Research on Contact and Non-Contact Power Transfer Methods Discussed for Transport Applications

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Abstract--- The world of automation has already being into existence for prolong period which results in various researches and industries to develop commercial products. Power is extracted from the source and supplied through cables to various loads for numerous applications. Transfer of Power through a conductor and medium is called contact power transfer (CPT) and transfer of power without a conductor and free space medium is called as non-contact power transfer (N-CPT). In this paper a complete review of power transfer with its evolution to its deployment to new transfer methods in present existence will be discussed. The applications will include battery load vehicles and to supply the direct current (DC) power to the battery load effectively. The paper will also give a contrast and hybridization idea of two or more power transfer possibilities in literature.

Keywords--- Magnetic Resonance Coupling, Separated Coils, Dynamic Charging, Electric Resonance, Quasi Dynamic, Conductive Charging.

I. NOMENCLATURE

ω_0	-	Resonant frequency
AC	-	Alternating current
CLC	-	Capacitor-inductor-capacitor
CPT	-	Contact power transfer
DC	-	Direct current
EMI	-	Electromagnetic interference
HB	-	Half Bridge
HF	-	High frequency
k	-	Coupling co-efficient
KAIST	-	Korea advanced institute of science and technology
kHz	-	Kilohertz
kW	-	Kilowatt
LCC	-	Inductance capacitance compensation
LCC	-	Inductor-capacitor-capacitor
LCL	-	Inductor-capacitor-inductor
N-CPT	-	Non-contact power transfer
OLEV	-	Online Electric vehicle
PEI	-	Power electronics interface
PEV	-	Plug-in Electric vehicle
PFC	-	Power factor correction
PP	-	Parallel-Parallel
PPFC	-	Passive power factor correction
PS	-	Parallel-Series
PV	-	Photovoltaics cells
Q	-	Quality factor
RF	-	Radio Frequency
R_x	-	Receiving coil
SP	-	Series-Parallel
SS	-	Series-Series
T_x	-	Transmission coil
UAV	-	Unmanned aerial vehicle
VA	-	Volt-ampere rating
VSC	-	Voltage source converter
WPT	-	Wireless power transfer
ZCS	-	Zero current switching
ZVS	-	Zero voltage switching

II. INTRODUCTION

As the electric power and transportation industries are causesfor the emissions of million metric tons of carbon dioxide (CO_2) in U.S. around the year 2011, since then internal combustion engines which is the reason for emissions resulted indeployment to lead to the battery operated vehicles which is being developed into the state of commercialization in the developed countries. [4].

The automotive industry stepped forward in introducing a technology of conductive charging which is a type of CPT and used in electrical vehicles (EV) termed as plug-in electric vehicles (PEV). Conductive method supply power through cables/conductors and have direct contact between the power supply and the Power Electronics Interface (PEI) [1].The PEI will be explained in proceedings of the paper with circuit diagrams and block diagram.

A contact power transfer method has been a solution to the fuel economy crisis and demand but suffers from various problems in hard wired connection with the applications as in considering there are levels of charging in a PEV which has a rating of kW power levels. The evolution of non-contact power transfer technology is not a new invention; the history of Testla coils is well known which began in the 80's with his experiment in controlling the power in the resonant circuit over an air gap.

Later in 1894 Hustin and Leblanc [7] powered the street cars over a free space i.e. without a medium or a contact with coils frequency in range of 2 kHz.The transportation in Korea and many other developed countries have increased and the non-contact power transfer methods were developed in the year 2008.

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Korea Advanced Institute of Science and Technology(KAIST) introduced the first electric bus; online electric vehicle (OLEV). OLEV powered to the battery in the range of 20 kW with transfer efficiency around 83% [3].

The paper flow will be divided into two main sections contact power transfer method and non-contact power transfer methods. In the first section conductive charging method will be discussed for EV. In the second section it is categorized further into transfer of power in free space through waves/beams, transfer of power in free space through resonance/coupling. Each power transfer method will be discussed with block diagrams and each blocks explained in detail.The review will be based on transportation applications especially electric vehicles with design considerations and parameters consideration like power transfer efficiency, distance etc., will also be elaborated.

III. Contact Power Transfer Method

Conductive power transfer

This type of power transfer includes charging station for Plug-in electric vehiclesinclude utility source, PEI, battery load and plug-in cables and wires with the socket as shown in Fig.1. Block diagram of conductive charging station [4], [5].The battery load in Plug-in vehicles are usually placed in packs i.e. batteries connected in series/parallel together like Photovoltaics cells (PV) combination. Battery operated vehicles suffer from issues mainly from its low life capacity, many battery technologies are emerging into the art of development and most of the companies and industries manufacture lithium ion (Li-ion) battery with low cost. Li-ion batteries are the recent batteries that are used in PEV's [5].

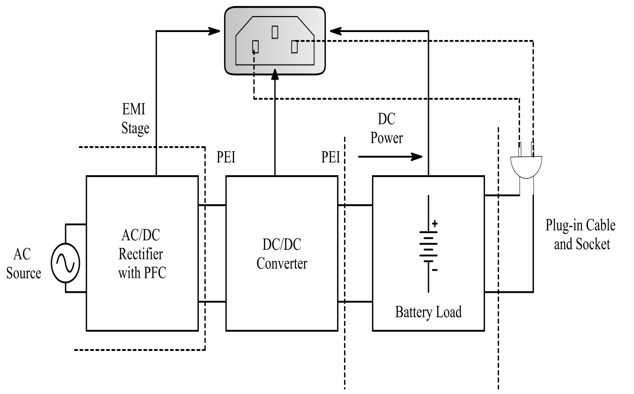

Fig.1: Block diagram of conductive charging station

Contact power transfer has a direct contact between the power supply and the load through a Power electronics interface, as seen in Fig.1. Plug-in and Socket connected to the battery the cables have direct contact with the charger. Conductive charging of EV is classified into two main categories AC charger and DC charger based on their power levels which is listed in Table.1. Level 1 charging is available only for household PEV, where the cables have to be connected for a long time to cover even for short distances. The cables have to be plugged overnight as it takes long charging time to power the battery [8].

The power electronics applications play a major and vital role in the charging and power transfer to the battery. The utility may be either AC or DC source but the rear end of the system has to be a regulated dc power applied to the battery. PEI is used for rectification and regulating purpose and also applied in the electromagnetic interference (EMI) stage [4].

Two types of converters:(i) AC/DC Rectifiers with Power Factor Correction (PFC) is used for suppressing the harmonics and also unwanted interferences are filtered. (ii) Single stage or two stage DC/DC for regulating and supplying DC power to the battery.Power electronics converters are classified into many topologies based on their switching frequency, switches like diode which is a unidirectional switch those rectifiers are called as uncontrolled rectifiers whereas bidirectional switches like Silicon Controlled Rectifier (SCR), and transistor family switches those rectifiers are called as controlled rectifiers, voltage levels.

Table 1: Conductive charging power levels

Types	Levels of charging	Power, current and voltage ratings	Charging time
Type1 AC	Level 1: Standard household socket.	3kW 13A 120V	8 to 12 hours
	Level 2: Industrial socket with cable control box.	7.4 kW 32 A	4 to 6 hours
Type2 DC	Level 3: Fast charger industrial socket for certain Manufacturers.	100kW 480V	30 minutes

The input supply with alternating non-sinusoidal current generates harmonics in the converters which is needed to be suppressed with the PFC with capacitors and boost converter connected to the AC supply [11]. Multi-level converters are being used for PEV in the recent literature; the aim of this converter application is to reduce the switching stress of the switches as the switching frequency increases [3], [9]. The review of topologies for AC to DC converters will be represented in contrast as shown in Table 2. and Table 3.

Table 2: Single stage AC to DC converters used for PEV batteries

Converters	Frequency	Inferences
Single stage Half Bridge(HB) Converter (Fig .2.)	>50kHz	The converter's number of switches is less and hence the size and weight of the bridge is reduced as shown in and many configurations are also listed as in [10].
Bidirectional HB converter (Fig.3.)	>50kHz	For the power direction of flow in either way bidirectional converters are adopted in charging method for transportation where it is useful during regenerative braking[9],[13]. Medium frequency isolation is provided between the converters connected back to back.

Table 3: Multistage and Multilevel AC to DC converters used for PEV batteries

Converters	Frequency	Inferences
Two stage full bridge converter	<25kHz	It can be used for on-board charging and for high power applications with low frequency operation two- stage HB converters topology is similar to its bidirectional principle but isolation is not required that makes it more advantageous[14],[18].
Three level voltage source converter (VSC).	>25kHz	VSC as shown in Fig.5.is the converters which enables soft switching, simple modulation to provide pulses to the switches [10], [12], [20]. Three level converters have extra clamped diodes and switches due to soft switching as mentioned the number of devices cannot have influence to the topology. Multilevel converters increase the voltage levels thus the harmonics from the input current can be reduced easily [9].

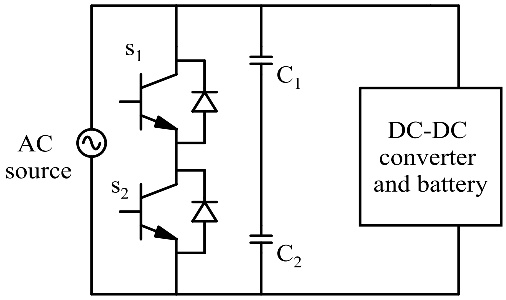

Fig.2: Single stage half bridge converter

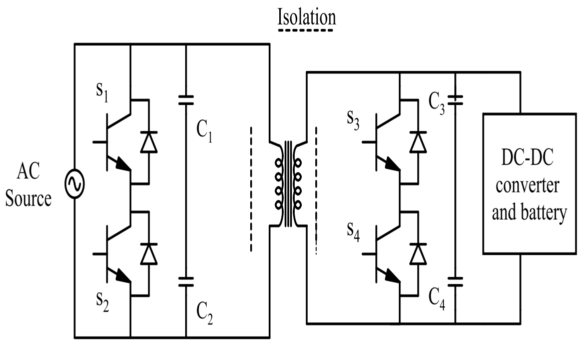

Fig.3: Bidirectional HB converter

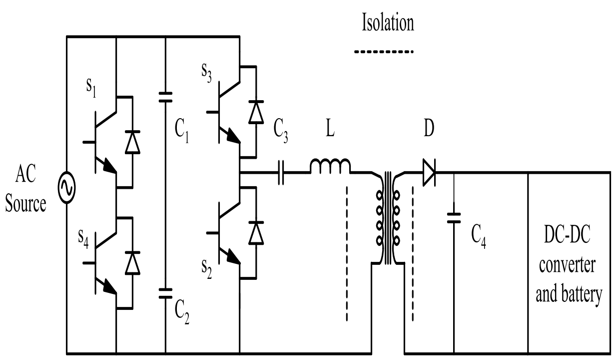

Fig.4: Two stage Full Bridge converter

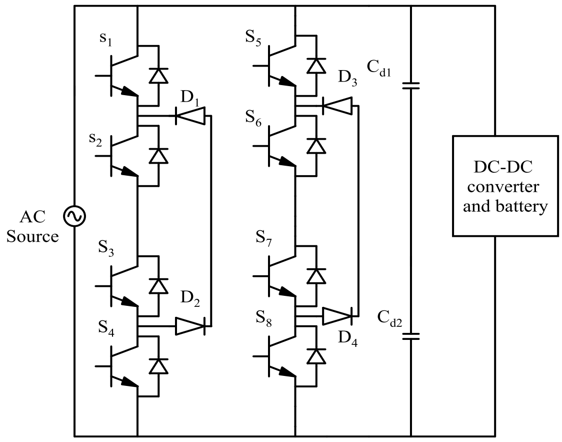

Fig.5: Three level voltage source converter

The rear end converters connected to the battery DC-DC converters that are in development and recent literatures are discussed in Table.4. The popular converters for buck, boost and the combinations of these converters were being studied. VSC converters are used to achieve the Zero Voltage Switching conditions (ZVS) and Current Source inverters for Zero Current Switching (ZCS)for soft switching applications [9].

Table 4: DC-DC converters

DC-DC converters in recent literature	Inferences
Bidirectional cuk converter (Fig.6.)	Bidirectional converters are similar to HB configuration which is connected back to back. The operation of this converter can be realised in all states of the battery for charging and discharging applications. It allows the power to flow in both ways for generating and regenerating modes [15]. Isolation is provided with low frequency transformers and also less number of devices than the other combination of buck and boostcircuits [15], [16].
Integrated boost converter (Fig.7.)	Isolation is provided in this converter with high frequency transformer for protection from the cables as it is directly connected to the battery. For DC-DC converter the step down and step up of the voltage operation in the transformer is similar to the buck and boost converters [19]. Full bridge converters are also employed along with resonant tank for the wired charging it operates at resonant condition and the frequency of the transformer will be high. Two stage converters like AC-DC converters are also the possible configuration with the resonant converter [16],[17],[19].

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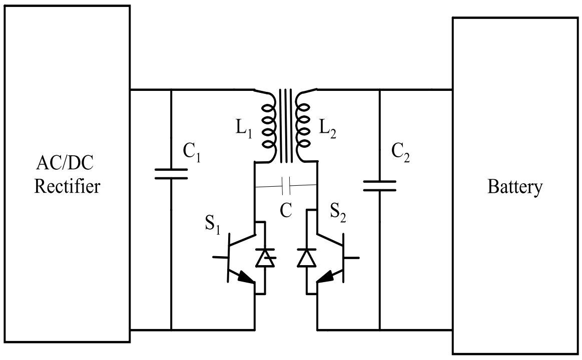

Fig. 6: Bidirectional cuk converter

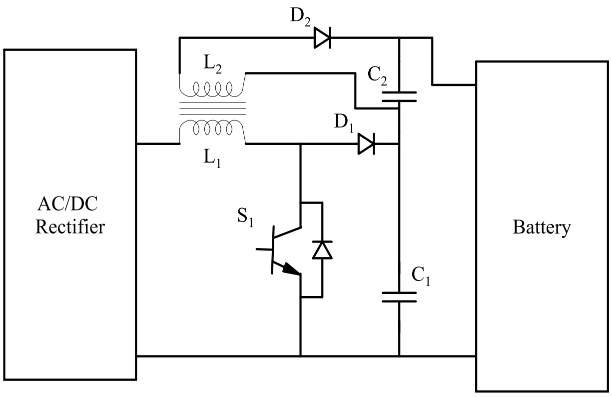

Fig.7: Integrated boost converter

IV. TRANSFER OF POWER IN FREE SPACE THROUGH WAVES/BEAMS

Microwave Power Transfer

The description for the block diagram is shown Fig.8.The advantage of using non-contact power transfer methods is that the socket power levels have to match with the chords of the cables and that would increase the cost. The risk of cables from shocks and wear and tear would damage the vehicle battery as well as the charging stations [26]. Considering the issues with the cables and plugged in charging we go for the power transfer method without a conduct between the transmitting section and receiving section[24].

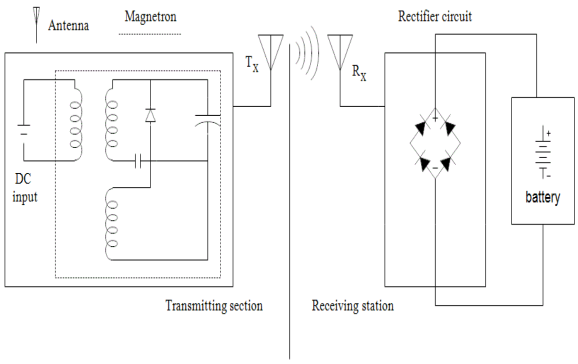

Fig. 8: Block diagram of microwave power transfer

The transmitting section include the transmitting antenna T_X and the source of power for radio frequency (RF) is the magnetrons or the klystrons that produces ultra-frequency source [27],[28] which will be captured in the antenna. The receiving section consists of receiving antenna R_x, the rectifier circuit to supply the DC power to the battery.

The transmitting section is at low cost with the magnetron used in microwave oven can also be used for power source high input DC supply is needed for the magnetron circuit. The converters and rectifiers used can also be with reference to Table.4. Resonant converters are mostly used in the microwave power transfer as the topologies discussed in [27], [28]. In addition to the transmitter and receiving section an impedance matching circuit may be added for tuning the source and impedance mismatch in the circuit.

The feature of this power transfer is that the distance of charging can be done for over several meters and also suitable for the vehicle charging in motion. With one transmitter the power can be directed to multiple receiver sections for which the direction of beam must not face any misalignment and be in uniform [21]-[23]. The beam efficiency determines the power transfer efficiency to the rectifier antenna and to the battery [25].

The drawback of the micro wave is that the frequency band range and also the visibility to the human eye are very less and prone to exposure which is in the range of 5.8 GHz of high density power which lasts for 30 msec for every six minutes that affects the human eye tissues [21]. The safety standards of wave are usually generalized with A B and C zones where the microwave region is below the C region the detection of foreign object detection device is implemented with micro wave power transfer which increases the cost.

Microwave power transfer pave way for airways transport applications apart from electric vehicles and land way applications. Unmanned aerial vehicle (UAV) [26] is powered through this type of transfer method with the transmitting array of very small sizes and rectifier circuit as shown in Fig.8.the whole setup is embedded in the vehicles but with lesser weight arrays we could also call them as light weight vehicles.

Laser Beam Power Transfer

Laser beam power transfer is not suitable for transport application as it is the complex phenomenon which includes the capturing of the monochromatic light in the PV cells. This PV cells emit photons and this can be converted into electrical energy which can used for biomedical implant devices.

As compared to microwave beams these beams and rays are available in the visible spectrum and dose not harm the human eye.

The exposure is minimum and hence it is used for medical applications the PEI cannot be used here high technology of converters are required to transmit power to the PV and extracting them for the load [2],[25],[29].

It is used in biomedical applications with the laser beam as the source at the transmitter and the receiver like a human tissue to be tested. It is widely used in optogenetic applications as they are less result of emissions of exposure they are used for surgeries in human eye. The operating frequency is very high in these applications which are experimented successfully in [37].

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V. TRANSFER OF POWER IN FREE SPACE THROUGH RESONANCE/COUPLING

Inductive Coupled/Resonance Power Transfer

The previous power transfer methods through micro waves and laser beam can be a solution to the conductive charging of electric vehicles. For applying wireless in free space for transport in motion is not possible using waves or beams hence we use the basic principle of electromagnetic theory, transformer and mutual induction lead to the transfer of power through coils that are separated in air gap [39], [47], [49].

Inductive coupling is categorized as magnetic field resonance [2],[6] and the distance of power transfer is only in inches. The motion of vehicles is classified into dynamic and quasi dynamic[30],[34]-[36],[38] where the T_X coils are placed inside the roads and the R_X coils are placed inside the vehicle chassis with PEI connected to the battery[45], [48].

The block diagram of the inductive coupled transfer consists of PEI similar to the conductive charging at both primary and secondary sides.

The difference from the former power transfer is that the transmitting section supplies high frequency AC with the help of power semiconductor technology. The transfer medium waves are replaced by magnetic field (resonance/coupling) through coils separated in air gap [6],[31],[43] as shown in Fig.9.

The secondary side where rectenna is replaced by R_X coils and the rectifier and battery load is similar to the conductive charging.

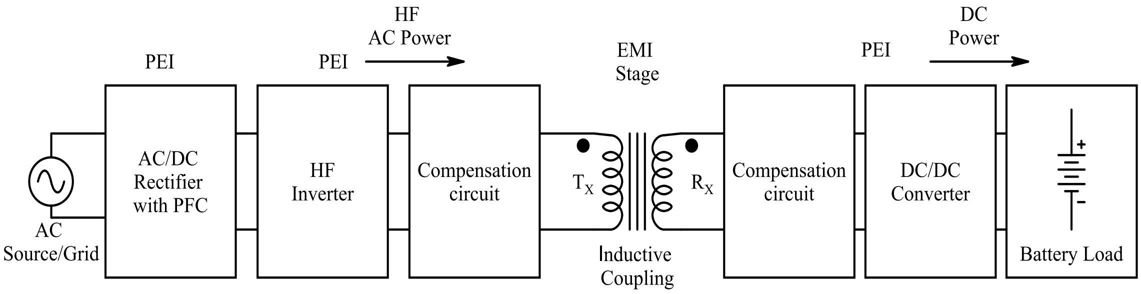

Fig.9: Block diagram of Inductive coupled/resonance power transfer

The AC power from the grid is converted to DC power with rectifier along with PFC circuit as discussed in Table.2 can be used. It is the inductive link we need to provide high frequency source to the inductor coils and a compensation resonant elements similar to RLC resonance circuit the resonance can be achieved hence we call it as a magnetic resonance field type transfer [2], [31],[38].The PEI here has more stages than conductive charging as compared with Fig.1. The high frequency inverter requires a pulse with modulation (PWM) controller to the switches [16],[32],33]. The VSC as discussed in Table.3 can be implemented with increase in the frequency.

The block diagram of inductive coupling shown in Fig.9 consists of $T_X$and R_X coils that are separated in free space with an air gap. In recent research literature and in commercialization the distance in dynamic motion is 5.3m with battery capacity of 20kW by Malaga [31]. Hence it is possible to increase the distance with more research and industries development. The coil structure is analyzed along with its compensation network so as to resonant at the same frequency to the input and transfers to the load side and also maintain the same frequency [32], [33].

The compensation basic circuit is built from the RLC resonance circuit as let us understand the basic principle of resonance as shown in Fig.10 and the combination of the capacitors inductors connection define the topology of the network. The compensation circuit was first implemented with the capacitors connected in series and parallel and the configuration was named as Series-Series (SS) and Parallel-Parallel (PP) similarly various combinations were implemented to achieve the resonance[45], [50]. Later the network was included with inductor elements and various combinations were implemented and named based on their configuration as T-type network [52] which will be explain brief in Table.5.

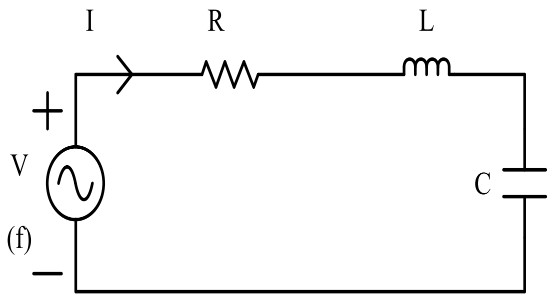

Fig.10: RLC resonant circuit

At resonance: ($X_L = X_C$) ; I will be maximum.

$$\omega L = \omega C;\ \omega = 2\pi f \text{- (1)}$$

$$L = \frac{1}{\omega^2 C}\ ;\ C = \frac{1}{\omega^2 L};\ f_0 = \frac{1}{2\pi\sqrt{LC}} \text{- (2)}$$

$$Q_0 = \frac{\omega_0 L}{R} \text{- (3)}$$

The coil design is based on the transformer leakage flux characteristics, compensation network, coupling factor, air gap distance between the transmitter and receiver coils. The distance of the coil in dynamic motion where the pickup coil is fixed inside the vehicle and the T_x coil inside the road must be in constant distance at all speeds of the vehicles [6],[32].

To reduce the electromagnetic exposure the coils are designed with Litz wire which has low conductor losses and skin proximity of the wire is less compared to the copper and various metal wires [40],[41]. There are two types of coil circular and rectangular coils.

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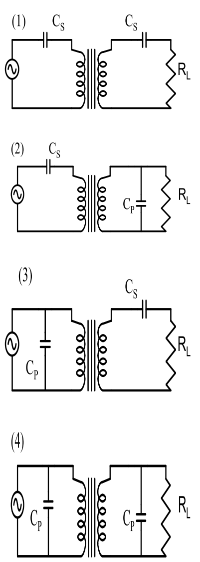
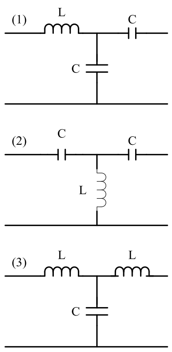
Table 5: Types of compensation networks used in inductive power transfer& Results

COMPENSATION NETWORK	CONFIGURATION	INFERENCES
WITH C (1) SS (2) SP (3) PS (4) PP		The compensation capacitors wereanalyzed based on their mutual inductances. The coupling factor k is dependent on the air gap distance which may vary for each motion of the vehicle. The frequency is fixed and to resonant at the same frequency the resonating circuit is added to the coils [50]. SS topology is superior to the other topologies as it remains constant with the variation in the load.
WITH L AND C (T-TYPE) (1) LCC (2) CLC (3) LCL		When the t-type network is implemented it acts as a current source in resonance, the additional inductors increases the cost of the circuit [51]. The load variations are very less compared to capacitor compensation. Dual control is employed in [11].The network with capacitors at primary side that reflects the secondary side with a impedance, hence we call this also as impedance matching network.

Spiral (circular coils) have high magnetic field surrounded at the center and hence the shielding has to be strong and most probably it is not suitable for dynamic motion of vehicles. Coils with one or more strands are called as bifilar, trifilar which have high resonance and compensate for lateral misalignment [44], [52].The cores for the spiral coils commonly used are pot cores.

Rectangular coils have uniform magnetic field all over the area and hence shielding can be concentrated with minimum cost and ferromagnetic materials may be used to guide the magnetic flux path in the area [6],[38],[52]. These coils are most suitable for dynamic and quasi dynamic motion of the vehicles. The cores for the rectangular coils commonly used are split cores which reduce the compexility and the size and as by the name it splits the magnetic path into double side. The leakage fluxes of the magnetic paths are reduced.

Capactive Coupled/Resonance Power Transfer

The components of the transfer method are same as inductor power transfer with PEI and the coils are embedded with electrolytic capacitors. The four capacitor plates are arranged as shown in Fig. 11 to form the closed circuit so that current flows inside the circuit. Two capacitors are connected in series and other two capacitors are connected in parallel [46].

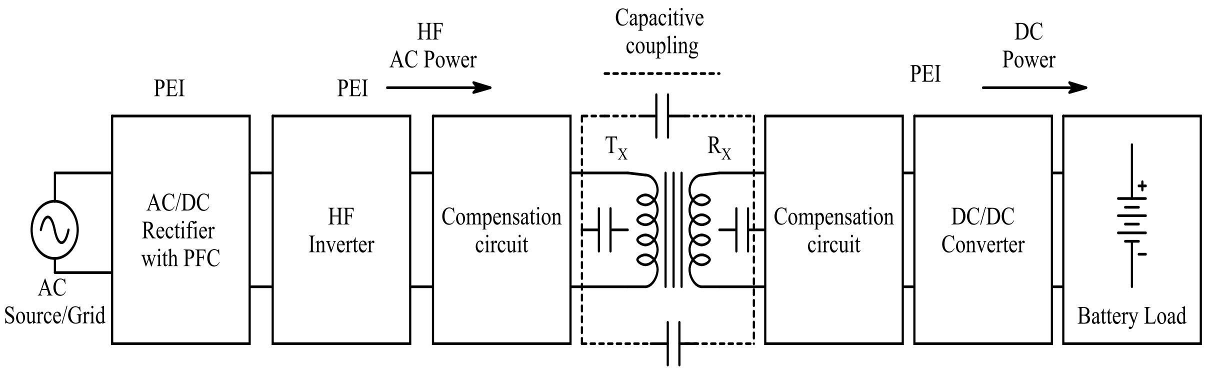


Fig.11: Block Diagram of Capacitive power transfer

The coupling capacitance value is in the range of nF to achieve higher power level. The metal plates reduce the exposure of EMI and penetration of magnetic field is suppressed. It is also known as the electric filed resonance power transfer. The electric field is being set up by the electrolytic capacitors [46].

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The design of coil is simple litz wire can be eliminated and copper wire of single or multi strands can be used which will be enclosed with the metal plates as given in [42],[46].The PEI interface is similar to the converters discussed in previous sections from Table 2-4.

VI. CONCLUSION

This paper is discussed for the battery operated vehicle applications with wide brief context on the power transfer methods,which are being successful as commercial products as discussed above in various developed countries. The situation of developing countries is still way behind with all these technologies due to the difficulty of congested roads to pave the way for the track lanes to implement inductive power transfer application. The transportation sector must also be developed not for producing products for commercial purpose and also as an evolution to destroy the effects caused by fuel and other emissions of harmful gases into the environment. The hybridization of the power transfer methods is the recent studies which are applied to the electric vehicle charging like the capacitive coupling and inductive coupling with primary and secondary side. The transmitter section can be designed with cost effective and also perfect shielding as they remain buried inside the ground and the pickup coil design like capacitive plates that can easily penetrate through any metal bodies can be used.

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