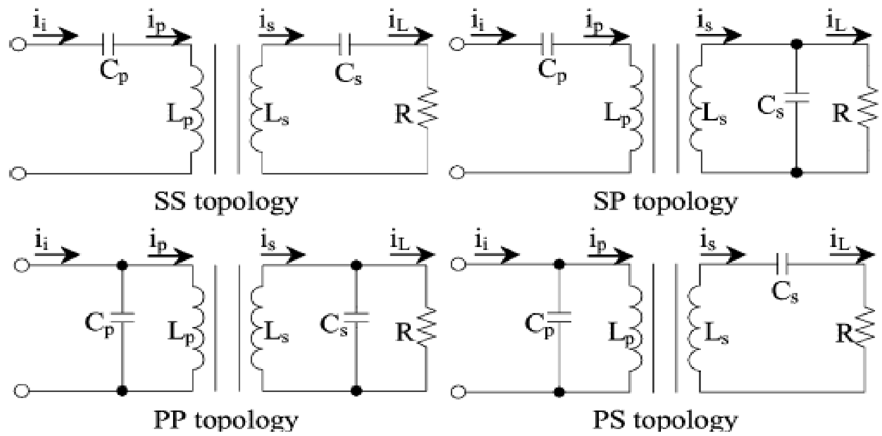


According to the analysis of the maximum flux destiny in the core, the inner diameter of the core was varied, under the constant output in [10]. It was confirmed that there was no magnetic saturation if the radius was 150 mm or less. On the other hand, the study showed copper and iron losses while the inner diameter was allowed to vary. This case proved that the increase in the inner diameter provided constant iron losses besides increasing the copper losses. This was due to the magnetism in the core being constant due a constant secondary voltage. The increase of copper losses led to an increase in current, which caused a reduction in the inductance as the inner diameter increased. Kobayashi [10] obtained a similar result, and pointed out that any decline in efficiency can be minimized by making a hole in the size of the core and making the centre of the core hollow, thus it can achieve a reduction in weight. In addition, there was an analysis of the maximum flux destiny in the core while the thickness was varied. It was confirmed that there was a small change in losses if the secondary core thickness was cut by half while holding the primary core thickness constant, which achieved a good reduction in weight.

4. Compensation Topologies

The main idea of capacitive compensation at both sides (primary and secondary), is reducing the value of reactive power that is drawn from the supply, in order to increase the capacity and efficiency of the system to transfer energy. This section reviews the most common compensation topologies which had been confirmed by previous studies [18-20]. Figure 3 shows the four basic topologies: SS, SP, PS and PP. The first latter of each type describes the compensation that is used at the primary side, (S stands for the series and P stands for parallel). The second latter represents the secondary compensation.

Figure 3: The structures of basic compensation topologies



The reflected impedance between the pickup and the track coil can be calculated by dividing the reflected voltage by track current. Meanwhile, the total impedance logically can be calculated by combining the both side's networks, as it depends on the used composition topology. The advantages between types of compensation should be taken into considerations, such as the reflected impedance at series secondary compensation which is equal to zero, as it would be negative for parallel compensation but would be more capacitive. For primary side compensation, the parallel type is preferred in order to produce a large primary current. Meanwhile, the series compensation is required in case of reducing the primary's voltage for long track. A comparison of the various characteristics of the compensated air core transformer is tabulated in Table 1.

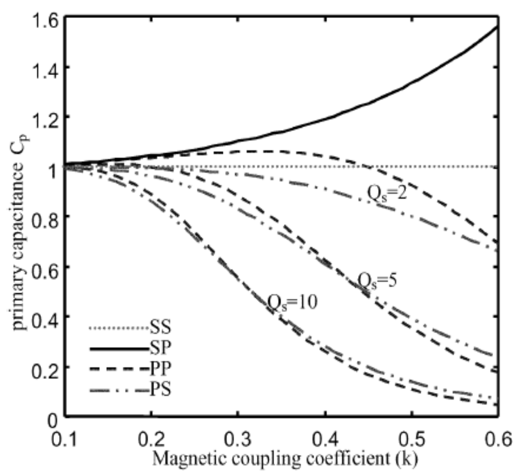
Table 1: Comparison of the characteristics of the various compensation topologies

Characteristic of the topology	SS Topology	SP Topology	PS Topology	PP Topology
Dependence of the primary compensation capacitance on load	None	None	Dependent	Dependent
Circuit equivalent impedance at resonance	Minimum	Minimum	Maximum	Maximum
Type of AC source to be applied to transfer maximum power	Voltage source	Voltage source	Voltage source at high voltage/ Current Source	Voltage source at high voltage/ Current Source
Power transferred at constant source voltage (SS, SP)/ current (PS,PP)	Lower	Higher	Lower	Higher
Peak efficiency	Higher	Lower	Higher	Lower
Tolerance of power factor to variable frequency	Tolerance of power factor to variable frequency	Tolerance of power factor to variable frequency	Tolerance of power factor to variable frequency	Tolerance of power factor to variable frequency

With the aim to decrease the VA rating, the primary compensation was used to ensure the power transfer at unity power factor, which made the primary compensation, depending on the self-inductance of the primary winding. In this situation, the calculation of the capacitive value at the primary could be done by using the equality of the imaginary part of the impedance to zero.

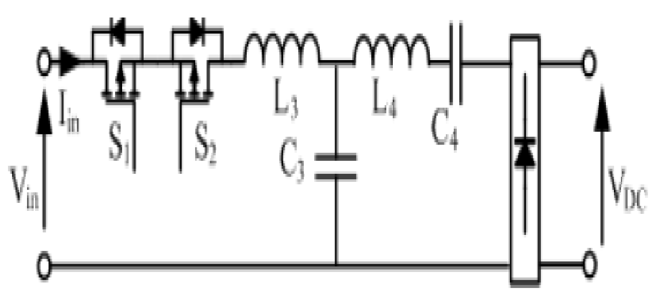
The selection of the needed compensation topology in both sides depended on the type of application that should be used [21-22], whereas, the secondary part the series compensation would be preferable in case of electrically-driven power supply applications, because it can provide a voltage source. Parallel compensation is recommended in battery charger application cases, because parallel compensation in the secondary side provides a current source which is stable for battery charger. The advantages between the types should be taken into considerations, such as the reflected impedance at series secondary compensation, which is equal to zero, while it is a negative but more capacitive for parallel compensation. For primary side compensation, the parallel type is preferred in order to produce a large primary current. Meanwhile, the series compensation is required in case of reducing the primary' voltage for long track.

Figure 4: The coupling effects and secondary quality factor.



In order to make the right choices of determining which topology can achieve the best capability in transferring the power, [18] investigated the relation between the secondary quality factor and the coupling. As a result, the SP topology needed much better coupling with such a large primary capacitance, but for PP topology, there was a need for a little increase in the primary capacitance with small secondary quality factor. The PS topology is shown in Figure 4. The changes became quite large with good coupling and large secondary quality factor, in order to satisfy the demand of increasing the capability of IPT system. Several studies were carried out for the development of the magnetic coupling. The results proved that the coefficient of coupling between 0.3- 0.6 are normally achievable for single pickup [23-25], while for multi pick up, the coupling coefficient is normally less than 0.1 per pickup[8-26].

Figure 5: The structures of the single LCL network



Chang-Ya Huang [3] designed a multi-path pick up controller as shown in Fig 5, which was able to control the mutual inductance between the cores. This topology achieved efficiency of 96% at 2 KW output, and provided above 90% for all power ranges. In addition, it worked by controlling the number of active LCL networks based on the induced voltage in the secondary, and then the power could be regulated between the coils, as shown in the following equation.

5. Control Consideration

Previous studies have shown that the relationship between the frequency and the transferred power is linear during the operating period. It indeed makes sense to use the frequency, in order to control achieving maximum power capability. The main task of the primary and power supply is to control the frequency and the primary current to produce the best possible transfer of power capability. The variable frequency and the fixed frequency strategies are the most widely used in the primary side.

Fixed frequency controller: This strategy will cause a phase shift in the impedance, and then the source should produce higher VA o transfer the same power, in case of the phase shift is significant.

Variable-frequency controller: This controller normally works at zero phase angle (ZPA) which will cause a shift in the operator frequency, which is a reason for losses in the transmitted power and instability in the control and frequency [21-25-26].

Besides shifting the frequency, the pickup will not be suitable in many applications, because there are pickups that will not be able to receive the necessary power. As an alternative solution, a switched mode controller in the pickup side is usually used to regulate and control the transferred power flow [8-9-26].

Direct and Indirect controllers: In order to keep the primary current constant, a feedback loop had been designed to control the current directly. This is the simplest method that can be done in a direct manner, but cannot always be considered the most appropriate option. Other than that, when we need to achieve many objectives and tasks at the same time, the indirect control could be more useful and efficient. As mentioned earlier, keeping the primary current constant was the main task of the controller. There are another tasks needed to be taken under consideration, such as achieving soft switching and the harmonics components contained in current waveforms. Based on the ZVS conditions, the magnitude and frequency of the primary current were constant at high quality. The ZVS was within an acceptable range for the IPT. This method also offered high efficiency and low switching stress. In general, the indirect ZCS control can achieve a very good performance [8, 9].

Jr-Uei William Hsu [27] proposed a control method in an IPT system, which is the directional tuning control algorithm (DTC). This method was considered as an alternative to PI controller to complete the tracking. DTC algorithm uses the results of the past and present control to hold the right decision for the following plan to regulate the output power. In [28] the decision was to have microcontrollers in sides. Using a processor in the pickup will increase the ability of controlling the charging current and parameters measurement, which are needed for safe and fast charging. The advantages of using the microcontroller is that, this strategy gives the opportunity to observe the system through a PC, and it can decide the needed power value in order to save energy. This strategy also works with any type of batteries.

6. Power Electronic Considerations

As we have noted previously, it is necessary to provide DC power to the output in charging batteries applications. We also pointed that using a switched mood controller is suitable to regulate the output power feeding a battery. In this study, an inverter was used in the primary side to control the primary current, and the power could be changed to DC from AC using a rectifier in the secondary side. Achieving DC from AC would be too easy if using diode rectifier. The previous studies mentioned that it is not good option, because the majority will be ignoring the diode losses, even although it is significant and will cause large losses in the system efficiency [29-34]. For this reason, an additional DC-DC converter was recommended to control the charging current.

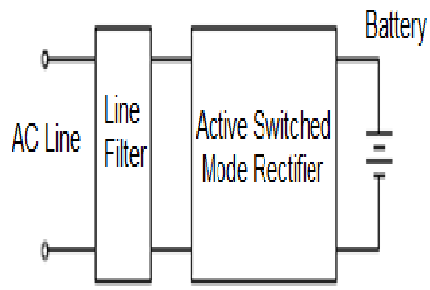
According to the high power battery chargers applications, the power electronic systems can be classified into two types: double stage type and single stage type [21] [32]. In the single stage type, the power factor correction is combined with the DC-DC conversion stage into one. Since it shares the controller and the semiconductor switch, the single type has more advantages than the double stage.

whereas, it is more efficient and has low frequency ripple which is two times the utility frequency, and the components such as transformer and the switches become larger due to single stage [35]. Meanwhile, the double stage type consists of two separate parts: the boost converter for the purpose of improving the power factor, which is at the front-end; and the DC-DC converter which regulates and controls the current and the voltage respectively at the rear-end.

6.1 Single Stage Type

The conceptual structure of the single-stage on board charger is shown in Figure 6. Compared to the two-stage approach, the single-stage approach uses only one controller to shape the input current and to regulate the output voltage.

Figure 6: Block diagram of single stage charger.

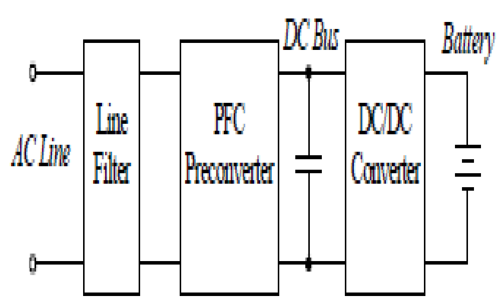


Generally, for any PFC converter, the instantaneous input power during a line cycle is pulsating, while the output power is constant. Therefore, in any PFC circuit, there must be an energy-storage capacitor to store the unbalanced energy. However, in a single-stage PFC converter, unlike in a two-stage PFC converter, energy-storage-capacitor voltage will no longer be loosely regulated at a constant value because the controller is used to regulate the output voltage. To reduce the component count and cost, a number of active single-stage techniques have been introduced lately [36]. Generally, in a single-stage approach, PFC, isolation, and high-bandwidth control are performed in one step.

6.2 Two-Stage Type

The most commonly used active approach which meets high power-quality requirement is the two-stage approach [37]. In this approach, a non-isolated boost converter, which is controlled in such a manner that the rectified line current follows the rectified line voltage, is used as the input stage which creates an intermediate DC bus with a relatively large second-harmonic ripple. This front-end PFC stage is then followed by a DC-DC converter, which provides isolation and high-bandwidth output-voltage regulation, as shown in Figure 7. For higher power levels, the front-end boost PFC stage is operated in the continuous-conduction mode (CCM), whereas the discontinuous- conduction mode (DCM) operation is commonly used at lower power levels due to a simpler control.

Figure 7: Block diagram of two-stage charger



The double stage power converters have the possibility of making the input current in the phase with the input voltage, which is in form of high quality sinusoid. Also, they can control the input current and output voltage at the same time by using different controllers. The advantages of double stage type are it has lower harmonic distortion and higher power factor. There is almost no low frequency ripple in the output in this type of converter. Moreover, it needs more semiconductor switches than the single type does. Since it has additional controller for power factor correction, the double stage type is more suitable for high capacity system [37-39]. Table 2 summarizes the difference between the single and two stage on-board chargers.

Table 2: Relative Comparisons of the Single and Two stages chargers

	Two-stage	**Single stage**
Power Factor	High	Medium
Efficiency	Medium	Low
Size (Volume)	Large	Small
Weight	Low	Low
Bulk Cap Voltage	Constant	Varies
Control	Complex	Simple
Component Count	High	Medium
Power Range	Any	≤ 200-300W
Design Difficulty	Medium	High

There are many switching topologies that can achieve higher power flow. These topologies can provide high efficiency by minimizing the switching losses and the overall size of the converter. The zero voltage switching (ZVS) and zero current switching (ZCS) are able to limit the switching losses during ON and OFF switching. Besides that, both can work at high switching frequency, compared with PWM hard switching converter.

6.3. Choosing the Switching Device

Making the right choice of the device is an important issue in order to minimize the losses and to guarantee the system working. The BJT is not popular in the power electronic, and is more preferred in the current amplifiers, and the difficult decision is to select between MOSFET and IGBT. The choice depends on the switching frequency and voltage.

Table 3: Comparison of switching devices

Device type	**Max freq**	**Max V/A rating**	**Von/Ron**
Diode	Slow- fast	High 7KV/5KA	0.3-1V
Thyristor	Slow- 1KHZ	High 3-7KV/5KA	Low 1-3V
MOSFET	Fast- 1MHZ	Low 0.2-1KV/1KA	1mΩ-4Ω
BJT	Med- 10KHZ	Low 1.5KV/1KA	Low 1V
IGBT	Med- 80KHZ	Med 1.7-6.5KV/2.4KA	Med 1-4V

Table 3 describes the specification of the most common switches. It can be noticed that the largest power capability is in the diode and thyristor. Meanwhile, when it comes to speed, the MOSFET is the fastest switching frequency. At switching frequency of 20 KHZ, the IGBT can be seen as a good device but the MOSFET can work at this frequency as well. The IGBT has low conduction losses, but the switching of time is high, compared to the MOSFET. The MOSFET has replaced others in many applications when the high switching frequency is needed. However, at voltage (>600-1000V) the IGBT is still preferred, but when it comes to high frequency (>20-100KHZ) the MOSFET is the only device that can be used.

7. DC-DC Converter

DC-DC converter is important to control the DC power to charge the battery. The DC-DC converter is important to finish the charging circuit. In designing the DC-DC converter, there are many points that must be taken into account, such as the size (lightweight), efficiency, simplicity and so on. This section reviews some of DC-DC converters that had been developed based on the aim of the battery charging. Most previous studies have shown that the use of insulation protects the DC-DC converter from external factors, but it increases the weight and cost. Since the converter will be placed in the on-board which is in a protected area, the use of insulation will be unnecessary. A resonant power converter contains resonant circuits, whose voltage and current waveforms vary according to sinusoidal during one or more subintervals of switching periods. For the IPT application, the converters have low harmonic distortion because the switching takes place at resonant frequency. Utilization of electrical resonant is the most common way of satisfying soft switching conditions. However, compared to traditional PWM converters, this has obvious disadvantages. These disadvantages include additional reactive components, higher peak current or voltage ratings, operating frequency uncertainties, and difficulties in controller design. In spite of all these drawbacks, resonant converters are becoming very popular because of their significant contribution to switching loss reduction and better waveform generation.

7.1. Conventional DC-DC Converters

The DC-DC converter topologies can be divided in two major parts: non-isolated and insolated converter, as tabulated in [40], depending on whether or not they have galvanic isolation between the input supply and the output circuitry. It is well known that the DC-DC converter can be either uni or bi-directional. The bidirectional one is always preferred, because it is able to transfer or convert the power in both directions. In battery charging applications, it can be used in charging and discharging modes. There are many types of conventional DC-DC converters, which can be seen in various industrial applications. However, some topologies are not suitable for the OBC due to the wide-range input condition. While a battery is charged, the output voltage also varies. Moreover, the input of the OBC is supplied from a residential line, so the unity power factor regulations have to be satisfied [41]-[42]. Based on these requirements, a comparison of the conventional isolation and non-isolation topologies had been done for the application to the OBC with the specifications, as shown in Table 4.

Table 5: Summarized characteristics of Conventional Topologies

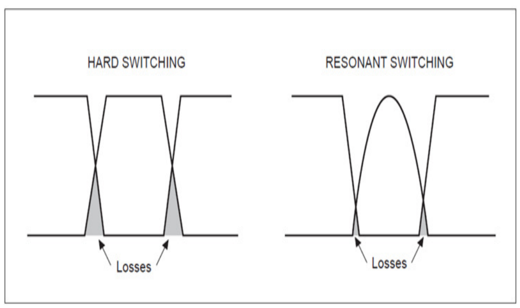
Topology	Galvanic Isolation	Number of Elements	Feature	PF	Total Stages
Boost PFC + SRC	Isolated	S : 5 / D : 5 C : 3 / L : 2 T : 1	• Low ripple of the output • Switching frequency of wide-ranging variation • Susceptive to the variation of output impedance	High	2
Boost PFC + LLC	Isolated	S : 5 / D : 5 C : 3 / L : 2 T : 1	• Low ripple of the output • Narrow variation of switching frequency • Advanced characteristic of output regulation • Complicated design and control	High	2
Boost PFC + PSFB	Isolated	S : 5 / D : 5 C : 2 / L : 3 T : 1	• Low ripple of the output • Low efficiency under light-load condition	High	2
Conventional Buck-Boost (with PFC)	Non-Isolated	S : 1 / D : 1 C : 1 / L : 1 T : 0	• High voltage stress (Vin + Vout) on switching devices • Reversed ground polarity between the input and the output • Line frequency ripple on the output	Low	1
Sepic (with PFC)	Non-Isolated	S : 1 / D : 1 C : 2 / L : 2 T : 0	• High performance of PF • High voltage stress (Vin + Vout) on switching devices • Susceptive to parameters and thermal condition • Line frequency ripple on the output	High	1
Cuk	Non-	S : 1 / D : 1	• Small size of input and output filter	High	1

Topology	Galvanic Isolation	Number of Elements	Feature	PF	Total Stages
(with PFC)	Isolated	C : 2 / L : 2 T : 0	• High voltage stress (Vin + Vout) and high current stress (IL1+IL2) on switching devices • Line frequency ripple on the output		

7.2. Basic Resonant Converters

The resonant converter was investigated intensively in the 80's [43]-[44]. It has the possibility to achieve low switching losses, thus will enable the resonant the switches to work at high switching frequency. However, increasing the frequency of operation also will increase the switching losses and hence reduce system efficiency. One solution to this problem is to replace the "chopper" switch of a standard topology with a "resonant" switch, which uses the resonances of circuit capacitances and inductances to shape the waveform of either the current or the voltage across the switching element. Thus, when switching takes place, there is no current through or voltage across it, and hence very minimum power dissipation will occur, as shown in Figure 8. A circuit configured with this technique is known as a resonant converter. A Zero Current Switching (ZCS) circuit shapes the current waveform, while a Zero Voltage Switching (ZVS) circuit shapes the voltage waveform. Resonant converter not only achieves zero voltage of switching turn on-off switches but usually has smaller turn off switching losses than the PWM hard switching converters.

Figure 8: Current and voltage waveforms of hard and resonant switching systems



In resonant topologies, the three most popular topologies are: series resonant converter (SRC), parallel resonant converter (PRC) and series parallel resonant converter (SPRC, also called LCC resonant converter).

7.2.1 Series Resonant Converter (SRC)

The Series Resonant Converter (SRC) forms a series resonant tank. The tank is connected in series with the rectifier-load network. In this configuration, the load and the resonant tank work as a voltage divider. The impedance of resonant tank will change by changing the frequency of driving voltage to the resonant network. The input voltage is split between this impedance and the reflected load [45]-[46]. The DC gain of SRC is always lower than the unity, because it acts as a voltage divider. At light-load condition, the load impedance is very large compared to the impedance of the resonant network; where all the input voltages are imposed on the load. This makes it difficult to regulate the output at light load. Theoretically, the frequency should be infinite to regulate the output at zero loads. When the resonant frequency is higher than the switching frequency, the performance of the converter will be under zero current switching (ZCS) condition. Meanwhile, when the resonant frequency is lower than the switching frequency, the performance of the converter will be under zero voltage switching (ZVS) condition. For the operating region of the series resonant converter at light load, the switching frequency should be highly increased to keep the output voltage regulated, which is considered as a disadvantage for the SRC. In this case, some other control methods need to be added to regulate the output voltage at light load.

7.2.2 Parallel Resonant Converter (PRC)

The resonant tank is connected in series, and the load is connected in parallel with the resonant capacitor, called as Parallel Resonant Converter. This converter can also be called as series resonant converter with parallel load. Since the transformer in the primary side is a capacitor, the impedance in the secondary side should be matched by adding an inductor on the secondary side [47]. At no load condition (the load is zero), the input is still seen as a small impedance of the series resonant tank. This will induce very high circulating energy because the load is parallel with the resonant capacitor.

7.2.3 Series Parallel Resonant Converter (SPRC)

The resonant tank of SPRC can be defined as the combination of PRC and SRC. Similar to PRC, the impedance is matched by adding the output filter inductor in the secondary side. For SPRC, it combines the good characteristic of PRC and SRC. The load is in series with series tank Lr and Csr, with the parallel capacitor Cpr. In SPRC, the output voltage can be regulated at no load condition [48].

At high input voltage, these converters are hard to be optimized. High switching loss conduction loss and conduction loss will occur from wide input range. As the frequency increases, the impedance of the resonant tank is increased. This means more energy will be circulated in the resonant tank instead of being transferred to the output. Table 4 below describes the difference between these three types of resonant converters. Besides that, in order to achieve the zero voltage switching technique, the operation frequency should be higher than the resonant frequency.

Table 5: The advantages and disadvantages of the resonant Topologies

Comparative points	Series Resonant Converter(SRC)	Parallel Resonant Converter(PRC)	Series Parallel Resonant Converter (SPRC)
Resonant components	Inductive Lr and capacitor Cr in series	Inductive Lr and capacitor Cr is in series with the inductive and parallel with the load	Inductive Lr series with capacitor Cr and parallel with capacitor Cpr
Operation region	Large	Small	Much smaller
The condition of achieving ZVS	fsw >fr	fsw>fr	fsw>fr
Sensitivity of Light load s	Other control methods need to be added to regulate the output.	The parallel capacitor regulates the voltage so the problem will not exist	Not sensitive to the load changes
Circulating energy	Large	Much larger	Small
The turn off current at high voltage condition	Increased	Decreased	Increased
The major problems	• Light load regulation • turn off current • High circulating energy	• High circulating energy • High turn off current	• Increasing the conduction losses at high input voltage • Switching losses is closer to PWM converter

8. An Overview of Previous Studies

Rajapandian Ayyanar [49] proposed a new soft switching for full-bridge converter using the secondary side as a tapped transformer. The switching was at 100KHZ for DC-DC converter with 500W prototype. The result of the experiential confirmed that the conduction losses were much lower compared to the conventional converters. Meanwhile, in [45][50-52] some of non-insolated bidirectional DC-DC converters were reported. The most widely used converter is the half-bridge topology which works in boost or in buck mode. The performance of interleaved and cascaded can be represented on basis of performance of half-bridge, for these converters when the ratio of the output and the input is less than 1, which means the converter works in charging mode. The three-level DC-DC converters had been proposed by X. Ruan in [53], where for this prototype, 600V IGBT was used instead of 1200V IGBT in order to reduce the switching voltage stress. The experiment result of the three level converter showed that the efficiency of charging mode was 98% with 10KW power rating and discharging mode was almost 96%. Lin Wenli [54] designed a converter with switching 20KHZ, 8KW using ZVS at full-bridge. The control was managed using a digital control system. As a result of this work, the switching losses were reduced.

Among the various ZVS PWM DC-DC converters, the ZVS HB LLC resonant converter has been used for reducing the current and voltage stress and switching losses of the components in [55]. Therefore, the HB dc-dc converter for charging the battery system needs to operate in the wide range voltage which is more than the conventional converters. Meanwhile, the 3 kW with two stage charger type using a phase shift full bridge converter with current doubler has been designed recently by Tae-Hoon in [56]. In this topology, the phase shift was able to achieve soft switching by phase shifting between lagging-leg and leading-leg switches without the need to any additional circuits (auxiliary components), owing to the fact that the switches of the leading leg used the energy stored in the output filter inductor to achieve ZVS, between the switches of the lagging leg achieved by ZVS by using the energy stored in the leakage inductor. The current doubler was adopted at the secondary side of the converter to reduce the current rating of the transformer and current ripple. As result, the charger converter efficiency was 93.12 % at the rated load and84.58 % at the light load.

Jong-Soo Kim designed a 3.3 kW two stage type on board battery charger series loaded resonant DC-DC converter with full bridge type [57]. The resonant was used to increase the switching frequency to reduce the additional switching losses. The PFC was designed with CCM which allowed a smaller design and size by reducing the input filter. The frequency control was used in this topology. A controller was designed to perform an optimal switching frequency in the range of 80-130 kHz to ensure that the converter worked under ZVS region and to provide 250 410 V of the output voltage. As a result, the charger achieved 93 % of efficiency and 0.995 of power factor. Moreover, the half bridge LLC resonant converter has been proposed for the on board battery charger in [58]. This converter is designed to work at resonant converter of SRC to achieve high efficiency. Thus, it was able to operate at lower than the resonant frequency of SRC, which still obtained ZVS because of the characteristic of PRC dominating in that frequency range.

9. Conclusion

There has been a noticeable trend for alternative energies to receive increased attention from the marketing of electric vehicles, which has forced the researchers to find solutions to the many questions that consumers have, plus lack of confidence in the performance and effectiveness of electric vehicles. Regarding these concerns, this paper discusses the possibility of charging car batteries wirelessly. As we have noted, the use of IPT in charging systems is the most recommended.

In this paper, the principle of IPT work is discussed, including explanation on the importance of each part together with the advantages and disadvantages. For example, based on the comparisons of the compensation topologies, we found that the best method used in the battery charger is PP topology. PP topology is produced in the secondary current source, which is the initializer current to charge the battery, as used in the primary side to produce relatively large current. Meanwhile, in the electronic section, the discussion includes switching types and how to choose the right device for switching. The rationales of using the DC-DC converter were also mentioned, and some of the converters in this application were viewed.

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