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Inductive Wireless Power Transfer Charging for Electric Vehicles–A Review

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ABSTRACT Considering a future scenario in which a driverless Electric Vehicle (EV) needs an automatic charging system without human intervention. In this regard, there is a requirement for a fully automatable, fast, safe, cost-effective, and reliable charging infrastructure that provides a profitable business model and fast adoption in the electrified transportation systems. These qualities can be comprehended through wireless charging systems. Wireless Power Transfer (WPT) is a futuristic technology with the advantage of flexibility, convenience, safety, and the capability of becoming fully automated. In WPT methods resonant inductive wireless charging has to gain more attention compared to other wireless power transfer methods due to high efficiency and easy maintenance. This literature presents a review of the status of Resonant Inductive Wireless Power Transfer Charging technology also highlighting the present status and its future of the wireless EV market. First, the paper delivers a brief history throw lights on wireless charging methods, highlighting the pros and cons. Then, the paper aids a comparative review of different type's inductive pads, rails, and compensations technologies done so far. The static and dynamic charging techniques and their characteristics are also illustrated. The role and importance of power electronics and converter types used in various applications are discussed. The batteries and their management systems as well as various problems involved in WPT are also addressed. Different trades like cyber security economic effects, health and safety, foreign object detection, and the effect and impact on the distribution grid are explored. Prospects and challenges involved in wireless charging systems are also highlighting in this work. We believe that this work could help further the research and development of WPT systems.

INDEX TERMS Electric vehicle charging, wireless power transfer, inductive wireless charging, magnetic resonance charging, compensator networks.

I. INTRODUCTION

Large scale deployment of Internal Combustion Engine (ICE) based vehicles in transport system lead to the release of harmful fumes into an atmosphere lead to global warming and climate change, which is main concern of global community. Therefore, to lessen dependence on fossil fuel based energy sources and to reduce its harmful impacts on the atmosphere, there is a need for alternative solutions such as EVs charged on renewable energy sources [1]–[3].

Normally, batteries have low energy density, makes them weighty, costly. bulky. In addition slow in charging and provides shorter lifetime. Now a days lithium ion batteries are mostly used in EVs. Battery capacity restricts the cruise range. Adding the batteries will increase the cruise range, which further increase the weight and cost of the vehicle. Some authors presented fast battery charging methods to minimize the full charging time less than 30 min [1], [4]. However, available fast charging systems are costly and complex in control. Still, the charging time of battery more than time that needs to refuel a car based on fossil fuel. Another solution proposed is based on the use of ''swapping stations,'' where the depleted EV batteries are exchanged with fully charged batteries [1]. For the development of EVs, charging systems are playing the main role. The currently available technology for EV battery charging

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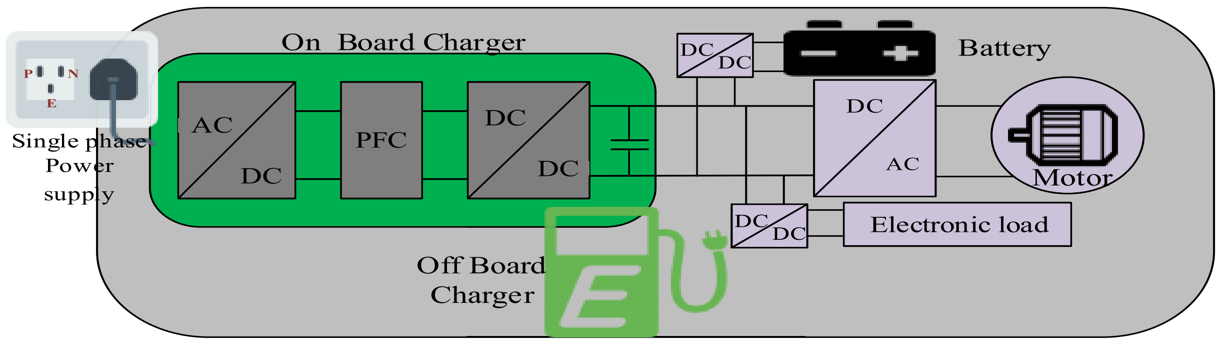


FIGURE 1. Block diagram of plug-in charging model.

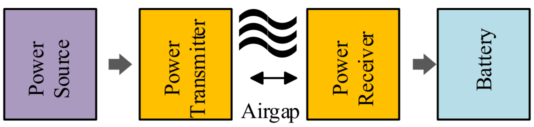


FIGURE 2. Basic structure of WPT system.

consists of plug-in charging (conductive charging or wired charging) and Wireless charging (contactless) methods. Plug-in charging system further classified in to Off-Board and On-Board chargers based on charging platforms. The generic charging model of conductive charging system presented in Fig. 1.

One of the main concern with conductive charging is high power cables, to plug EV, those are difficult to handle. Hazards can happen due to damaged cables or mishandling. Furthermore, Conductive charging methods are prone to vandalism and theft. An alternative new technology is WPT, introduced by Nikola Tesla in 19th century, with the time this technology developed and became competitive solution for wired charging systems. This technology has capability to replace the plug-in interface by transmitters and receivers, allowing power flow in a contactless manner in the form of electromagnetic or static waves as shown Fig 2. In WPT systems the receiver transfer power to the batteries or drive system through power electronic converters.

Furthermore, the wireless charging system is capable of working without human intervention. It is also safe due to the fact that there is no cables present in the system. The hazards caused by using cables can be avoided. This advantages makes Wireless technology suitable for large-scale deployment. Also makes it fully automated charging infrastructure in electrified transport system. The main drawback of wireless charging system is its charging time. That can be resolved by different changes in the system. In this paper those points are discussed. Another concern with WPT is its leakage EMF radiation at higher frequencies. This radiation is restricted by using proper shielding to make it safer. Arresting methods are mentioned in this paper.

Wirelessly charging of electric vehicle can be done in 3 modes: 1) Stationary Wireless Charging (SWC); 2) Dynamic Wireless Charging (DWC); and 3) Quasi-Dynamic/stationary Wireless Charging (QDWC). SWC is method to charge the EV in standstill position. SWC technology is being gradually matured [5]. Because of limitations in the battery capacity, Electric Vehicles need more charging cycles to travel longer distance. This problem can be solved by DWC [6]. In DWC transmitting pads positioned on a small section of the pavement and receiving pads placed on EV chassis to provide an opportunity charge EV in a motion. This makes a huge capital investment. While implementing DWC system, speed of the vehicle needs to be considered. An alternative method is a quasi-dynamic wireless charging system, which takes some advantages from the DWC. It needs less investment compared to DWC. The QWC mode provides charging to EVs as they are stationary position or while moving slowly for short periods of time. This method is suitable for the public transit EVs to charge when halts at bus stops or taxi stands, traffic signals. In this method battery won't be charged fully [7]. The flexible nature of WPT technology makes it suitable for commercially viable.

Main features of WPT system are:

- WPT system can be divided in different categories with respect to transmitting power ranges. Low power range WPT system covers: <1 kW, medium range WPT covers: 1–100 kW and high power range WPT $>$ 100 kW.
- In WPT system power can be transferred unidirectional (G2V) and bidirectional (vehicle to grid vice versa). V2G application in conductive charging is more complex than wireless charging. Vehicle to vehicle (V2V charging is possible while stationary or moving)
- We can transfer power small distances to long distances i.e. several cm to kilometers.
- Transfer of power can be happen with different mediums.
- The power transmission medium effects the efficiency of the system. Major losses occurs in this region For instance, In the article [8] author presented that underwater WPT(water as a medium) system provides 5% lower efficiency compared to air-gap system(air as a medium).

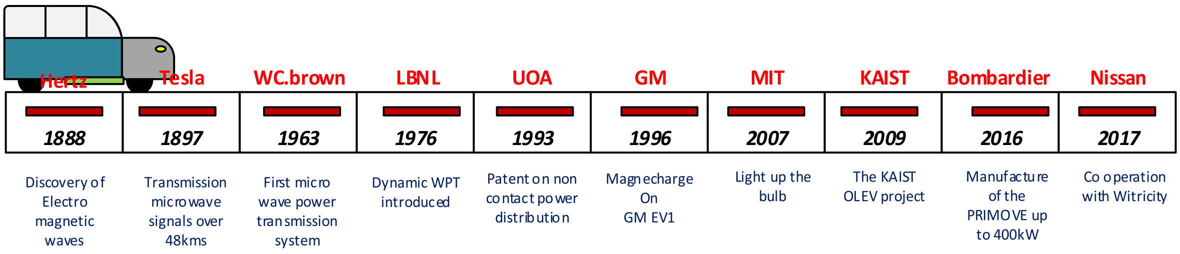


FIGURE 3. Major events of the history of WPT.

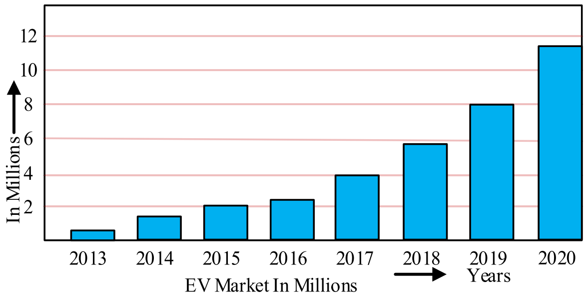


FIGURE 4. Number of EV's sold every year.

Although study on WPT systems going on from over century but in recent years it got more momentum due to EV technology. In literature [9], brown et al categorized WPT history into three time lines. Fig. 3 shows the main events on history and development of WPT.

The first period was related with Maxwell and Hertz. In 1873 Maxwell presented equation for electromagnetic energy transmission in a free space. Around 1885-1889, Hertz with series of experiments verified Maxwell's predictions and the presence of electromagnetic radiation.

The second period mostly associated with Nikola Tesla, the creator of Alternating Current(AC) and poly phase systems, who wanted to transfer energy to any point on our earth by using our earth and its atmosphere as a conductor [9]. In the year 1896, tesla transmitted microwave signals to over the distance of 48 km, and in between1891 to 1904, Tesla conducted numerous investigations on electromagnetic and electrostatic energy transmission [10].

As per brown et al third period or current era WPT's history started in the period of II World War, in that time researchers used curved reflectors to concentrate energy into one small area. In his study, Brown concentrated on energy, that is accumulated by utilizing solar cells mounted on satellites, and then transmitted to earth by beaming, where that beamed energy transformed into Direct Current(DC) [9], [11]. In 1976, DWC was first introduced and Lawrence Berkley National Laboratory (LBNL) evaluated its system feasibility [12]. The Fig. 5 shows the generic presentation of WPT charging system for EV.

The history of commercialization stationary charging started in between 1997 to 1998 by German company Conductix-Wampler. First EVs charged by Inductive Power Transfer (IPT) based Charging Technology presented at Rotorua district in New Zealand and since 2002 the first wirelessly charged buses running automated through bus stops of Genoa and Turin. They achieved 90% efficiency at air gap of 40 mm for 60-kW powered 40 foot buses [13], [14]. Oak Ridge National Laboratory (ORNL) in USA worked on both static and dynamic charging models. A 100 kW single-phase SWC system, attaining an efficiency near to 97% for a separation of 5 inches. In this system a single transmitter and receiver used [15], [16]. ORNL has also incorporated their wireless charging system into various EVs with 6.6 kW power and achieved end to end 85% efficiency [17].

Qualcomm's Halo (HaloIPT) with collaboration of Auckland University (AU) introduced new magnetic pads called "Double D" or DD pads, which are more efficient and misalignment tolerant than the circular pads and rectangular pads. Qualcomm's Halo acquired by WiTricity in 2019 [18], [19]. HEVO Power, New York based company is working on implementing both SWC and dynamic charging systems for EVs and they introduced smart phone app for simplifying EV charging for customers [6]. Fraunhofer Institute in Germany has designed a test model using SiC MOSFET switches for a 22kW WPT charging system. The efficiency achieved around 96% (dc-to-dc) by a bi directional novel controller design [20].

The WiTricity one of the leading company in the wireless charger production. They offered static wireless chargers up to the range of 3.6-11 kW and is further scalable up to 22 kW power transfer. A power converters based on SiC MOSFET showed a grid to battery efficiency of more than 91% and claimed 98% of coil-coil efficiency [21], [22].

Momentum Dynamics US based company has developed the 3.3 kW SWC system for gap of 24cm and reported 92% efficiency. Furthermore, they upgraded this charging system to 7.2kW and 10 kW, which can charge the Chevrolet Volt in approximately 1 h [6].

Momentum Dynamics has availed wireless chargers up to the power ranges of 50 to 300 kW, a 200 kW wireless charger with transfer efficiency of more than 90% for an air gap of 30cm [23]. They successfully installed a wireless charging infrastructure with 200 kW power transfer capacity for Link transit consists of 10 buses fleet.

Toshiba corporation developed a 44 kW cascaded parallel WPT system with misalignment tolerance of +/− 10 cm for

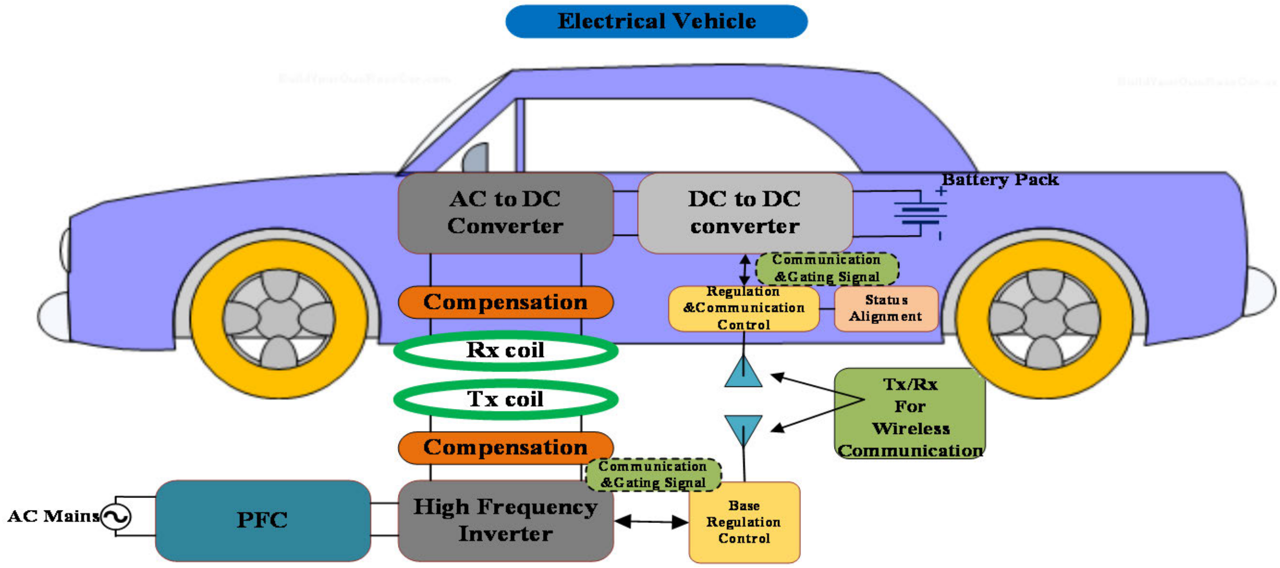


FIGURE 5. Generic presentation of WPT charging system for EV.

electric buses and complied with International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommendations [24].

Integrated Infrastructure Solutions (INTIS) located in Germany, developed several stationary charging systems in between 11kW to 15kW [25]. WaveIPT has developed a comprehensive design of the charging for in-route fleets in Southern California. The newly system is used by drayage trucks [26]. KAIST university has developed several WPT, which ranging from 3kW to 15kW [27]–[29].

The Dynamic WPT (DWPT) application covers all types of land moving vehicles. Commercial deployment of DWC facing tough challenges like large scale infrastructure modification resulting disruption in available services and high initial investment [14], [30]–[32]. Bombardier-PRIMOV has demonstrated a DWC system with frequency of 20kHz achieved approximately 250 kW for trams with minimum coupling distance [49]. Korean Advanced Research Institute (KAIST) has done demonstrations on dynamic charging for railway and EV transit, in that to improve magnetic coupling and compatibility of pavement construction they introduced various magnetic rail structures [47]. 800 kW high speed prototype designed by kRRI [46]. INTIS research lab tested 200 kW EV on the track of length 25 m [48]. They also employed a 30 kW DWC for industry movers [48]. Utah State University in USA worked on a 25 kW DWC system that allows 150mm of horizontal misalignment tolerance while performing at full capacity [43]. Some of the recent developments by the institutions/Research centers are shown in Table 1.

A. PRESENT MARKET AND FUTURE ESTIMATION

There is a growing demand for non-fossil fuel based and safe electric vehicles. These vehicles bring high investment in fast-charging applications. As per global outlook 2021, despite of pandemic the electric vehicles globally registered is 3 million, 41 % more than for previous year in the more than 60% share belongs to BEVs [50], as depicted in Fig. 4. This figure presents clear deviation from the progress rates of 2013-2020. at the end of the year 2020 electric vehicles on the road reached more than 10 million. As per survey conducted by IEA, the global EV stock (excluding two/three-wheelers) expected to reach 145 million at the year 2030 and will have 7% share of the global vehicle Market. Battery electric vehicle (BEV) is anticipated to become largest EV market, by propulsion, during the forecast period compared to PHEV. As per the present scenario BEV market crossed more than 60% percent in EV market. as per the report [51], The contactless Charging in EV Market is anticipated to develop at a 46.8% CAGR during period of 2020 to 2027. It can reach 234 million USD by 2027.

B. WIRELESS CHARGING METHODS FOR EVS

There are several available methods for WPT. It depends upon technology using and transferring frequency level. According to that categorized in to two types. 1) Coupling (Near field), 2) Radiative (Far field). Coupling system further categorized into magnetic field and electric field radiative type categorized into two types microwave and laser types, as show in Fig. 6.

The WPT methods, and their air gap range of operation as per the frequency shown in Fig. 7. The sizes of transmitter and receiver increases with the frequency. Advantages and disadvantages of coupled and radiated methods are outlined in Table 2.

1) MICROWAVE POWER TRANSFER (MPT)

MPT is a micro wave based WPT technology in a far-field context [52], [53]. This method can also be operated

TABLE 1. Units for magnetic properties.

Mode	Institution /Research Center	Frequency	Efficiency	Power	Air gap (mm)	Year
Static Mode	ETH Zurich [33]	85kHz	96.50%	50-kW	52	2015
	Bombardier Primov[34]	TBA	-	-	10TO 30	2015-17
	Conductix-Wampler WC Torino,Italy[13]	20kHz	90%	60kW	400	2013
	Momentum Dynamics[35, 36]	TBA	>90%	3.3-10kW	24	2015-17
	HEVO power[14]	85kHz	90%	10kW	300	2017-18
	Toshiba [37]	85kHz		44kW	100	2017
	INTIS[25]	TBA	TBA	11-30kW	110-130	2013-18
	ORNL[15, 16]	-	95%	50 kW	15	2018
		-	97%	120 kW	5	2018
	WAVE [26]	TBA		50&250kW	TBA	2012-19
	WiTricity Corporation[21, 38, 39]	>85kHz	>90%	3.6-11kW	100-200	2009-19
	Toshiba [29]	-	-	7 kW	160	2014
	Fraunhofer Institute in Germany[20]	100kHz	97%	22 kW	135	2015
	KAIST University[29]	90kHz	95%	3.3kW	200	2016
	KAIST University[27, 28]	20kHz	72-80%	3kW	100	2010-14
		20kHz	74-83%	15kW	120-200	
Dynamic Mode	ORNL[40, 41]	22kHz	93%	20kW-30kW	162	2016
	Bombardier[42]	20kHz	90%	200kW	60	2010
	WAVE [26]	20kHz	90%	50kW	152-254	2011
	Utah State University [40, 43]	20kHz	86%	25kW	-	2016
	University of Auckland [44]	12.9kHz	85%	20kW-30kW	500	-
	North Carolina State University[45]	100kHz	77-90%	0.3kW	170	-
	KRRI[46]	60kHz	82.70%	812kW	50	2012
	KAIST[47]	20-60kHz	72-88%	3kW-27kW	10-200	2009-16
	INTIS [48]	-	90%	30-60kW	150	2013

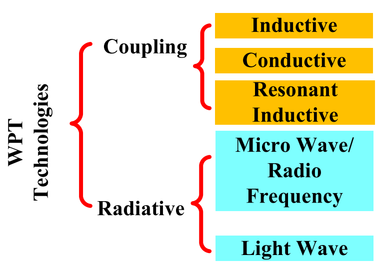


FIGURE 6. Classification of WPT methods.

in Radio-Frequency (RF) range with little adjustments. A high-voltage DC generator feds magnetrom (vacuum based oscillator), which generates microwave signal. The generated microwave signal sent out through the antenna, this signal is received by receiving antenna. This receiving antenna also referred to as rectenna. This rectenna consists of both receiver and rectifier which converts the signal in the form DC to charge the battery or load as presented in Fig. 8.

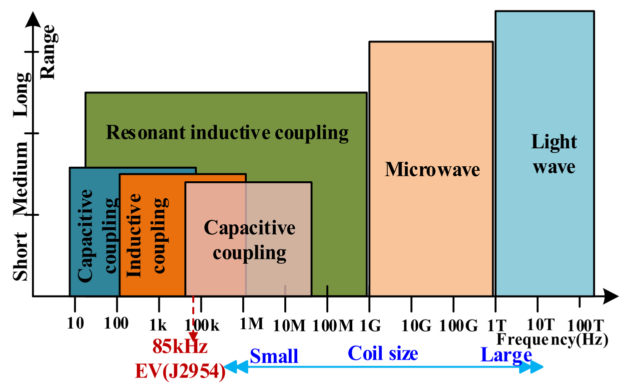


FIGURE 7. Operation range and frequency of different WPT methods.

2) OPTICAL WPT

Optical WPT or Laser based power transmission is radiated in the form of electromagnetic waves; however, it is in THz and thus, exists as light. According to this technique, the

TABLE 2. Advantages and disadvantages of coupling and radiated technologies.

WPT technologies type		Advantages	Disadvantages
Near Field	Capacitive	• Offers Medium power transfer(several kilowatts) • Power transfer possible through metallic objects. • Cheap because of relies on aluminum plates for power transfer. • Suitable for air gap up to 10 cm. • Restricted electric field: shielding not needed for EMI control.	• Power transfer capabilities depends upon the gap between transmitter and receiver. • Parasitic capacitance forms. • Efficiency around 70-80%.
	Inductive	• Implementation is simple. • Galvanic isolation provided. • Simple control. • High efficiency in low air gap (typically less than a coil diameter). • Safe operation compared to resonant mode • Bi directional power transfer possible.	• Short air gap few millimeters to centimeters. • EMI shielding is needed. • Very low efficiency at larger air gaps. • Heating effect in the presence of metal objects. • Tight alignment needed between transmitter and receiver to achieve good efficiency.
	Resonance	• Offers High power transfer compared to other methods. • Commercialized technology for EV charging. • Able to transfer power in misaligned conditions. • Provides galvanic isolation. • Bi directional power transfer possible	• Cost of the system increases with power. • Extremely sensitive to the obstacles in between coupler coils. (Especially the metallic ones). • Shielding is needed for EMI.
Far field	Micro Wave	• Power can be transferred up to several km. • Dynamic power transfer is possible (for moving loads). • Possible to transfer power up to several kilowatts power • Higher efficiency achieved at beam forming. • Compatibility with existing communication system.	• Low efficiency compared to inductive and capacitive methods. • Very difficult to implement. • Unidirectional power flow • Unsafe for living things when exposed to microwave beam. • Size of the antennas increases with power transfer capability increases.
	Optical	• Effective gap in kms • Dynamic power transfer is possible (for moving loads). • Capacity to transfer several kilowatts power. • Transmitter size is small compared to MPT.	• Low efficiency (around 20% depends upon air gap). • Unidirectional power flow. • Difficult to operate. • No obstacles allowed in way of light beam. • Unsafe operation for living beings, if exposed to radiation.

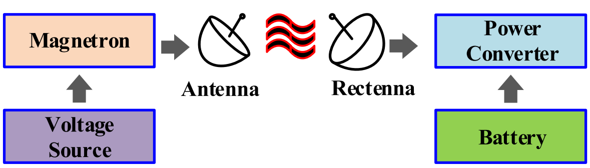


FIGURE 8. Block diagram of a microwave power transfer system.

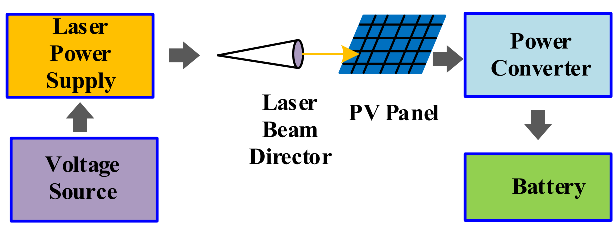


FIGURE 9. Block diagram of an optical WPT.

transmitter consists of laser diode which generates a light beam with particular power and wavelength. Beam director serves to adjust laser diode to control the direction of the light beam. Secondary side consists a Photo-Voltaic (PV) cell and rectifier, PV cell receives light beam converts into a power signal. The power signal converted to DC signal by rectifier. The DC signal fed to power a load or a battery. Fig. 9 presents the block diagram of optical WPT.

Ideally, a High Intensity Laser Power Beam (HILPB) system have the ability transfer power to any point Practical limitations like conversion efficiencies limits the performance of the system. In the HILPB system, for effective conversion of laser power to electricity design of PV cell plays major role. For that, the dynamics of the laser power

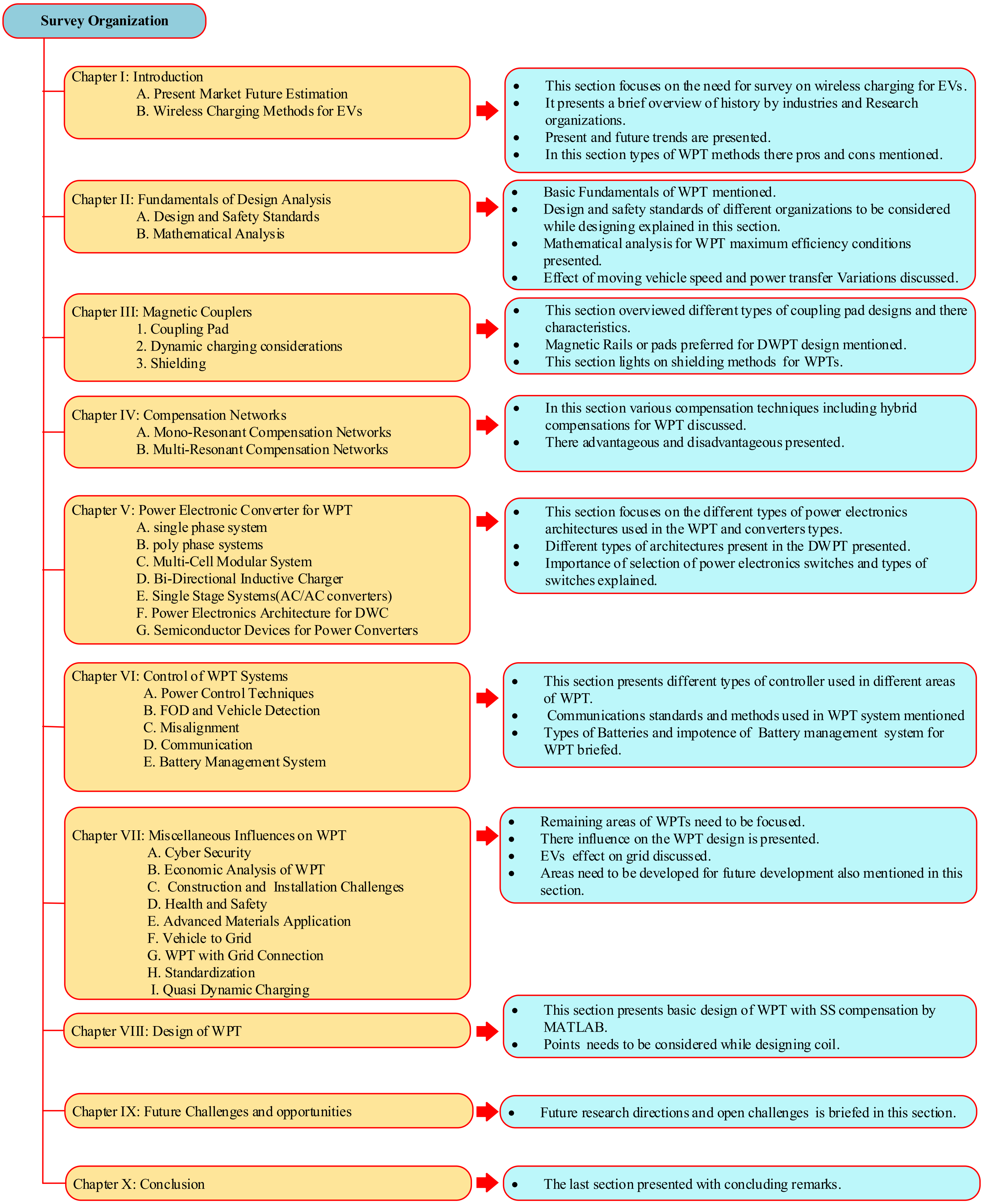


FIGURE 10. **Survey organization of article.**

such as wavelength, temperature and the materials of the PV cells should be analyzed carefully [54]. Laser technology for EV still need to be implemented.

3) INDUCTIVE WPT

Inductive WPT (IWPT) system comprehended with the electromagnetic wave. The working theory of IWPT system

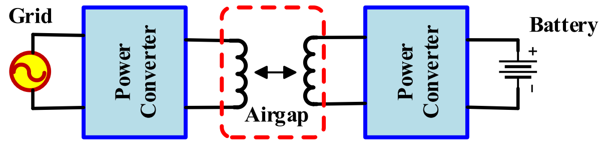


FIGURE 11. Generic diagram of a inductive WPT.

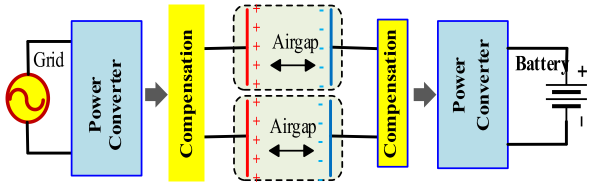


FIGURE 12. Generic diagram of a capacitive resonance WPT.

based on traditional transformer operation. On the primary side, as per the Ampere's law, an Alternating Current (AC) develops a magnetic field around the conductor (primary side coupler). The developed time varying magnetic field is linked to the magnetic coupler in the secondary side. The Linked field induces a voltage across secondary coil presents Faradays law. Fig. 11 shows the block diagram of IWPT system. This induced voltage converted to DC power signal by rectifier. This power can be used for charging battery. Tuning of secondary coil frequency equal to operating frequency enhance the efficiency of the system [55]. When operating at the range of radio frequency, the limit of air gap extend up to 20 cm at the cost of lower efficiency [56].

4) CAPACITIVE WPT

It is Electro static field based systems also referred as Capacitive WPT (CWPT) systems. The CWPT utilizes a two parallel metallic plates facing each other acts as a transmitter and receiver to form an equivalent capacitor for transmitting power in the form electro static energy, as presented in Fig. 12. The CWPT system can transfer power through the metallic medium. Compared to IWPT, the CWPT system applicable for both low current and high voltage systems. Additional inductors added to capacitor plates on each side to reduce impedance. This is also called as inductive compensation, it enables soft switching operation and increases power transfer efficiency. Exited voltage in secondary side is altered to Direct Current(DC) by rectifier circuit, to power the battery bank or load with filter circuitry [57]. Furthermore, it is having advantageous such as low weight and less cost than the IWPT systems;

5) MAGNETIC RESONANCE WPT

The Resonant Inductive WPT (RIPT) is improved model of traditional IWPT, in terms of power transferring capability, designing and coupler coils. Fig. 13 illustrates base model of the RIPT system for battery charging. Similar to the other WPT system, existed grid voltage is transformed to the High Frequency AC (HFAC) by utilizing power

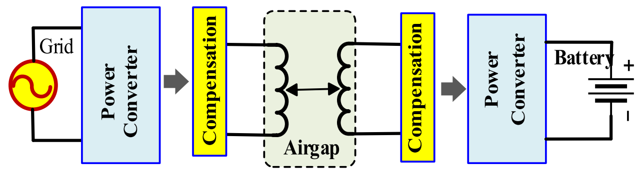


FIGURE 13. Generic diagram of a magnetic resonance WPT.

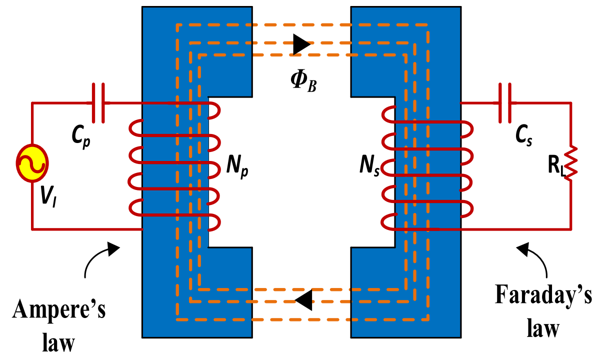


FIGURE 14. Generic diagram of a magnetic resonance WPT.

electronics converters. The HFAC signal delivered to the coupler coil. The secondary coupler coil generates voltage by linked magnetic fields. Generated voltage is converted to DC for the powering the battery through power electronics converters and filter circuitry [58]. Compared to IWPT system, Compensation networks (capacitors/inductors or both) added in the series or/and parallel formations to both transmitter and receiving side of the coils to form the resonant condition. That helps improve efficiency by reducing additional losses.

This review article mainly focuses on the resonance inductive wireless power system. This article contains magnetic coupler designs for both static and dynamic methods and compensation networks, power electronics circuits and architecture, shielding techniques, control system, standards and communication networks in stationary and dynamic wireless charging. It also presented miscellaneous causes effecting WPT technologies like batteries, grid integration, V2G, and infrastructure. Furthermore, this article addresses issues like cybersecurity, health, and safety, DWC infrastructure installation. The structure and pattern of the article is shown in the Fig. 10.

II. FUNDAMENTALS OF DESIGN ANALYSIS

The resonance inductive WPT operating principle is based on Amperes Law and Faradays Law as mentioned above, the HFAC signal passing through the primary winding produces a time varying magnetic field (Ampere's law). The resultant magnetic flux is proportional to Permeability of free space, number of turns and current flowing through it (1). The time varying magnetic flux induces electric current the secondary winding (Faraday's Law), equation (2). Generic model of magnetic resonance based system shown in Fig. 14

$$\sum B_T \Delta l = \mu_o I N_p \tag{1}$$

$$E = -N_s \frac{d\phi_B}{dt} \tag{2}$$

where B_T, μ_0, Δl, E, and ϕ_B represnets magnetic flux density, permeability of free space, length of the conductor, induced voltage and magnetic flux respectively. N_p and N_s indicates number of primary and secondary turns.

In WPT system power need to transfer larger distances (large air gap). Due to inductive nature of the circuit and the large air gap, a high current (i.e., magneto motive force) is need to produce required magnetic field to couple the secondary coil. To minimize the Volt–Amp (VA) rating of the primary converter, it is necessary to compensate inductive nature of the circuit with capacitor. Similarly, secondary side inductance also compensated to increase power transfer capability.

A WPT system able to function at resonant or above resonant condition. At low power applications leakage inductance results small voltage drop even with high current. For high power and high frequency applications results higher voltage drop due to large leakage inductance. it is difficult archive high power without increasing current input. In other side increase current causes more conduction losses. In addition, extra reactive power(compensation) needed to increase the VA rating of the inverter [59], [60]. Usually, achieving ZVS or ZCS at higher frequency is very difficult and it is required to achieve high efficiency [47].

As shown in Fig. 4. A RIPT system be made up of different components, mainly:

1. Transmitting and receiving coils with shielding
2. The compensation scheme;
3. The power electronic architecture.

While designing WPT system following factors should be considered. Those are structure, air gap between two coils, compensation scheme, resonant frequency, coil and design, power electronics topology and alignment. These factors directly or indirectly influences the performance of the system. The Fig. 15 presents the design procedure of WPT charging system. In the following sections different parts of WPT system designs and developments is discussed.

A. DESIGN AND SAFETY STANDARDS

Commercialization of wireless EV chargers requires automotive manufacturers to guarantee their compatibility and interoperability of the charger for any vehicle and also ensure their safety and environmental sustainability. For that they need to comply with the guidelines recommended by international organizations. Standards also make it easier to sell, manufacture, understand and compare competing produces for automobile manufacturers. The Society of Automotive Engineers (SAE) one of the main organization sets standards for high powered wireless charging systems for EV. The first version of SAE j2954 recommended

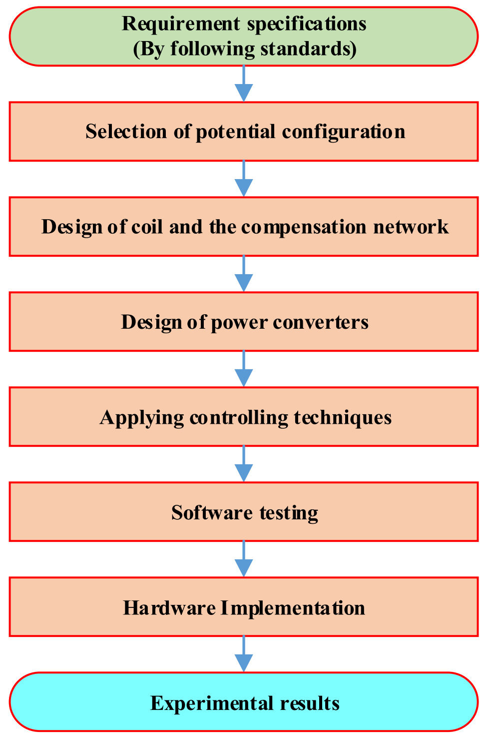


FIGURE 15. Flow chart: design procedure of a WPT.

standards for WPT was published in 2016 [61]. Most recently fourth version recommended SAE j2954 released in 2020 [62]. It recommended 3 standards for three power classes follows as WPT1 with 3.7kVA, WPT2 with 7.7kVA and 11kVA, WPT3 transmission standards established and 22kVA (WPT4) design standards are in the way development. Table 3 shows the J2954 suggested design requirements for power classes, frequency, related air gaps (Z1, Z2, etc.) In addition, subjected to misalignment in different directions, magnetic coupler need to keep significant percentage of their coupled inductance. Similarly Roll of up to ±2%, a Pitch of up to ±2% and Yaw of up to ±6% occurs simultaneously. Apart from them it recommended pad models, interoperability and maximum stray field levels. The joint experiments from research institutions and automotive industry shown circular and double-D pads are have good interoperability in power transfer capability and efficiency [63]. Communication protocol guidelines defined by J2954 relies on other recommended guidelines such as J2836/6, J2931/6 and J2847/6, and. SAE recommended another version guidelines for WPT as J2954/2 for medium and heavy-duty vehicle.

Another important organization who set standards for Wireless chargers is IEC (International Electro-technical Commission) as IEC 61980. IEC-61980-1, 2 and3 focuses on the general requirements, communication and magnetic field requirements respectively, but shares mostly common information with SAE J2954. it covers up to power level 22kVA and limited the air gap up to 24cm. Furthermore,

TABLE 3. WPT charging standards recommended by J2954 [61].

WPT power class				Z-class Gap between GA to VA	Misalignment Offset Direction	Misalignment Value(mm)
WPT1 3.7kVA	WPT2 7.7kVA	WPT3 11.1.kVA	WPT4 22kVA	Z1 100-150	ΔX	±75
>85%	>85%	>85%	TBD	Z2 140-210	ΔY	±100
>80%	>80%	>80%	TBD	Z3 170-250	ΔZ	Z_{nom}-Δ_{low}->Z_{nom}+Δ_{low}
Functioning frequency 85 kHz in Band Of 79-90 kHz					Roll, Rotation, and Yaw	±2,±2, and ±6 Degrees Respectively

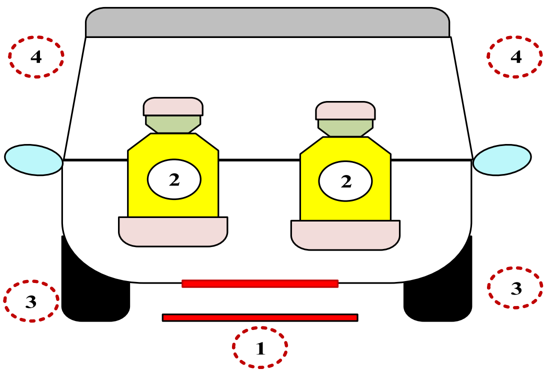


FIGURE 16. SAE J2954 WEVC EMF divided regions.

TABLE 4. EMF reference levels SAE J2954.

Limits	Region	Magnetic flux density B (μT)	Magnetic field strength H (A /m)
ICNIRP guidelines	2, 3, 4	27	21
Pacemaker / IMD	2, 4	15	11.9

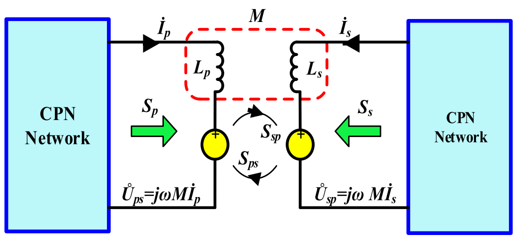


FIGURE 17. Generic double-coil model of WPT system.

provides requirements for bidirectional power transfer. The guidelines for heavy-duty electric vehicle in the development phase. The International Organization for Standardization (ISO) has defined under standards under ISO-19363 close synchronization with SAE J2954 and IEC 61980 [64]. These organizations sets operating frequency as 85 kHz and 81.38 to 90 kHz as a band range, later extended to 79-90 kHz for light duty vehicles.

The increase power levels and air gap creates issues like EMI and leakage magnetic fields, causes heating issues and not good for human exposure. To prevent these adverse consequences, several organizations have prescribed the allowable limits to EMF intensity and according to those guidelines It requires safety practices like shielding and FOD methods.

The ICNIRP declared the recommendations for restricting field radiations and EMI and limits to the human body exposure. The ICNIRP 2010 recommended standards focuses on frequencies ranges between 1 Hz-100 kHz, which covers almost wireless EV charging applications [65]. The new version of ICNIRP 2020 guidelines covers frequency range between 100 kHz to 300 GHz [66]. Table 4 summarizes the EMF exposure limit according to ICNIRP 2010 guidelines [45]. SAE J2954 follows the same limits and areas as ICNIRP without taking consideration of first area, as shown in Fig. 16, while the IEEE C95.1-2005 [67] and IEEE C95.1-2345-2014 [68] offers more insights.

B. MATHEMATICAL ANALYSIS

In typical WPT system several conversion stages are included, as shown in Fig. 5. By improving each conversion stage maximum efficiency can be acquired [69]. In this section generalized approach for the compensation network is going to be discussed. Features of compensation network will be assessed later. Fig. 17 shows the simplified of WPT setup with compensation network. In the literature [27], derived condition for maximum efficiency. Ignoring the magnetic losses and resistance of the coil, simplified form of apparent power exchanged between L_p to L_s can be calculated.

$$\dot{S}_{ps} = -\dot{U}_{ps}\dot{I}_s^{\,*} = -j\omega M\dot{I}_p \quad (3)$$
$$= \omega M\dot{I}_p I_s \sin\varphi ps - j\omega \cos\varphi ps \quad (4)$$
$$\dot{S}_{sp} = -\dot{U}_{sp}\dot{I}_p^{\,*} = -j\omega M\dot{I}_s\dot{I}_p^{\,*} \quad (5)$$
$$= -\omega MI_p I_s \sin\varphi ps - j\omega MI_p I_s \cos\varphi ps \quad (6)$$

where the true power transfer can be presented as,

$$P_{ps} = \omega MI_p I_s \sin\varphi ps \quad (7)$$

Fig. 17 shows the active power exchanges between both coils. In following analysis, consider that L_p to L_s power transfer happening. when $\varphi ps = \frac{\pi}{2}$ the power flows from L_p to L_s reaches maximum.

The apparent power transferred to two-coil system is,

$$\begin{aligned}\dot{S} &= \dot{S}_P + \dot{S}_s \\ &= j(\omega L_p \dot{I}_p + \omega M \dot{I}_s)\dot{I}_p{}^* + j(\omega L_s \dot{I}_s + \omega M \dot{I}_p)\dot{I}_s{}^* \\ &= j\omega(L_p I_p^2 + L_s I_s^2 + 2MI_pI_s \cos\varphi\text{ps}) \end{aligned} \tag{8}$$

Hence, the total reactive power flows between two coils is

$$Q = \omega\left(L_p I_p^2 + L_s I_s^2 + 2MI_pI_s \cos\varphi\text{ps}\right) \tag{9}$$

To Maximizing the efficiency of transformer, the ratio between the P_{ps} and Q to be kept maximum. The ratio is goes as,

$$f(\varphi\text{ps}) = \frac{|P_{ps}|}{Q} = \left|\frac{\omega MI_pI_s \sin\varphi\text{ps}}{\omega(L_pI_p^2 + L_sI_s^2 + 2MI_pI_s\cos\varphi\text{ps})}\right| \tag{10}$$

$$\begin{aligned} &= \frac{k\sqrt{\cos^2\varphi\text{ps}}}{\sqrt{\frac{L_p}{L_s}\frac{I_p}{I_s}} + \sqrt{\frac{L_s}{L_p}\frac{I_s}{I_p}} + 2k\cos\varphi\text{ps}} \\ &= \frac{k\sqrt{\cos^2\varphi\text{ps}}}{x + \frac{1}{x} + 2k\cos\varphi\text{ps}} \end{aligned} \tag{11}$$

where, $\frac{\pi}{2} < \varphi\text{ps} < \pi$

$$x = \sqrt{\frac{L_p}{L_s}\frac{I_p}{I_s}} > 0$$

'k' indicates coefficient of coupling in between L_p and L_s $f(\varphi\text{ps})$'s maximum can be achieved by solving the following equations,

$$\frac{\partial f(\varphi\text{ps})}{\partial\varphi\text{ps}} = 0, \quad \frac{\partial^2 f(\varphi\text{ps})}{\partial\varphi\text{ps}^2} < 0$$

and obtained the solution as

$$\cos(\varphi\text{ps}) = -\frac{2k}{x + \frac{1}{x}}, \quad \sin(\varphi\text{ps}) = \sqrt{1 - \frac{k^2}{\left(x + \frac{1}{x}\right)^2}} \tag{12}$$

In resonance condition k value near to 0, at $\sin\varphi\text{ps} = 1 f(\varphi\text{ps})$ gets maximized, at same instant the power transferred also maximized. The phase angle among the two currents $\dot{I}_p$ and $\dot{I}_s$ is about 90° contrary to 180°. Where $k > 0.5$ i.e. tightly coupled. In this condition to achieve high efficiency $f(\varphi\text{ps})$ value to be increased. In this case, if self-inductance of the coil resonates with capacitor and it makes $\varphi\text{ps} = \frac{\pi}{2}$ and lowers $f(\varphi\text{ps})$ value, this method is not suggested.

Instead of self-inductance if capacitor resonates with leakage inductance of the coil. Coupler behaves as a transformer and $f(\varphi\text{ps})$ value increases, however, the whole system doesn't work under resonant condition.

When $k < 0.5$ (loosely coupled), the capacitor needs to resonate with self-inductance of the coil so that maximum power transfer can be achieved.

To get more efficient power transfer at a certain coil current. $\dot{U}_{ps}$ and $\dot{I}_s$ should be in phase since $\dot{U}_{ps}$ lags $\dot{I}_p$ by 90° on the secondary coil. At the receiving side, the pure resistive nature can be observed. In same time, complex power S_T at the primary side must be minimized.

When $\cos\varphi\text{ps} = 0$ the complex power given as,

$$\dot{S}_P = j\omega L_p I_p^2 + \omega MI_pI_s \tag{13}$$

We have,

$$U_{12} = I_s(R_s + R_{lr}) = \omega MI_p = \omega k\sqrt{L_pL_s}L_p$$

where R_s indicates resistance of secondary winding and load resistance as R_{lr}

Describing quality factors by, $Q_1 = \frac{\omega L_p}{R_p}$, $Q_2 = \frac{\omega L_s}{R_s}$, the transfer efficiency is defined as

$$\eta = \frac{I_s^2 R_{lr}}{I_1^2 R_p + I_2^2 R_2 + I_2^2 R_{le}} \tag{14}$$

Expression of efficiency can be rewritten as,

$$\eta(a) = \frac{1}{\frac{a + \frac{1}{a} + 2}{k^2 Q_1 Q_2} + a + \frac{1}{a}} \tag{15}$$

where $a = \frac{R_{le}}{R_s}$

The maximum efficiency

$$\eta_{max} = \frac{k^2 Q_1 Q_2}{\left(1 + \sqrt{1 + k^2 Q_1 Q_2}\right)^2} \tag{16}$$

$$\text{Is achieved at } a_\eta = \left(1 + k^2 Q_1 Q_2\right)^{\frac{1}{2}} \tag{17}$$

Many researchers have derived equation for the maximum efficiency with a different compensation network [70]–[72]. The results are like equation (16). From above equation to get maximum efficiency, both coils quality factor should be kept at higher values. For SWC the coupling factor usually around 0.2 and a quality factor in between 10 to 300.

Dynamic wireless charging depends on vehicle speed. Along with vehicle movement, secondary coil (assembled to vehicle), the position also changes with respect to primary coil (ground assembled). Flux transfer efficiency depends on proper alignment between transmitter and receiver. While moving of EV, when secondary pad perfectly aligned with one of the transmitter pad, maximum power transfer occurs. As vehicle moves forward secondary pad moves toward the next transmitting pad and its alignment with first transmitter pad reduces as alignment with next transmitter increases, which results dip in power. Fig. 18. shows the variation in the power transfer with shifting position of secondary coil [73].

The reason for change in power transfer is because all transmitter pads connected in phase with series connection. Hence this indicates that, all the time exited current runs through both the coils and "Fountain" of magnetic field generated by each coil and that field returns over by gap between coils, as shown in Fig. 19. In literature [74], the derived equation is for energy transfer and shows the effect of moving EV(DD coil) on lumped track.

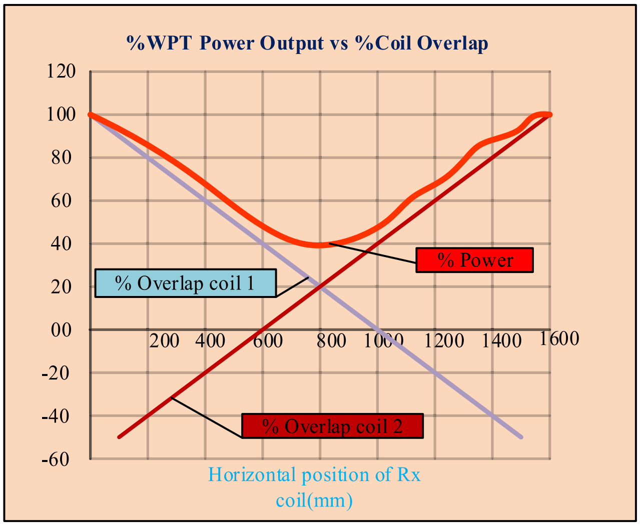


FIGURE 18. Primary to secondary power transfer while moving one coil to another [73].

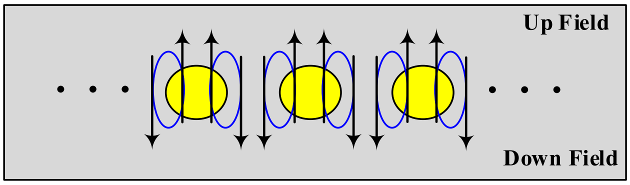


FIGURE 19. Magnetic field reversal in moving pick up coils [73].

This effect of moving EV (DD coil) on lumped track, it is derived as,

$$E = \frac{1}{U}\int_{0}^{D} [M_b(x) + M_a(x)]^2\, dx \tag{18}$$

where U speed of the EV, D is distance between coils, M_a, M_b mutual inductances.

According with equation (18), velocity of EV is inversely proportional to the energy transfer between coils. Although EV speed doesn't affect the total energy transferred in a time particular interval.

III. MAGNETIC COUPLER

A. MAGENTIC COUPLING PAD

In RIPT system, magnetic coupler is the basic and important part. Magnetic coupler made up of transmitter coil, receiver coil and shielding. Transmitter and receiver coils exchange power through an air as a medium and shielding controls flux distribution. Coupling pads are mostly used in SWPT system [44]. Initially, traditional transformer structures like 'E' core [75] and 'U' core [75] are investigated for IPT system. Because of their high cost, fragile, heavy weight and sensitive to misalignment nature researchers proposed pad shaped structures, which are less weight and size compared to traditional transformer cores.

The performance of the coupling pads is depending upon the coupling factor (k), quality factor (Q) and misalignment tolerance. For that different type of coil designs/shapes proposed by researchers. Magnetic couplers usually made up of Litz wires to reduce losses due to skin effect. Ferrite cores used for proper flux guidance, which increases the mutual inductance, minimizes leakage inductance and also provides shielding. The kQ factor depends upon the geometry of coil, core material, and the distance between two coils.

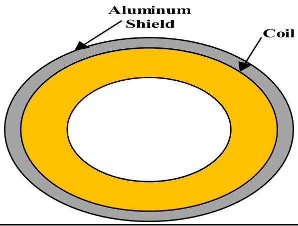
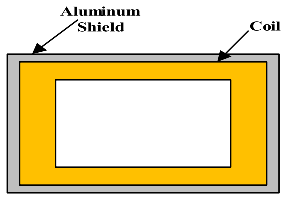
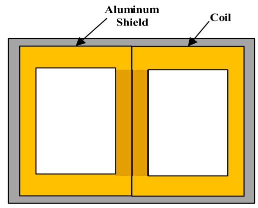
Planar pad structures were proposed in [76]–[80]. In these structures, the core, coil and shield are designed and arranged in a way to minimize volume and weight of the pad, and misalignment tolerant in all directions, which are very important features of a WPT system. Planner pads are classified into two types based on the coupled flux component: Non-Polarized Pads (NPPs) and Polarized Pads. (PPs). Non-polarized (NPPs) is defined as a single coil with vertical flux components to be coupled with the receiver coil and transfers the power. Example: circular pad (CP) and rectangular pad (RP). Polarized (PPs) pads: generate vertical and horizontal flux components and both are coupled with the receiver coil and responsible for power transfer. As an example: double-D (DD), double-D quadrature (DDQ) and bipolar (BP) pad. Introducing intermediate coils enhance the power transfer between the source and load [81]–[85].

At the primary-side coil, intermediary coil could be placed in a same plane to improve load variance operation, misalignment tolerance, efficiency and co-efficient of coupling, which is also called as coplanar coil. [86]. Similarly other multiple coil couplers are designed by many researchers to increase the efficiency and tolerance to variance in load resistance [29], [81], [87]–[90]. In a transmitter and receiver set, a third coil added to improve the efficiency of the system, flexibility to load variations. If source coil kept close to the transmitting coil, which lowers the coil efficiency. Co-efficient coupling of the coil is improved by adding the coil on receiver side and increase in transfer and distance and overall efficiency. Adding coil may induce bifurcation phenomenon, while designing the coil extra carefulness and complicated process need to be followed.

Similarly four coil structures is designed to improve the co-efficient of coupling and misalignment. Compensating with elements LCL and LCC makes the magnetic coil efficient and compact [89]–[94]. A hybrid solenoid coupler introduced in [95], for reduce leakage losses and increase tolerance toward lateral misalignment. For similar cause a Unsymmetrical coupling structure is introduced in [96]. In literature [97], new DDC pad was introduced which is showing better performance than the DD pad.

By using three phase system in pads increases power transfer density. Provides uniform flux and improves transmitting distance. Three phase system advantageous over single phase system. In three phase system to increase power transfer density and to achieve balanced inductance and electrical balance a trifoliate coil introduced in [98]. This structure powered by single three phase inverter.

TABLE 5. Comparison of single sided coils-1.

Single sided coils			
Pad Structure	**Circular (CP)**	**Rectangular (RP)**	**Double-D (DD)**
View			
Misalignment	Poor	Moderate	Moderate
Magnetic flux	one sided	one sided	one sided
Shielding impact	weak	Moderate	High
System complex	simple	simple	simple
Charging zone	Small	Small	Medium
Distance	Low	Low	Medium
air gap	Non-Polarized	Non-Polarized	Polarized
Interoperability	Very poor	Very poor	Non-interoperable with NPPs
Commonly used as	Transmitter	Transmitter and receiver	Transmitter
Flux leakage	High	Medium	Extremely low
# coils	1	1	2

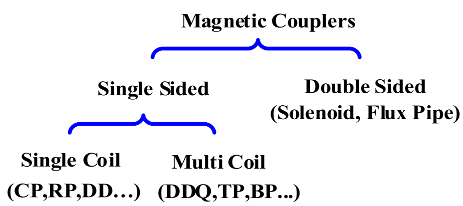


FIGURE 20. Classification of inductive pads.

Three-phase for DWC system introduced in [99], which gives power to a 1.2-meters long test track made up of six square coils. That gives Longer charging zone for dynamic charging system. In article [100], a tripolar pad with decoupled coil structure introduced, each of the coil in it exited separate inveretr. This structure gives better performance in tesrms of cross-coupling and flux density compared to trifoliate coil and drawback is, it needs more power electronic infrastructure. In the article [16], three phase bipolar coil introduced. This structure has capable of transferring high power with high density and usable in heavy duty applications. Disadvantage of this coil structure is heavy, costly and high translational crosscoupling inductance. Single and three phase system compared in [101], Proposed three phase system has more efficient and uniform power, and it requires small DC link compared single phase system [102]. While using three phase magnetic couplers in VSI is best option [98], [100]. In Fig. 20 Pad structures classified in to two types based on flux path and further classified on the basis of number of coils. In many literatures used coupling factor k as the main factor to assess the different designs [103]–[105]. Some of them used kQ as the criteria [106]. Ahmed et al compared most of the structures based on his knowledge. The comparison was achieved, considering several factors, such as shape, coupling performance, misalignment tolerance, shielding, polarization, interoperability, magnetic flux, and charging zone [107]. Table 5 and Table 6 compares single sided coils Table 7 and Table 8 compares double sided coils. The dual coupled transmitters with multiple inverters proposed in [108] to achieve high power transmission. In this method transmitting side two decoupled transmitters overlapped with each other and receiver side only one receiver is used. It hardly meets the demand due to design constraints. To resolve this issue dual coupled transmitters and receivers proposed in [109].

B. DYNAMIC CHARGING CONSIDERATIONS

In dynamic charging mode vehicle charges while moving. In this method transmitter coils and its components usually buried under the road, which may be implemented as segmented IPT or long power rail track. In the segmented system each pad have separately powered while EV moving on those pads there power supply switched on [47], [110]. secondary pads mounted on vehicle chassis.

The long rail track has simple structure and easy distribute power through it. However, it causes extra power losses if secondary coil (vehicle assembled) not able to cover the entire track. The power range required for the power rail is several watts to kilo watts and mainly depends on the magnetic power transfer capability of coupler magnetic properties. The Table 9 shows rating and shape of power rail constructed by using magnetic pads. Segmented power rail proposed to reduce leakage EMF and wastage of energy [47], [110], [113]–[115]. These are consisting of

TABLE 6. Comparison of single sided coils-2.

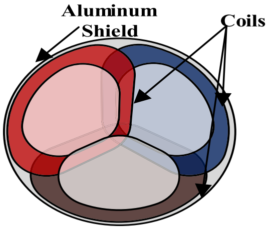
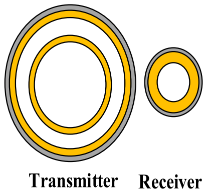
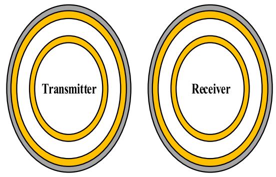
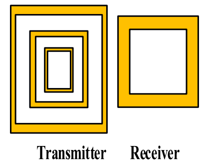
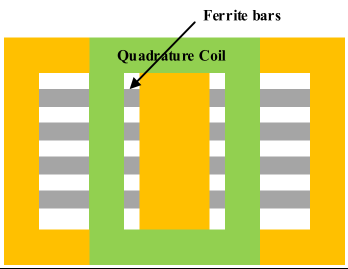
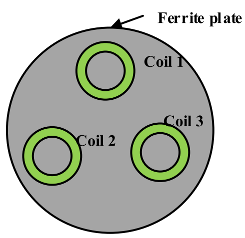
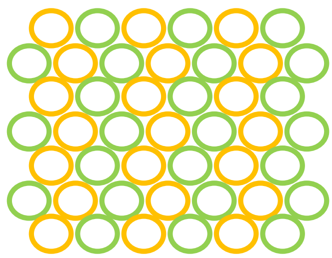
Single sided coils				
Pad structure	**Tri-polar (TP)**	**Dual transmitter-one receiver**	**Dual transmitter-Dual receiver**	**Multi transmitter-one receiver**
View				
Misalignment	Very good	Good	Very good	Very good
Magnetic flux	One sided	One sided	One sided	One sided
Shielding impact	Low	Low	Low	Medium
System complexity	Complex	complex	complex	complex
Charging zone	Large	Medium	large	large
Distance	High	Small	Medium	High
Polarization	Polarized	Non-Polarized	Non-Polarized	Non-Polarized
Interoperability	High	Medium	High	High
Commonly used as	Both	Transmitter	Both	Transmitter
Flux leakage	Low	Low	Low	Medium
# coils	3	2	2	3

TABLE 7. Comparison of double sided coils-1.

Double sided coils			
Pad structure	**Double-D quadrature (DDQ)**	**Poly-phase**	**Homogeneous pad (HP)**
View			
Misalignment	High	High	Good
Magnetic flux	Double sided	Double sided	Double sided
Shielding impact	High	Medium	High
System complex	complex	complex	complex
Charging zone	Large	Large	Large
Distance	High	Medium	Medium
Polarization	Polarized	Polarized	Polarized
Interoperability	High	Medium	Poor
Commonly used as	Receiver	both	Transmitter
Leakage flux	Extremely low	Low	High
# coils	3	3	more than 1

many sub rails operated by centralized power supply. This method requires lot of cable. To reduce that, distributed switching supply system was proposed [79]. To further decrease the cable length Cross-segmented power supply rail was introduced, which minimizes expenditure of the cable to half, and offers high efficiency. The more information is segmented, and long rail tracks are discussed in lateral sections.

TABLE 8. Comparison of double sided coils-2.

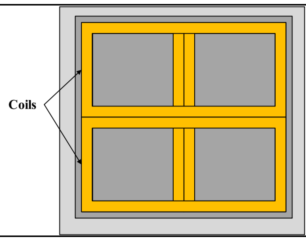
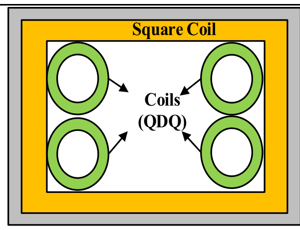
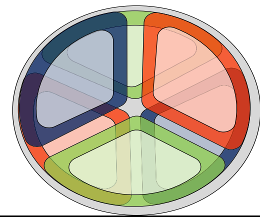
Double sided coils			
Pad structure	**Quadrupole**	**Quad D Quadrature (QDQ)**	**Bipolar three–phase double layer coil**
view			
Misalignment	High	High	High
Magnetic flux	Double sided	Double sided	Double sided
Shielding impact	High	Medium	Low
System complex	Complex	complex	complex
Charging zone	Large	Large	Large
airgap	High	High	Medium
Polarization	Polarized	Polarized	–
Interoperability	High	High	–
Commonly used as	both	both	both
Leakage flux	Low	Low	Low
# coils	4	5	6

TABLE 9. Some of researchers/organizations used magnetic pad as power rail.

Organization/ Article	Rail Structure	Power Rating	Frequency	Track Length
[111]	Rectangular	2-kW		
[112]	Meander-Type	5kw	20kHz	10.8 m.
Qualcomm HALO[22]	Rectangular	20 kW	85kHz	100m
ORNL[22]	Rectangular	6.6-7.8kW	22-144kHz	
Polito[22]	Rectangular	50kW	85kHz	700m
ORNL	Circular	2kw	22 & 48kHz	

TABLE 10. KAIST (OLEV) DWC comparison [116], [117].

Parameters	1G	2G	3G	4G	5G	6G
Shape of rail	E	U	W	I	S	coreless
Rail Width(cm)	20	140	80	10	4	N/A
Leakage EMF	10	51	50	15	<10	N/A
Air gap(cm)	1	17	20	20	20	10 - 30
Lateral Misalignment (mm).	0.3	20	15	24	30	N/A
Efficiency (%)	80	72	71	74	71	N/A
Power output(kW)	3	5.2	15	25	22	3.3

Commercially DWPT system is not yet implemented. Most of the research are done at the institution level, such as KAIST, ORNL, Auckland University and many more.

OLEV (KIAST) has went through six generations of advancement and solved several problems in the way of development. Such as low EMF characteristics, misalignment tolerance, reducing the construction cost. They worked on 24 m, 60m, and 240m length tracks. In each generation they introduced different rail structure as shown in Fig. 21 Comparison of OLEV (KAIST) generations are presented in Table 10 and their features are shown in Table 11.

ORNL team developed DWC system with 6 circular coil track for GEM EVs. Main aim of this project is to smooth pulsation on In-vehicle and grid side. To reduce the pulsation, LiC (lithium capacitor) used on grid side and ultra-capacitors used on In-vehicular side [118].

AU worked on roadway powered system having large segmented primary track with independent individual charging section to control multiple EVs charging [119]. In this method a double coupled system with varying frequency capability without inducing unwanted VA power to the supply. However segmented track has issues like complex control, High maintenance cost and complex power distribution architecture.

Optimization DWC system mainly concentrates on the power optimization, segment allocation and pad length. From the equation (1): we know that mutual inductance of the system depends on speed. In [120] to obtain the appropriate primary pad length, the researchers studied primary pad mutual inductance with secondary pad with different sizes. In literature [121], authors find out that optimum length of the pad doesn't influenced by the speed of vehicle when one vehicle/one pad charged and optimum length of the pad decided as 3 meters by average coupling coefficient. The charging power optimization is similar to SWC Segmentation optimization techniques are studied later in the paper sections.

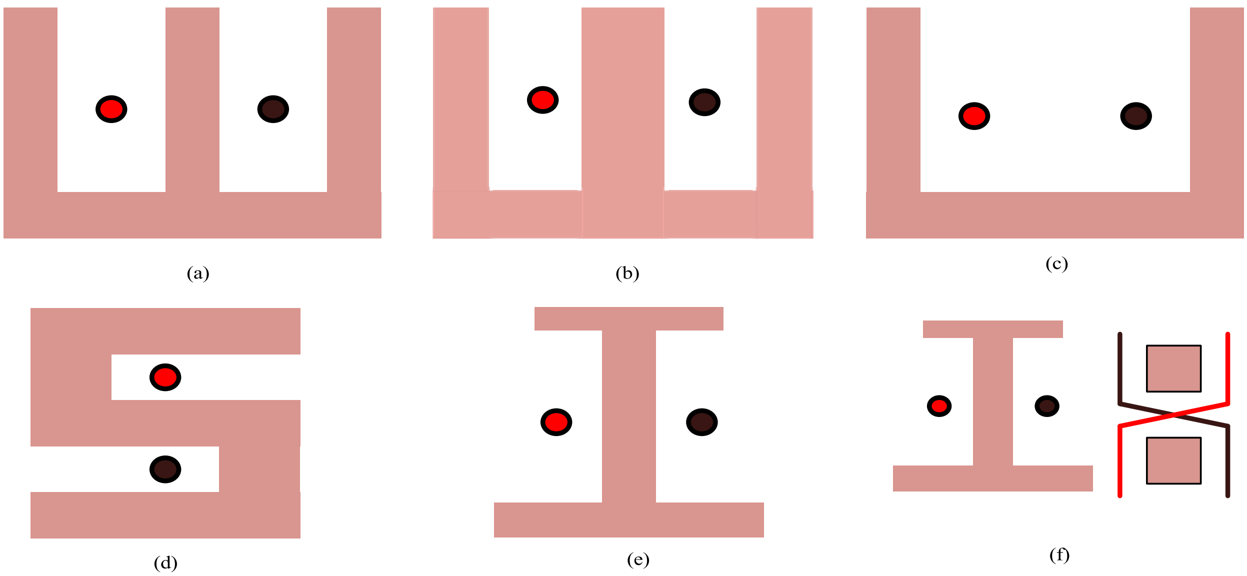


FIGURE 21. Power rail basic shapes (a) E-type. (b) W-type. (c) U–type. (d) S-type. (e) I–type. (f) Cross-segmented structure.

TABLE 11. Power rails and there features [116].

Power Rail	Features
E-type	• Simple design. • Manufacturing cost is low
U-type	• Higher efficiency • Large air gap • Reduced EMF.
W-type	• Many W shaped cores for a structure arranged for particular interval. • Reduced magnetic resistance compared to u shape. • Higher power output. • High co efficient of coupling. • Shielding doesn't required. • Reduced width compared U shape.
I-type	• Reduced cost up to 20%. • Reduced manufacturing time. • Less EMF due to its positioning. • Width of the rail reduced. • Increased power output.
S-type	• Reduced cost with respect to I.
Ultra slim S-type	• Reduced cost with respect to S. • Reduced width. • Low leakage flux.
Cross segment S-type	• Higher efficiency. • Low leakage EMF. • Reduced cost of cable due to common power supply.
Coreless	• Lower cost than the remaining structures. • Requires Less insulation • Power loss due to core is less. • Good Lateral Misalignment tolerance

C. SHIELDING

The most significant problem of RIPT system is leakage EMF, which can affect the surrounding material and living things. The design of EV charging structure must compliant with international standards to reduce leakage EMF to allowable levels as mentioned in the Table 4. Shielding is method refers to placing some metals under the coils to restrain the leakage EMF. As shown in the Fig. 22, the shielding procedures categorized into: passive shielding, active shielding, and reactive resonant shielding.

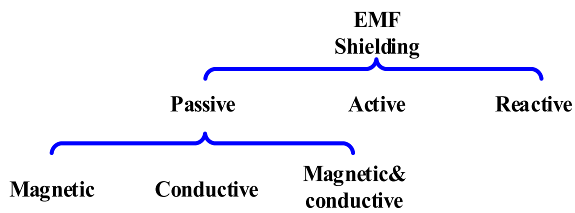


FIGURE 22. Classification of EMF shielding.

1) PASSIVE SHIELDING

To reduce or block the leakage flux by adding passive components (conductor or magnetic) to the system. Magnetic passive shielding are done from materials which are non-conductive and high permeability, to direct flux in particular path to enhance self and mutual inductance by increasing the system performance and reducing the leakage flux [122], [123]. The magnetic shield is achieved by magnetic core (ferrites) installed in the pad. Although using ferrites system the performance increases but it also increases weight and cost. Magnetic loop around the coil is minimizing the leakage flux, as was proposed in [123]. This method can reduce the emission by 60%, by considering matched DD. There is another method for minimizing the magnetic materials in the system for flux controlling. This is done by combining conductive and passive shielding, which is the trend in IWPT systems.

2) CONDUCTIVE PASSIVE SHIELDING

This method depends on Faraday and Lenz's law. When we place conductive material (aluminum plate) in the presence of alternating magnetic field induces currents (eddy currents) on it (faradays law). Due to the inductive nature of the material, a new magnetic field is generated by the Eddy currents. Which is in the opposite direction of original magnetic field. It tries cancel original flux in opposite direction (Lenz's law). This helps to the lower the net field around the system (conductive shielding). Drawbacks of this method is large magnetic field loss on metallic plate and eddy currents can't be controlled., it adversely effects on system performance by reducing efficiency 1% - 2% and temperature generated by eddy currents on the plate. For that suitable material should be chosen for coil design to resist these temperatures. Many researchers have proposed different methods with changing conducting plate, shape and position [106], [124]–[128]. some of the applications vehicle chassis taken as conductive material for shielding [129]. Normally conductive shielding applied with ferrites to improve the magnetic field around the coils so it is called conductive passive shielding. As per SAE J2954 recommended dimensions for aluminum back plate is 800mm × 800mm × 0.7mm, applicable for the power ranges WPT1 to WPT3.

3) ACTIVE SHIELDING

It is difficult to manage leakage EMF in the high power applications by using conventional passive shielding [130]. In this case extra turns(shielding turns) wounded in reverse direction to create a magnetic field in a reverse direction to the original magnetic field created by coupler to minimize the leakage field [130], [131]. This method requires extra power source for the shielding turns. Main challenges in this method is positioning and sizing of shielding coils, control system needed for the controlling current flowing through the shielding coils. This method shows effectiveness compared by passive shielding method. However, because of the impact on original field system performance is affected. In addition, adding extra turns and power source makes power loss in the system. Furthermore, cost and weight of the system increases [132]. compared to above methods field opposite field can be controlled properly.

In [133], shielding with multiple coils and design procedure of their independent feeding is proposed to limit the EMF in critical areas and hence compliance with ICNIRP guidelines. In this method four independent active coils placed at the sides of the transmitter and receiver coils.

4) REACTIVE SHIELDING

In this method extra reactive elements (capacitor) and turns are added into the system No need of extra source to induce field in the shielding turns. By using original magnetic field to current induced in a shielding turns. Current flowing in shielding turns creates opposite magnetic field to oppose leakage flux. Magnetic field depends on the resonant capacitor and number of turns added. Opposite field can't be controlled as active shielding method and needs more current in shield coil [134].

Passive shield method is effective in low- and medium-power IPT systems (<100 kW) and they are able to suppress EMFs levels to be below the safety limits. In addition, they are cheaper, simpler in implementation and more robust [122]. For high-power IPT systems, active and reactive shielding are more promising for the system to comply with standards.

Adding ferrite cores (Passive Shielding) will improve the system efficiency by reduce leakage inductance at some extent but it alters the value of inductances system performance. It means that the inductance value must be readjusted. Aluminum shielding or metallic shielding decreases system performance but it also significantly reduces EMF level. Reactive shielding improves EMF leakage suppression compared to metallic shielding. However, the position shielding loop and shielding impedance need to be carefully considered.

IV. COMPENSATION NETWORKS

The compensation is playing a major role in the resonant inductive power transfer system. To reduce VA rating of the system when coupling co efficient decreases less than 0.3. compensation at both sides needed to have flexible and good working characteristics. Due to the network design, parasitic capacitance will not resonate enough or compensate the system. Therefore, additional reactive elements (capacitors or inductors), to adjust the operational resonant frequency.

Basic compensation can be achieved adding one capacitor in series/parallel this compensation can be called as mono-resonant topology. There are other compensation techniques works on more than one reactive element referred to as multi-resonant compensation. However improper compensation causes higher reactive current. Higher reactive currents cause more semiconductors loses and conduction losses, particularly on inverter side.

Other main objectives of the compensation are:

- Minimizing reactive power;
- Achieving soft switching operation.
- To avoid bifurcation;
- Making system high misalignment tolerant;
- To achieve low cost, compact design and bifurcation tolerance;
- To achieve high efficiency.

Voltage source inverter can directly connect to a series compensated transmitter coil. For parallel compensated coil an inductor introduced to change inverter into current source inverter. The secondary compensation done to minimize the VA rating of the coil. Constant current output from a transmitter coil can be modified as voltage source, by making secondary as a series compensation. Similarly parallel compensation at secondary makes current source [59].

To reduce VA rating of the system achieving Zero Phase Angle (ZPA) condition is necessary. For that current and voltage should be in phase. This can be achieved by tuning the primary capacitor at particular load and coupling condition. Similar, primary side compensation tuned to achieve Zero

TABLE 12. Primary capacitance and bifurcation condition for basic resonant topologies.

	Primary Capacitance	Bifurcation
SS	$\frac{1}{\omega^2 L_p}$	$Q_p > \frac{4{Q_s}^3}{4{Q_s}^2 - 1}$
SP	$\frac{1}{\omega^2 L_p \frac{M^2}{L_s}}$	$Q_p > Q_s + \frac{1}{Q_s}$
PS	$\frac{L_p}{\left(\frac{\omega^2 \cdot M^2}{R}\right)^2 + {L_p}^2 \omega^2}$	$Q_p > Q_s$
PP	$\frac{L_p - \frac{M^2}{L_s}}{\left(\frac{R \cdot M^2}{{L_s}^2}\right)^2 + \omega^2 \left(L_p - \frac{M^2}{L_s}\right)^2}$	$Q_p > Q_s + \frac{1}{Q_s}$

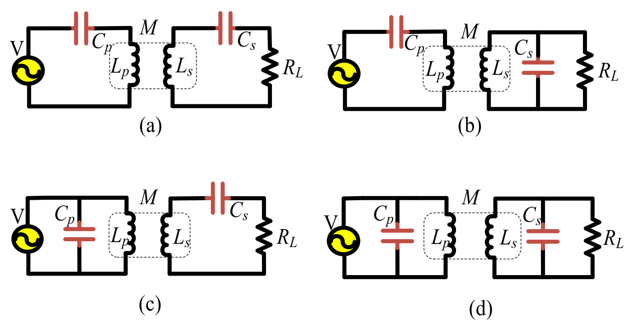


FIGURE 23. Basic compensation structures a) SS b) SP c) PS d) PP.

Current Switching (ZCS) or Zero Voltage Switching (ZVS) by keeping small amount of reactive power [135]–[137].

For compensation topologies, tuned to resonant frequency which is also the ZPA frequency, it is very common that this resonant frequency to be divided into multiple resonant frequencies due to sudden changes in some parameters. This phenomenon known as bifurcation in the RIPT system and the parameter which causes this phenomenon to occur is known as the critical parameter. Bifurcation causes changes in electrical parameters. It may cause damage to the electronic components. Conditions to avoid bifurcation phenomenon in basic compensations is given in the Table 12.

A. MONO-RESONANT COMPENSATION NETWORKS

As per connection of capacitor we get four compensation topologies. They can be addressed with two letters as per the series/parallel connection. First letter indicates primary side connection and second letter indicates secondary side connection. as shown in the Fig. 23. Those are Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS) or Parallel-Parallel (PP).

A secondary side quality factor Q_S needed to calculate to get primary compensation. For series compensation $Q_S = w_0 Lp/R_L$, for parallel compensation $Q_s = R_L/w_0 Lp$ where ω_0 indicates resonant frequency. Quality factor is ratio be4tween the reactive and active power. Table 12 shows the primary capacitances of basic compensation techniques.

In common applications, SS and SP compensations implemented, because they provide good efficiency. The advantage of SS and SP compensation is capacitance value doesn't depend on load variation. In addition, SS compensation is primary capacitance doesn't depend upon coupling coefficient. This condition is very useful in DWPT, because Independent nature on the coupling coefficient, makes less sensitive to the misalignment. On the other hand, SP compensation depends on coefficient of coupling and primary capacitance value needs to be larger for a strong magnetic coupling [59], [138]. In SP topology, the primary side transferred impedance is square of mutual inductance. Due this condition implementing DWC is very difficult.

Two other topologies PP and PS are capacitance values, depends on the coupling co efficient and load resistance. These systems driven by current source converters. PP topology needs higher primary capacitance value compared PS topology [59].

The PF for the SS compensation is unity and high efficiency for the low coupling coefficient. The main setback of the SS topology happens at light loads, in the absence of receiver and equivalent impedance becomes zero at the resonance frequency, in this condition current is limited by parasitic impedance [116], which leads to unsafe operation. On the other hand, SP compensation depends on coefficient of coupling and primary capacitance value needs to be larger for a strong magnetic coupling [59], [138].

Two other topologies PP and PS are capacitance values, depends on the coupling co efficient and load resistance. These systems driven by current source converters. Due to their symmetry, SS compensation secondary side's eases the development of similar control topology is a common option bidirectional wireless chargers. The Table 14 presents the total impedance of four topologies. From the paper [139], mutual inductance between two coils can be expressed as,

$$M = \pi \mu_o r^4 N^2 / 2D^3 \tag{19}$$

where, μ_0 is the permeability of vacuum, r is the radius of the coils, N is the number of turns, and D is the distance of two coils, which are coaxial.

Transferred power to the load given by,

$$P = (w_0 M^2 Q_s)/Ls * I_p^2 \tag{20}$$

Misalignment reduces the mutual inductance, results change in total impedance of the system. From equation (19) and (20), power transfer directly proportional to transferred power and as per basic efficiency formula output power increases efficiency increases. Basic compensations and there relation with misalignment to the mutual inductance and total impedance, mutual inductance to transferred efficiency and transferred power shown in Fig. 24. In the SS and SP compensation, as current increases to the load, the total impedance decreases. In the PS and PP compensations, as misalignment increases the total impedance also increases, instigating a rapid fall of both currents [141]. The PS and PP compensations at low mutual inductances offers relatively

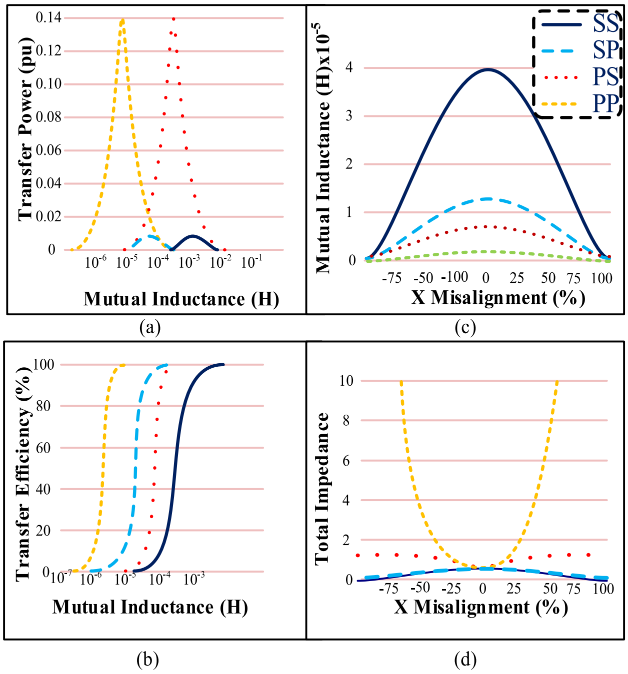


FIGURE 24. Basic topologies: behavior mutual inductance to a) transferred power; b) efficiency, misalignment to c) mutual inductance; d) of total impedance [139], [141].

high PF and High efficiency and a relatively large range of the mutual inductance and load variation [121], [139]. The PP topology suffers from low PF, parallel secondary need high voltage loads and parallel primary needs high current source [142]. Series compensation at secondary side (SS or PS), achieves smaller average primary input impedance compared to parallel compensation at secondary side(SP or PP) [143]. comparison of basic topologies presented in Table 13.

According to [144], the copper utilization of basic compensation techniques for 200kW are in the order of SS < SP < PP < PS. The SS compensation needs least amount of copper and SP slightly more than that. PP and PS compensation requires more copper compared to SS compensation. Although PS compensation needs less operating frequency because of the higher required current and lesser operating frequency. Hence, SS and SP topologies are appropriate for high power application in view of cost.

B. MULTI-RESONANT COMPENSATION NETWORKS

Basic compensation techniques are suitable for the ideal conditions. Due to the factor like misalignment, frequency deviation etc. makes WCS application never function at ideal conditions. Using multiple elements in series-parallel combination makes effective compensation method to overcome challenges of basic compensations. Some multi resonant compensation topologies shown in Fig. 25.

The multi resonant compensations like LCC-LCC, LCL-LCL etc., over their full range of loading and coupling offers high efficiency [145]. However, additional elements may cause more losses to compare to mono resonant compensation, particularly for high power applications. The advantages of LCL compensation is works as a current source, provides harmonic filtering capabilities, and offers high efficiency [145].

In literature [146], authors compared hybrid LCL compensations: LCL-S, LCL-P and double LCL, particularly their load characteristics, observed presented similar characteristics as LCC. The short circuit is undesired for the LCL-S topology at the risk of large secondary side current. In literature [147], a boost converter cascaded with LCL-P compensation, In this application, Primary compensation reflected as current source to connect a boost inductor. LCL-S and LCL-LCL topologies provide constant voltage and current output respectively, ZPA is achievable. In [148], LCL-S applied to modified coil design to achieve load independent operation and field enhancement. When it compared with LCL-LCL topology delivered same power with less number of inductors [148].

LCC compensation with four current mode operations proposed in [89], which is having same features of LCL topology and offers high efficiency, less weight and low cost. Zhou *et. al.* [149] applied LCC compensation topology for DWC, to reduce the EMI and decrease the power loss on the system. In article [90], double-side LCC(LCC-LCC) compensation topology presented with ZCS application and provides constant current when input voltage becomes constant. In addition, the LCC forms a UPF pick up by compensating reactive power. This method is independent on the co-efficient of coupling coefficient and load conditions [89], [150]. This topology is popular because of the characteristics like high misalignment tolerance, high efficiency and load independence characteristics [89], [90], [150]–[152].

In [153], the comparison between S-LCC, LCC-S and LCC- LCC is done. The LCC-S shown good performances in terms of efficiency, over a wide load variation. For the S-LLC and LCC topologies, optimal operation, in terms of efficiency, can be achieved over a shorter load span compare to other two. Nevertheless, the voltage stress across the compensation network components is generally lower. In article [137], mathematical analysis for LCC compensation was done to get ZCS operation and compared with ZPA operation. ZCS operation have less switching loses than the ZPA operation. Drawback is it needs higher currents.

In articles [154], [155], authors proposed a new compensation topology LCCL compensation. Compared to SS compensation, maximum power transferred by the LCCL topology. Furthermore, this scheme produces high power transfer levels at high efficiency and coupling co efficient.

In literature [156], double sided LCCL was presented. In this method, at calculated frequency, constant current from primary coil achieved.

The SP/S compensation proposed in [141], which offers combine characteristics of SS and SP compensation. Allows higher position tolerance. The disadvantage is declining coupling conditions causes increase in the reactive power.

TABLE 13. Comparison of basic compensation topologies [140].

Property	SS	SP	PS	PP
Dependency on load(R_L)	• Primary and secondary capacitances are Independent on load	• Secondary capacitances are dependent on load	• Primary capacitance are dependent on load	• Secondary capacitance are dependent on load
Dependency on coupling factor(k)	• Primary and secondary capacitances are Independent on coupling factor	• Secondary capacitances are dependent on coupling factor	• Primary capacitance are dependent on coupling factor	• Secondary capacitance are dependent on coupling factor
Function	• Voltage source v	• Voltage source	• Current source	• Current source
VA rating	• Large at input	• Large at input	• Low at input	• Low at input
Load independent output	• Voltage And Current	• Voltage And Current	• Voltage	• Current
Reflected reactance	• Zero	• Depends on frequency	• Zero	• Depends on frequency
Copper requirement	• Lower than all results in less weight	• Slightly more than SS	• Higher than all results in more weight	• Slightly less than PS
Sensitivity To Misalignment	• Slightly sensitive	• Moderate	• High	• High
Zero Coupling Tolerance	• Not Permissible	• Permissible	• Permissible	• Permissible
Inverter device voltage rating	• Needs smaller DC-link voltage needed(higher than SP)	• Needs smaller DC-link voltage	• Higher voltage required as compared to SS and SP	• Higher voltage is required as compared to SS and SP
Inverter device current rating	• Primary coil current	• Primary coil current	• Active component of primary coil current	• Active component of primary coil current
Total Impedance	• Drops with misalignment	• Drops with misalignment	• Increases with misalignment	• Increases with misalignment
EV applications	• Suitable for EV application both SWC and DWC. Bi directional power transfer possible.	• Suitable for EV applications.	•	•
Other Advantages	• Offers better efficiency than SP for frequencies >1MHz • output current doesn't depend on the load, resonant frequency	• Requires smaller receiver coil self-inductance than the SS • Parallel resonant circuit supplies constant current.	• Not seen	• Not seen
Disadvantages	• At partial load condition, load depends on voltage transfer ratio • Needs larger receiver coil • High capacitor voltage because of high current flows through series capacitor.	• Less DC component blocking	• To avoid instantons charge in voltage requires current source • Needs High driving voltage to transfer high power	• Low PF High load voltage • Large current source • High voltage requires for high power applications

In article [157], novel S/SP type compensation was proposed. ZPA of input impedance achieved, which is independent on load change and coupling factor K. This method can achieve both high efficiency and a constant gain at the full resonant frequency, with this method High power applications with wide range operations achievable. [158]. The advantageous and disadvantages of modified compensation topologies is summarized as shown in Table 15.

Normally in WPT system one transmission and one receiving coil will be there. These systems are called as Single-Input/Single-Output SISO. However, in some of the cases multiple coils are used in transmission side and receiver side to increase the maximum efficiency, and to improve sinusoidal wave at a constant frequency. These schemes can be classified as Single-Input/Single-Output (SISO) Multiple-Input/Single-Output (MISO) Single-Input/Multiple-Output (SIMO) as shown in the Fig. 26.

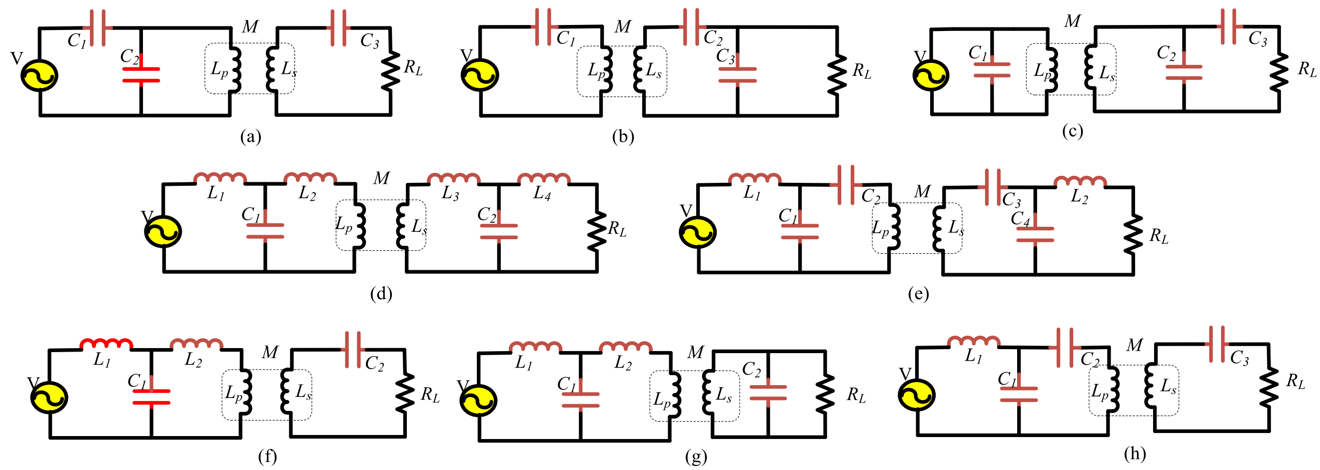


FIGURE 25. Classification of modified compensation topologies structures a) SP-S b) S-SP c) P-PS d) LCL-LCL e) LCC-LCC f) LCL-S g) LCL-P h) LCC-S.

TABLE 14. Total impedance of mono compensation topologies.

Symbol	Equation
Z_{T-SS}	$\left[R_p + j\left(\omega L_p - \frac{1}{\omega C_p}\right)\right] + \frac{\omega^2 M^2}{\left[R_s + R_L + j\left(\omega L_s - \frac{1}{\omega C_s}\right)\right]}$
Z_{T-SP}	$\left[R_p + j\left(\omega L_p - \frac{1}{\omega C_p}\right)\right] + \frac{\omega^2 M^2}{\left[R_s + j\omega L_s + \frac{R_L}{1 + jR_L C_s \omega}\right]}$
Z_{T-PS}	$\frac{1}{(R_p + j\omega L_p) + \frac{\omega^2 M^2}{\left(R_s + R_L + j\left(\omega L_s - \frac{1}{\omega C_s}\right)\right)} + j\omega C_p}$
Z_{T-PP}	$\frac{1}{\frac{1}{(R_p + j\omega L_p) + \frac{\omega^2 M^2 (1 + jR_L C_s \omega)}{(R_L + (R_s + j\omega L_s)(1 + jR_L C_s \omega))} + j\omega C_p}}$

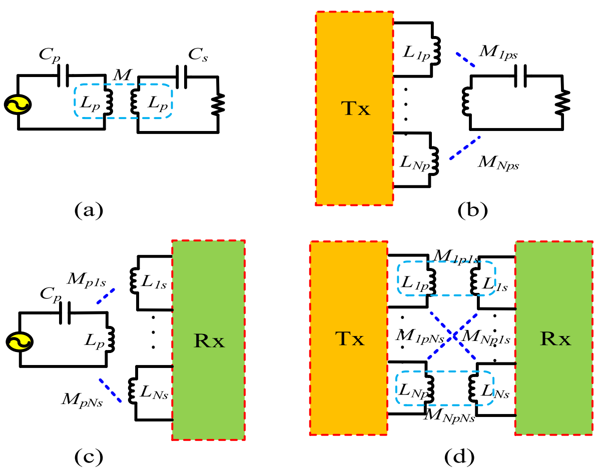


FIGURE 26. Magnetic induction model for IPT: a) SISO; b) MISO; c) SIMO; d) MIMO.

A WPT system with three coil S/S/S compensated proposed to achieve the CV characteristic [159], three coil S/S/LCC for CC characteristics. Both of these systems can Zero Phase Angle (ZPA). MISO systems mostly used DWC applications [160], [161].

SIMO systems is used to charge multiple coils at a specific time [162]. This scheme applied in maglev train [163]; for the V2G applications cascade IWPT converters with 3 coils LCL compensation presented in [164] and 3-coil SSS compensation with load isolation presented in [165].

In MIMO is multiple coils used in the transmitter and receiver is known as MIMO system and it is used for increasing the magnetic communication range [166].

The cross inductance coupler coils is low. In article [167] LCL-T topology to achieve maximum power transfer efficiency a parallel inverter. In MIMO system the transmission and receiving frequency should be maintained very precisely. The point-to-point efficiency in the MIMO system is obtaining very difficult due to the inter coupling between receivers and transmitters. According to the article [168], the MIMO technology used in communication technology and mobile charging applications, MIMO in EV still need to be explored. Establishing coupling in MISO or SIMO easier compared to MIMO system.

In some of the applications like dynamic charging relative position between coil changes because of misalignment or working method of the system, causes changes in the coupling factor. Since coupling factor effects the both leakage and magnetizing inductances. In this condition achieving compensation is very difficult. Hence the researchers came up with position tolerant compensation methods. To get more stable output, LSS and SS combined to get power stability, compared to single compensation technique [169], [170]. Mostly position tolerant systems used in DWPT systems.

V. POWER ELECTRONIC CONVERTERS FOR WPT

In WPT system power electronics plays a vital role. Furthermore, in order to improve the power transfer capacity, generating a high frequency is required. These operations

TABLE 15. Comparison of modified compensation topologies [140].

	LCL and its variants	SP/S	S/SP	LCC and its variants
Advantages	• Provides high efficiency over the full range coupling of and loading • Maintains high efficiency at low quality factor • Reduced VA rating • Lower losses in the pickup winding and rectifier	• Constant output power for high misalignment • Higher position tolerance than SS topology	• Gain value doesn't depend on coupling coefficient and change in load • Low circulating losses than SP under wide range	• At time ZCA and ZPA operation possible • Does not depend on coupling co-efficient and lad conditions • Current stress on the inverter reduced and compensate a reactive power on the secondary side. • Miss alignment tolerance
Dis Advantages	• Primary side transfer impedance contains both imaginary and real parts of the load if load is parallel compensated	• Reactive power surges with diminishing coupling conditions	• No data	• Complex tuning
Size and Cost	High	Less	Less	Less cost and size compared to LCL

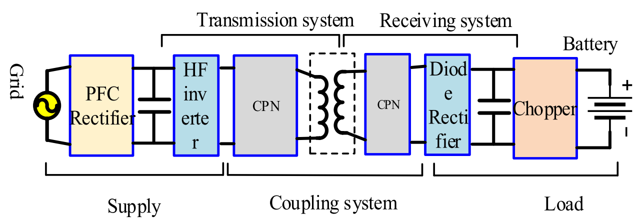


FIGURE 27. Power conversion architecture of WPT system.

carried out by the power electronic converters. Basic power electronic architecture presented in Fig. 27. WPT system reliability, control and efficiency depends upon the performance of converters. In general WPT system consists of two parts, first one to create high frequency and second one converting high frequency to usable frequency or DC. In first part grid voltage(50/60Hz) is converted to DC using PFC or rectifier and the DC signal inverted HFAC by using HFI. Second part consists of rectifier to HFAC to DC. Additional DC-DC converter may require for addition voltage control. While designing WPT system, maintaining level of THD values recommended by IEC1000-3-2 and IEEE-1547should be considered [171], [172].

The power transfer level and operational methods decides power electronic architecture and topologies. Other factors like cost, weight, flux leakage and switching losses also effects the Outcome. The power converters is classified in the WPT system based on number input phases to coupler and unidirectional or bidirectional power flow.

A. SINGLE PHASE SYSTEM

Single phase WPT system is the most common type of converter used in wireless charging system. It could be made up of controlled or uncontrolled converters with a Voltage/current source. Secondary side different type of bridges used depends upon the application, power capacity and direction [173]–[175]. For high power applications three phase rectifier used in grid side. Although, single-phase wireless charging system covers all power ranges mentioned by J2954. Single phase system has simple construction and control.

A good commutation network and a gate driving method is essential to handle the load allocation and reliable operation. To improve power handling capacity, in literature [33], three power semiconductor devices paralleled to share the current stress and reduce the on-state resistance. Using of SiC MOSFETS minimizes the threshold gating voltage. Parasitic sensitivity parameters makes attention design procedure. Current-source converter has advantages over voltage fed system, such as short circuit protection, higher reliability and lower circulating current [176]. Due large inductor in input, the weight, size and cost of the system increases. Which indirectly effects system efficiency. While designing Compensation, current characteristics should be considered, which makes system design complex.

B. POLY PHASE SYSTEMS

To overcome the single phase system draw backs, poly phase systems are developed. Especially three phase system provides higher power transfer capability, and power density compared to the single phase system. Three phase couplers provide more uniform flux distribution, by that allocated space can be utilized properly and can achieve higher power transfer capabilities. Different flux combination can be generated by using tree phase couplers, which are helpful for achieve different design concepts. Other features associated with three phase rotating magnetic field based WPT system is reduced filters and ferrites mass [16], In literature [99], researchers increased charging zone by using three phase couplers. In [177] and [178], developed misalignment tolerant three phase system for dynamic charging and bi directional charging is developed. poly phase system offers same features of three phase system as number of phases increases complexity increases.

In [16], a three phase bipolar phase winding is adopted to 50 kW wireless charging system. This solution has achieved highest power density so far in WPT systems. This methods shown drawbacks with IPMI in misalignment condition.

Poly-phase topology have the ability to combine multiple coils to increase the power density. Inter phase mutual inductances (cross coupling between phases) is a major concern, which eventually results failure of ZVS operation. Hence, most of the works aimed to reduce the impact of the IPMI [100], [179]–[181]. However, poly phase windings have electrical and spatial phase shift. By using them, it takes the advantage of inter-phase mutual-inductance (IPMI), if the winding are designed in the way to aid the flux of other winding instead of cancellation.

In three–phase track systems, resonant tuning done to balance the IPMI [182]. In article [183], addition ferrites cores added in between phases to achieve proper current balance. In other methods equations derived for the capacitor tuning, by considering IPMI [184], [185]. Therefore, to achieve best operation in three phase system, great understanding modulation index and flux path of power converters required. Compensation needed to design in way that handles cross coupling.

In article [186], a DWC system proposed to drive multiple transmitter coils with single multi-phase inverter with different polarities proposed. This method practically applied to three phase 3kW DWC system achieved efficiency nearly 90% and achieved constant power output. Drawback of this method is short-circuit or failure of one leg causes failure of system. Maintaining inductance in each phase need to study more.

In literature [187], multi-phase WPT system with multi-intercell transformers (ICTs) connected to primary coil and with hybrid control strategy implemented to three phase 1kW prototype. This method achieved ZVS operation for full range of load variation and draw back this system is extra ICT added to increase the weight and cost of the system.

C. MULTI-CELL MODULAR SYSTEM

To alleviate voltage/current stresses on semiconductor switches, multiple converters with low voltage rating connected in series/parallel. This method reduces harmonic density and increases power transmission capacity [188]. Another benefit of this technique is related to the use of conventional power converters, such as full bridge and half bridge converters are readily usable. In addition, by employing this topology of converters, reliability improves due to modular redundancy.

Multiple converters(low-current rating) arranged in parallel are improve the transmitting current of WPT system in [167]. A parallel topology constructed by connecting identical LCL-T is demonstrated to reduce the irregular Power-sharing through parameter tolerance. The robustness and reliability is also improved owing to modular redundancy.

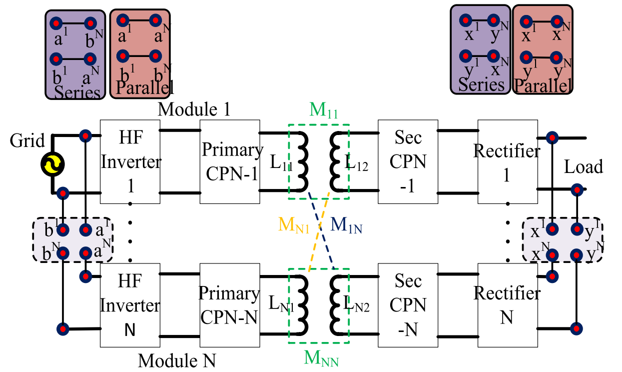


FIGURE 28. Multi modular architecture of two side parallel/series connection.

In literature [189], the authors have investigated a method based on multi inverter modules connected to single coil realize constant control of the track current and minimization of circulating current for RIPT high power systems. In addition, a protection scheme is designed to disconnect the fault inverter unit, which can ensure the whole system to work continuously and so as to improve the reliability as well as availability dramatically.

In [190], an Input-Parallel/Output-Series (IP/OS) system is constructed with two transmission side coils with paralleled inverter connection and secondary-side coils connected to load with series connection. To regulate input impedance of resonant circuit, cross coupling should be considered. Fig. 28 depicts block diagram of the multiple converters cascaded in primary and multiple converters cascaded in secondary connected in parallel/series connections. In literature [24], a 44 kW WPT system with rapid charging is proposed for a transit bus. For that two modules of 22 kW power connected in parallel on both sides (IP/OP). In this method primary and secondary kept at a good distance to avoid cross coupling but mounting on vehicle chassis is costly and difficult.

In article [191], extreme fast charging (XFC) technology is studied considering the charge rates of 300 kW for wireless power transfer (WPT) applications. In this method series and parallel connection of three-phase WPT system are presented by comparing the voltage and current stresses on power electronics active or passive components with multi-level NPC type, series resonant, and star or delta connected three-phase system and simulation results are presented. Considering both voltage and current stresses compared to LCC tuning in conventional and multi-level converters, multi-level series-series tuning circuit shows better performance.

In some of the methods only the primary side multiple converters connected in parallel/series to supply several windings, whereas a single converter is applied on the secondary side. In [100], tri-polar pad with three separate excitation and secondary side CP/DD pad connected as shown in Fig. 29. Dis advantage of this method is secondary side need to bear all losses and load. So this kind of arrangement only useful to perform flexible operation and regulation in primary side and reduce IPMI on one side.

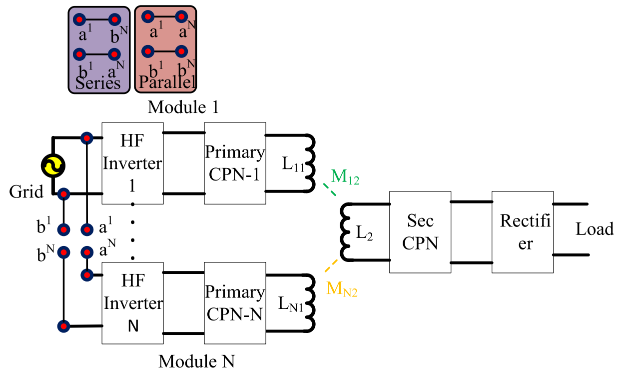


FIGURE 29. Multi modular architecture of primary side parallel/series connection.

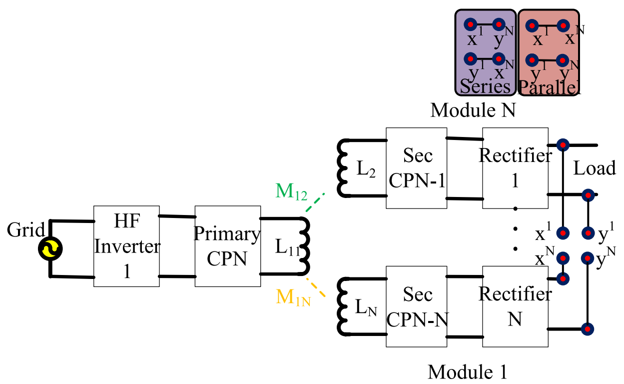


FIGURE 30. Multi modular architecture of secondary side parallel/series connection.

This method reduces complexity in secondary side if we consider multi modular network.

Some researchers used multiple secondary side power units, to facilitate multiple users or coils, as shown in Fig. 30. In literature [192], two rectifiers in receiver side connected to power the DDQ pad. In [193], the N type power rail as primary coil with multiple receiver coils proposed. This method minimized power fluctuation developed by coupling variation.

D. BIDIRECTIONAL INDUCTIVE CHARGER (V2G & G2V)

In literatures [194], [195] bi-directional WPT systems for grid and mobile ESS connectivity are discussed. The proposed method interfaces the EV batteries to the AC grid and also can redirect the power from the stationary ESS to grid, to EV batteries, or both simultaneously;

In [196], a multi-level inverter is studied for bidirectional IPT systems. A phase shifted modulation technique is used between primary and secondary inverter ports in order to obtain maximum efficiency points. The topology is explored with different load conditions at the constant frequency and constant output voltage.

In [197], a phase shift modulation strategy to drive the proposed primary side is presented. A cascaded multilevel converter with minimized switching loss in the switching devices in employed on primary side. In secondary side a single coil receiver is used. Multiple sources can be used for single system. Down side of this technique load on the secondary side increases. In literature [198], multilevel converter used offers simple control, having the advantages like lower switching losses and power scalable operation. The disadvantage this method is, it needs more number of switches and multiple isolated dc voltage sources.

E. SINGLE STAGE SYSTEMS (AC/AC CONVERTERS)

Direct ac to ac converter offers a good replacement to obtaining high frequency power without using a dc link or bulky energy storage elements. As show in Fig. 31, instead of using PFC and HF Inverter, an ac to ac converter is used. The advantages of this topology are to reduce weight, equipment and cost of the system.

A full-bridge current-fed direct ac-ac converter is proposed in [199], which satisfied requirements of wireless topology with ZVS boost operation.

Commonly Matrix converters are used to produce HFAC from grid AC supply [200]–[202]. These converters doesn't required any energy storage elements. Matrix converters with reduced number of switches introduced in [203]. the power rating of the system is low due to high stress across the power semiconductor devices. Hence, this converters not suitable for high power applications.

In literature [204], a three-phase matrix converter proposed with six reverse blocking switches and one regular switch. This topology has advantages like low EMI, soft switching operation achievable. Practical conversion efficiency for low power application is 88%.

A three phase ac input and three phase ac output conversion system with single coil is proposed in [205]. In [206], symmetric ac–ac converter of an WPT system with different control techniques is proposed. Furthermore it offers bidirectional operation. In addition ZCS operation is achieved. In this topology only four switches are used because that stress on switches more. Suitable for low power applications. In [207], hybrid frequency ac/ac converter is proposed for EV charging applications. Furthermore, converter can be operated with constant frequency without requiring closed-loop control.

F. POWER SUPPLY ARCHITECTURE FOR DYNAMIC WIRELESS CHARGING

DWPT is a method to charge the vehicle while moving. DWPT system requires less battery size compared to SWPT, which reduces vehicles cost and weight. In addition vehicles range increases with same size battery [47], [110]. Moving of the vehicle makes the short interaction time between transmitters and receiver for that high power conversion system needed. In addition, should have good misalignment tolerance especially horizontal. DWC design architecture needs careful considerations. Power conversion depends on speed of the vehicle and length of primary coil. Considering that it is unfeasible to change drivers mind and habits, when it comes to speed. Another parameter is length of the track.

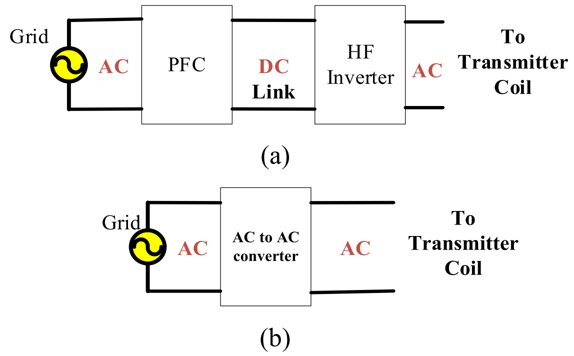


FIGURE 31. AC to AC conversion stages a) two stage conversion b) single stage conversion.

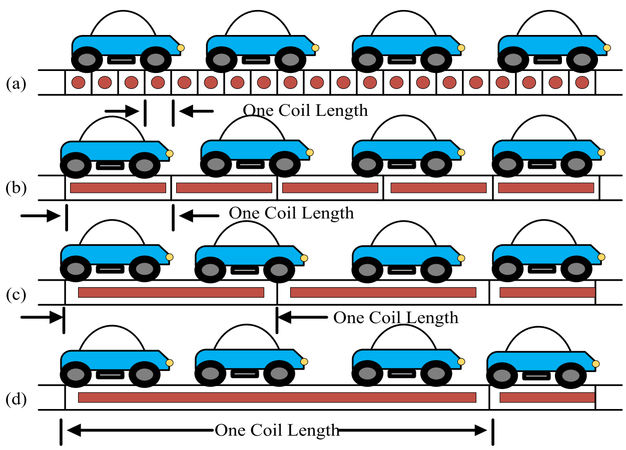


FIGURE 32. Segmentation of a track in different lengths.

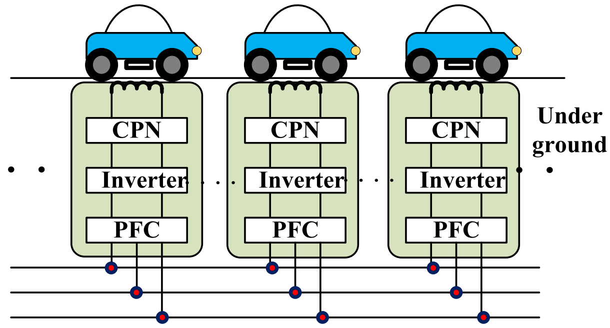


FIGURE 33. Common AC line supplying to H bridges having long track.

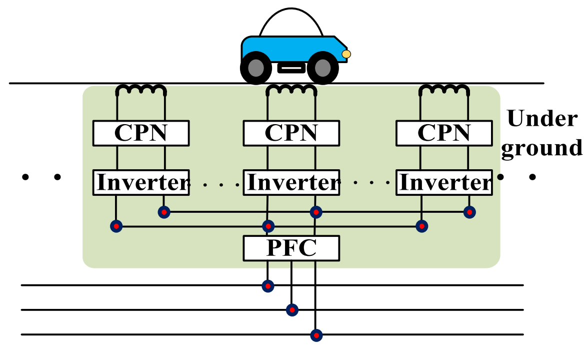


FIGURE 34. Common PFC for multiple modules.

The transmission track along the road, long enough to be successful operation, this track can be divided in to segments in order to optimize the system. But, its optimization depends on operation frequency, speed of the vehicle and traffic on the road. Furthermore each segment in the system consists of one or more coils. As show in Fig. 32, coils can be arranged in series of small segments or long track system. Compared to SWC system, the DWC system behaves as a distributed manner coordination between power electronic converters and coupling pads needs to be increased to improve the system efficiency and charging facility utilization.

DWC can be divided into two types considering the architecture of power electronics. The first type uses a single long track (shares single A/C line). The second one uses a segmented track have multiple small coils [30], [47] (shares common DC bus). Coil designing is a very difficult task, while designing the ratio length and span (the pitch) of the coil should be considered [208].

In one approach, each local coil or ground pad powered with separate H-bridge power converter has highest redundancy, fault in converter least impact on power supply and on other power converters as shown in Fig. 33. Cost of the system decreases when it comes to cables, but when it comes to power converters, it increases the cost of the system and complexity [118], [119].

Alternative approach is a centralized single power converter supplies power to the moving pick through extended power track [198]. Number of power electronic components reduces in this method compare to previous method. Maximum power rating of the track and number of EVs on the track influences design of centralized converter. Uncoupled area is more in this system when EVs are not occupied the transmitting pads.

By above considerations one method is as shown in Fig. 34. Single power converter supplies power to the number of inverters by single DC bus. By this method the number of converters is reduced. DC bus designed in order to power more number of inverters to reduce the cost and losses cost instigated by long cables.

The modified design of above architecture divided into two categories, one centralized PFC with inverter powers the multiple transmitting pads. Disadvantage of this model is reaction time between transmitting pads to coming vehicle [209]. This problem can be solved by power supply splitting, where transmitting pads powered by single inverter split part to power other converter, which increases reaction time [209]. However, this method increases AC conducting wire results increase cost of the system.

The scheme shown in Fig. 35 the transmitting pads are turned ON and OFF through a switch box. This arrangement reduces the use of power converters and losses. In addition

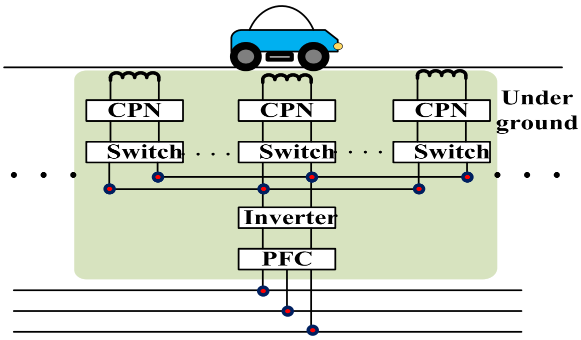


FIGURE 35. HF inverter feeding multiple modules.

individual control of pads to power particular vehicle [119]. Drawback of this structure relates to high power loss at connecting the pads.

In paper [210], in the proposed topology, multiple transmitter coils are series connected. Each transmitter coil is in parallel with a bypass switch. In this structure, multiple transmitters are supplied with only one inverter and one resonant network which reduce the implementation costs and power losses. Moreover, to detect the load on each segment, a new load detection method based on the amplitude of the transmitter coils voltages is proposed.

G. FLUX PATTERN ON RAIL

According to the authors in [211], the couplers forms three types of flux patterns, which are:

- Double sided waterfall: north and south poles created and with vertical flux orientation.
- Single sided N-S flux across the road: North-South poles formed across the road.
- Single-sided N-S flux along the road: N-S poles forms along the road.

Among these patterns, DD pads with alternate flux formation along the road are provides good interoperability with SWC standards, even in higher coupling variations. To develop flux pattern different type of multi coil pads like DDQ, Bipolar and overlapped DD pads used. The comparison of different flux patterns is tabled in Table 16.

H. SEMICONDUCTOR DEVICES FOR POWER CONVERTERS

In WPT systems, power electronic switches commonly used are diodes, Thyristers, GTO, MOSFET and IGBT. Based on operating frequency, voltage rating and current rating suitable semiconductor switch will be selected. WPT converters operate under high frequencies, which indicates that the switches in WPT converters must operate at those frequencies (>20 kHz). As per SAE j2954 operating frequency recommended to keep above 85kHz. To operate in these frequencies only MOSFET and IGBT are the viable option. In WPT system power transfer proportional to the frequency. Increase in frequency results in improve power transfer capacity. IGBTs are touching their limits in wireless charging operation, further increase frequency of switching

TABLE 16. Comparison flux patters in DWC [211].

Flux pattern	Couplers	Flux continuity along road
Double sided waterfall	• Rails: W-type ,E-type , • Pads: Circular , Rectangular , Cylindrical	• Good, with coupling drops during pad-to-pad transition
Single sided N-S poles across road	• Rails: U-type • Pads: DD , Bipolar (when directed perpendicular to road)	• Good, with coupling drops during pad-to-pad transition
Single sided alternate N-S poles along road	• Rails: N-type , S-type , I-type • Pads: DD, Bipolar (when directed along the road)	• Poor, In the course of transition forms zero coupling • For a smooth coupling profile secondary with multi coils or modified structures needed.

creates losses and heating problem. They would also need cooling arrangements. In other hand Conventional Silicon MOSFETs have high switching rating but they have low power rating.

Introduction of wide band gap devices (WBG) like Gallium Nitride (GaN) and Silicon Carbide (SiC) in wireless charging applications witnessed good result. WBGs offers reduced switching losses, thermal stress and operates at high power levels [212]. The SiC devices have four superior material properties because of wider bandgap [213] those are higher breakdown voltage, lower leakage currents, higher thermal conductivity and lower on-state resistance. These qualities avails the devices to operate at much higher frequencies, temperatures, and voltages. Designing power converters with WBG devices will add more energy efficient and powerful than the conventional switches. In the Fig. 36 shown the power levels and frequency levels of switches. These materials have been applied on most of the semiconductor devices. In those SiC MOSFET is the most developed one. Despite of all features this technology not fully commercialized due to limited production [13].

In the power converter switches on/off at high frequencies results heat, changes in the magnitudes *di/dt* and *dv/dt* infer stress in the components and excessive EMI, Which causes losses in the converter. By using snubber circuits these effects can be reduced.

A fully commercialized wireless chargers built by full SiC semiconductor based operation developed and achieved more than 92% efficiency [21]. In article [214], semi active bridge made-up off SiC MOSFET switches achieved 93.4% at power level of 7kW. In article [15], a wireless charger for 100kW system proposed. However, practically implemented for 50kW system. This method achieved 96.9% efficiency, due to contribution SiC modules. In compared to SiC devices GaN devices not implemented in application and it also high cost. GaN devices offers compact size. They are in still developing stage. Working with WBG devices offers advantages like high efficiency, high power transfer

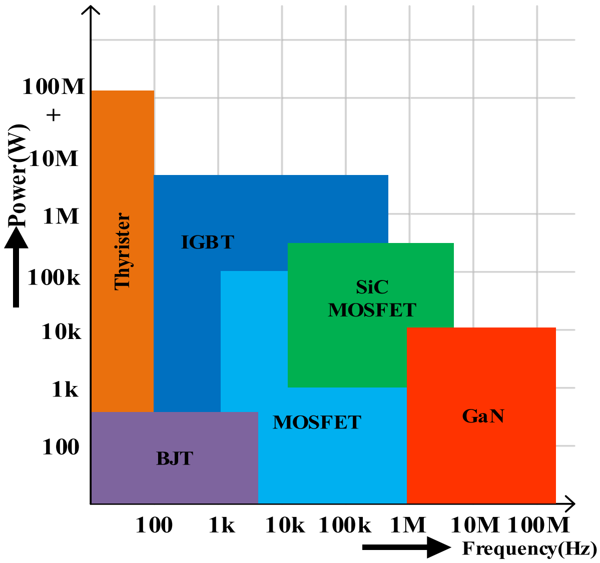


FIGURE 36. Operation ranges of controllable switches.

capability with high frequencies. Special attention needed in about EMI.

VI. CONTROL OF WPT SYSTEMS

A. POWER CONTROL TECHNIQUES

The control of the WPT done by three methods: primary-side control, secondary-side control, and dual-sided control [116]. In primary side control most of the control concentrated around the primary side. In this method primary full bridge controlled to regulated transmitter current. Some of the cases PFC also regulated. To regulate primary pad according to the load, the secondary side information required in primary side control such as the SOC information, battery voltage, SOC and SOH information. Under this approach minimum interaction with secondary side needed. Hence, On-board electronics minimized, which reduces cost and weight of the Vehicle [60]. In Secondary-side control :active rectifier with dc/dc converter are regulated to charge battery, due to increase secondary electronics, weight and cost of the vehicle increases.

Dual-sided control, in this technique both sides of WPT system need to be controlled. In This method communication link between two sides required. Both sides controlled independently or jointly depends on operation. In article [215], dual side control is applied SWC method, when it comes to dynamic charging facing difficulties in application [116]. Preferably independent control of both sides most suitable in DWC applications. Nevertheless, while using two independent controllers stability issues should be considered carefully [116].

Some of the basic control strategies are:

1) FREQUENCY CONTROL

In this method, switching frequencies regulated to control the input power. Drawback this method is, rated power deviation causes increase in reactive power of the system. It results drop in efficiency and may system go out of control [216], [217]. This method does not need any mechanical movement or extra components, which means smaller size, less complexity and higher reliability.

2) PHASE-SHIFTING CONTROL TECHNOLOGY

In this method, varying the turn-on angle of the switches by regulating the turn-on time of converter switches, to regulate the voltage fed to the magnetic coil by keeping constant frequency. In this method no need to concern over frequency of control operation and it also helps to eliminate selected harmonic frequencies. However, selection of switching frequency plays main role due to pole splitting [150], [216], [217].

3) CHANGING CIRCUIT PARAMETERS

This method is mostly suitable for the low level applications. As mention in the name of the system this method depends on controlling parameters of the system such as resonant frequency, input voltage, input current. The change resonant frequency achieved by the tuning the resonant capacitance [218]. In another approach input voltage of this system regulated to control the transmission power. This scheme suitable for high power applications. However, extra DC-DC converters needed for the voltage control operation [219], which increases the system size and cost.

4) PHASE-LOCKED LOOP CONTROL (PLL)

In this method power transmission controlled by adjusting PWM pulses and utilizes PLL to get the soft switching. After analyzing difference between zero crossing point of current and voltage signal, it adjusts the switching frequency of the converter to achieve soft switching operation [220]. Implementing this scheme is very complex. In article [199], to regulate the bi directional power flow, resonant circuit's real and reactive power measured. It is positioned at the receiver side, reduces the resonant circuit reactive power.

In the paper [221], author proposed to reduce the volume and cost for a semi bridgeless active rectifier (SBAR) with a variable frequency impedance tuning control. Just applying the fixed frequency control in EV application is not enough, because of the large aluminum shield and the wide range of the misalignment cause a large impedance mismatch. Although, the value of the fixed-frequency control must be designed with a sufficient margin to ensure ZVS) even if the large mismatch occurs. However, this application is not useful for high power applications due to load on the switches.

DC-DC buck-boost converter of the DWPT controlled by PI and Fuzzy controllers, and their performances compared in [222]. PI controller has longer settling time, even though, it produces ripple-free output voltage, current, and power signals. On the other hand, the Fuzzy controller quickly settles to the reference parameters. Proportional-integral (PI)

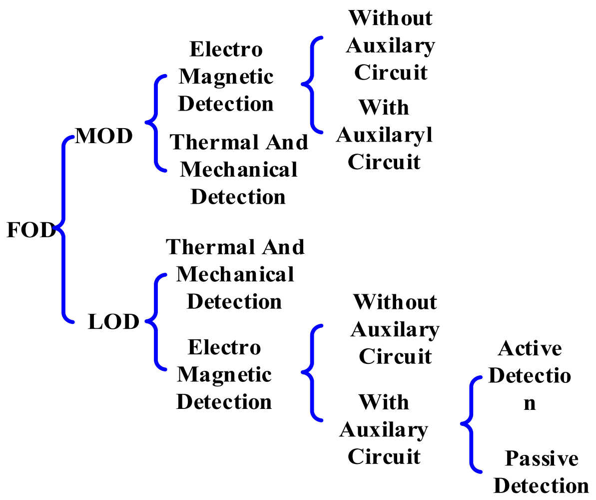


FIGURE 37. Classification of foreign object detection methods.

based controller is most commonly used in the control system. Sliding mode control and Perturbation and Observation (P&O) method used some of the WPT applications [223], [224]. In literature [224], decoupled controlling system is proposed, In this method only receiver side DC to DC converter regulates the output voltage, while the secondary side rectifier takes care of impedance matching [224].

B. FOD AND VEHICLE DETECTION

Most of the people having dilemma about radiation coming from the WPT system. Another method to remove this dilemma is FOD [61], [225], [226]. If not present on charging zone or misalignment is more than expected primary pad should turned off automatically to prevent the exposure of radiation, leakage flux. Any conductive material (foreign object) present in the vicinity of flux transmission causes heating due to eddy current losses; its temperature also increases rapidly during the charging process, making it a critical heat source Since it has been proven to cause burns to living bodies, such as kids, incautious operators and small animals. To prevent this kind of incidents, several FOD methods have been reported in [38].

According to type of foreign object, FOD methods can be categorized into two groups: Metal Object Detection (MOD) and Living Object Detection (LOD), which are further classified according to the method of detection and extra circuits' used, as shown in Fig. 37.

1) METAL OBJECT DETECTION METHODS

Based on the detection method MOD methods categorized into 2 types: Mechanical/Thermal detection method and selector magnetic detection methods. Mechanical/Thermal Detection(MTD) methods are consisting of the radar or sonar sensors [227], [228], temperature sensors [229], image processing [230], [231] and light sensors [227] which detects the mechanical/ thermal signs of metallic body like size, shape, temperature, and distance [227], [232]. Electromagnetic detection(ED) method concentrates on the electromagnetic reaction of a metal object such magnetic field redistribution, power loss and variations operating performance of wireless charging system. These changes can be used as detection parameters. Giving to whether an auxiliary detection circuit is employed or not, these detection techniques classified as two approaches with auxiliary circuit and without an auxiliary circuit.

2) WITHOUT AN AUXILIARY CIRCUIT

This method focuses on the electrical parameter like resistance, impedance, voltage and current etc. changes in WPT system due to metal objects. In this method we assumes that only the transmission coil is affected.

3) WITH AN AUXILIARY CIRCUIT

For parameter changes coil transferred power, coil impedance active circuit detection method is used, which requires additional source. In passive detection method, changes in EMF are detected by tunable magneto resistive circuit or detection coil without power source use.

4) LIVING OBJECT DETECTION METHODS

Based on the detection methods LOD methods categorized into two types: MTD method and ED method. Similar to the MOD method LOD method mechanical/thermal utilizes detectors like radar or soniic sensors [227], [228], [233], [234], temperature sensors [227], imaging processing [230], [231] and light sensors [227] to confirm the presence of a living object. Parameters used for detection are shape, distance, temperature and size. Electromagnetic detection methods concentrates on the coupling effect of the living object,

In the presence of electro static field living object characteristics changes based on capacitive coupling effect used. Based on the presence auxiliary circuit LOD method also further categorized in to two types.

5) WITHOUT AN AUXILIARY CIRCUIT

Switch voltage drain due to Drain voltage deviation of the power switches changes due to living object and are used as parameter in this method.

6) WITH AUXILIARY CIRCUIT

When living object comes under presence of detection circuit. This effects the mutual capacitance between the auxiliary detection circuit and the living object, which are detected by detection capacitor or detection circuit.

In the article [235], a symmetric detecting coil is utilized to remove blind zones in applications. In DWC system, generally, while EV approaching, an only transmitting pad energized. This method eliminates unnecessary power losses EMF leakage. To achieve this scheme, various authors proposed, various vehicle detection methods. In article [236], a three-coil sensing system is proposed, to let the supplied

TABLE 17. Foreign object detection methods.

Detection Method			Sensor	Parameter
MTD method			• optical sensor, image processing, thermal sensor, radar/sonic sensor	• The objects Size , Shape, Weight, Temperature and Distance
ED	Without auxiliary circuit		• Main WPT system acts as a sensor	**MOD:** • Change in Impedance ,change in current, voltage variation, phase shift ,resonant frequency, Q factor, power loss transmission efficiency **LOD** • Drain voltage deviation of the power switches
	With auxiliary circuit	Active detection	• Detection coil (Energized by power source)e	• Coil impedance • Coil transferred power
		Passive detection	**MOD:** • Detection coil(power source not needed) • Tunable Magneto Resistive (TMR) sensor **LOD** : • Detecting capacitive circuit, detective induction coil	**MOD :** • Variation in EMF **LOD :** • Impedance variation

TABLE 18. Advantages disadvantages of FOD methods.

Detection Method			Advantages	Disadvantages
MTD methods			• Not influenced by WPT system and type of foreign object	• High cost, occupies extra space, influenced by the environment and surroundings
ED	Without auxiliary circuit		• No additional equipment, cost effective, • Easy to implement	• Weak sensitivity, affected by misalignment and the load condition
	With auxiliary circuit	Active detection	• Highly sensitive, simple implementation	• Additional driving circuit needed, • Needs signal processing circuit
		Passive detection		• Requires signal processing circuit

power to detect an upcoming EV. In literature [237], resonant currents in transmitting pad utilized to detect the approaching EV.

As discussed above the MTD methods concentrates on the mechanical/thermal signatures of FOD sensors and requirements. These approaches won't depend on the type of the object and WPT system. Drawbacks of this method is the detection expensive detection sensor, needs extra working space and influenced by environment conditions.

Detection method concentrated on change in parameters caused by foreign object. These method most suitable for MOD and applied during charging. Advantages these methods are low cost and simple implementation. Disadvantages are weakly sensitive to small objects, load condition and misalignment effects the detection.

Detection methods based on the coupling effect with auxiliary circuit have effective detection sensitivity compared to other detection methods. The Table 17 shows sensors and related detection parameters being used in the FOD [238] Among them the active detection methods are implemented before or during charging being suitable for both MOD and LOD. The passive detection techniques are appropriate for MOD and can only be executed while charging. Moreover, these techniques requires signal-processing circuit. The active detection methods usually need an additional driving circuit, which makes system complex. However, sensitivity effective than the other methods. The advantages and disadvantages of the detection methods are categorized in Table 18 [238].

The authors in [239], suggested research areas for development of FOD: (a) combination of two different detection methods would improve the sensitivity, accuracy, signal-to-noise ratio, and object localization, (b) A method that can detect both living and metal objects simultaneously are not influenced by environment and conductive materials, (c) The EMI/EMC issues in FOD detection, and (d) automatically removing foreign objects without human intervention.

TABLE 19. Experimental study on misalignment effect on efficiency and output power (ORNL) [241].

Misalignment	Output Power	Efficiency
-100	4104	78.57
-80	5054	81.1
-60	5920	82.88
-40	6348	84.36
-20	6642	85.44
0	6725	85.5
20	6667	85.31
40	6567	84.97
60	6143	83.74
80	5573	82.38
100	4938	79.95

C. MISALIGNMENT

In WPT systems, depending on the regulations and guidelines maintaining alignment is a key issue. Due to misalignment between transmitting and receiver coil cause various problems like increase in flux leakage and reduction in mutual inductance results reduce the transfer efficiency, where in high power system The small misalignment can cause high power losses. Therefore, it is necessary to compensate for misalignment and maintain high efficiency [240]. In stationary/dynamic charging of EV, it is challenging to align secondary coil with primary coil, it depends on the driver, the vehicle, and the environment. The variation may be lateral, vertical displacement, rotation and angular tilt.

As per the SAE J2954 regulations, wireless charging systems should have misalignment tolerance in any direction [224] to some extent. The misalignment positional length is shown in Table.3. The results from the Table.19 are taken from the ORNL 6.6 kw wireless power transfer system with 85.5% efficiency [241]. The Table shows the results of the misalignment effect on efficiency. Also, the drop in efficiency. The Table displays the effects of misalignment on efficiency, the drop in efficiency due to misalignment clearly seen.

Researchers proposed different kind of method to reduce the effects of misalignment. The majority of research is focused on advance coil and core structures, like DD, DDC, DDQ, and BP have been analyzed and different coil combination of coils are used, which are shown to be some extent resistant to misalignment coils used, which are shown to be some extent resistant to misalignment [242]–[245]. Researchers also proposed misalignment tolerant methods based on frequency tuning technologies and compensation circuits for power electronics [246]–[248].

Advanced power electronic converters, proposed to improve power transfer between coils in influence of misalignment [178]. Also, on mechanical structures designed to reduce the misalignment [249], [250]. Angular misalignment is corrected based on technique used antenna positioning in the paper [251].

Misalignment and operating inverter frequency affects the mutual inductance that further influences the resonance frequency [71], [252]–[254]. In literature [255], the ideal operating frequency for maximum power transfer has been estimated under contingency of misalignment. Detection of misalignment is the important part of the WPT system. In many studies various types of misalignment techniques proposed acoustical positioning [256], optical positioning [257], [258] and RFID positioning [259]–[265]. optical positioning methods are vulnerable to obstacles and effected by the surrounding environment. Acoustical positioning and RFID positioning effected by signal lack of multipath detection and non-line-of-sight. These methods difficult to incorporate and costly.

In some of the WPT systems, electromagnetic positioning detection methods are implemented [266]–[271], these methods uses additional coils to measure changes magnetic field produced by primary couplers. This method wont influenced by environment, easy to incorporate, offers good accuracy and low cost. Primary pad needs to produce weak magnetic field by utilizing low voltage source for positioning of vehicle. To produce low voltage, high power inverter in primary side has to work at low DC voltage [269], [270], or have to work at small duty cycle [271]. Furthermore, In this method positioning and power transmission doesn't work at a time.

D. COMMUNICATION

In contactless charging system communication plays vital role to guarantee timely information exchange between primary and secondary sides, to ensure reliable and efficient operation. The main factors influences selection of optimum communications method are: 1) low latency; 2)communication with multiple vehicles; and 3) medium range coverage [116].

Communication setup also depends upon the power control methods such as: primary-side (transmission-side), secondary-side (receiver or vehicle-side), or dual-side control. [272]: Primary and dual side control often involves data sharing of the battery's SOC parameters, like voltage and current levels, as well as coupling and efficiency parameters between the vehicle and ground pad module. Furthermore, communication required for initiation and termination of charging process and positioning of the vehicle, FOD and misalignment.

Most of the communication standards set by SAE, ISO and IEEE. SAE setup generalized communication standards for PHEV/BEV. SAE J2847-6 deals with communication between EVs and there wireless chargers. Also states the requirement and specifications. SAE J2836-6 provides guidelines for on-board chargers and there supply equipment support system. 2391-6 deals with conditions for physical and data link layer communications most of them taken

TABLE 20. Comparison of modified compensation topologies.

Type of battery	Lead acid	NiMH	ZEBRA	LFP	NMC	NCA
Cell voltage (V)	2	1.2	2.6	3.2	3.6	3.6
Energy density (Wh/kg)	35	70-95	90-120	90-120	150–220	200-260
Specific power (W/kg)	180	200-300	155	2000-4500	-	-
Life cycle	1000	<3000	>1200	>1200	1000–2000	500
Self-discharge (% per month)	<5	20	<5	<5	<5	<5
Operating temperature (◦)	–15 to +50	–20 to +60	–245 to +350	–45 to 70	–45 to 70	–45 to 70

from IEEE 802.11n. Other communication options include Bluetooth (IEEE 802.15.1), ZigBee (EEE 802.15.4 and Wi-Fi (IEEE 802.11). etc. ISO 15118-8 sets standards for high level communications between EVs and supply equipment.

In [273], the researchers have studied different standards for communication, recommended suggestions through conducting several experiments antenna on position, channel state estimation, effect of shielding on signal quality and SAE J2954 Message set implementation on Prototype testbed.

In literature [274], author careful factor such as latency, transmission range, speed of data transmitting and mobile connectivity for different DWC applications. A Dedicated Short-Range Communication (DSRC) for applied in article [272]. Other communication methods such as Wi-Fi (IEEE 802.11), Bluetooth (IEEE 802.15.1and ZigBee (EEE 802.15.4) need to researched for more options.

E. BATTERY AND ENERGY MANAGEMENT SYSTEM

Battery manufacturing technology determines the power storing capacity and energy density. Depending on that commercialization of EV happens. Different types of batteries used in EVs shown in Table 20. EV maneuvering like acceleration, regenerative braking are regulated by power. Initially lead acid batteries were used in traction applications. Automotive companies like general motors and Toyota already used lead acid batteries in their EVs. However, due to low energy density characteristics of battery, makes them not preferable for EVs. This makes EV vehicle heavy occupies large space. A typical family car need 40 KWh battery to deliver a 200miles range and a lead acid battery of 40kWh weighs around 1.5tons [275].

ZEBRA batteries were utilized in urban bus models. Despite having good energy density these batteries not succeeded in EV industry due to high operating temperatures. It is difficult to maintain high temperatures for continuous EV operations [276]. NiMH batteries are mostly utilized battery in the market [277]. Despite These weighing heavier than most of other types of batteries and provides low efficiency, These batteries have low maintenance, good power, good life time and energy density. As we know that BEV needs to have more battery capacity than the PHEV and HEV. Lithium-ion batteries are good solutions for BEVs. Li-ion batteries are preferred due to the specific chemical combination found at anode and cathode. The most commonly used batteries for traction applications are Li-NMC), Li-NCA and LFP. NMC batteries provide a high energetic density. These features

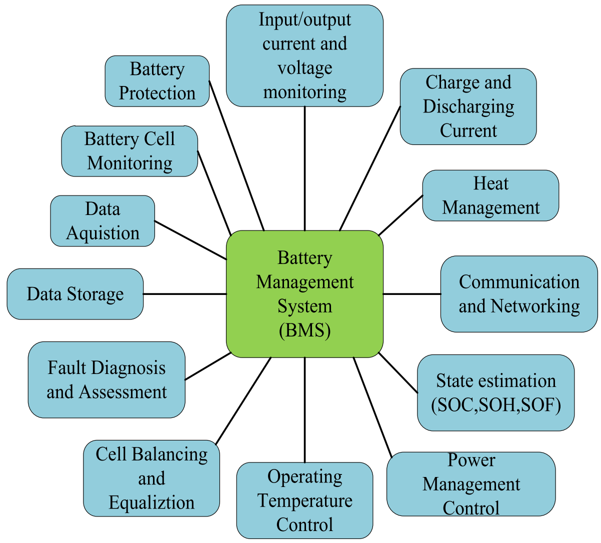


FIGURE 38. Summary of Battery management system.

reduced the weight of the battery. NCA batteries have been more expensive than the NMC batteries due to Tesla and Panasonic efforts to reduce the cobalt used in battery results.

NMC is the cheapest battery in the present market [278]. LFP batteries are used in heavy vehicles (e.g. buses), because of negligible weight. Table 20. Shows a comparison of the main electrical properties of batteries. Due to the properties of lithium ion battery, it should be maintained and controlled properly to get maximum output [116]. Over charging, over-voltage or over-current affects the on the battery lifespan and sometimes even lead to issues like fire or explosions [279]. The cell operating voltage, temperature and state of charge (SoC) must be kept within the limits as shown in the Fig. 39. For all these, a proper controlled system required for the battery.

A Battery Management System (BMS) observers and controls several key parameters related to battery like temperature, State of Charge (SoC), State of Health (SoH), input/output current, battery charge equalization, voltage Monitoring, battery protection and so on. The summary of BMS is given in Fig. 38. The BMS controls the charging state of the battery and SOC according to the battery properties. It controls discharging and state of discharge based on the load demand and the charging level present in the batteries. Cell level voltage estimation need to done, to protect the cells from unwanted charging conditions the battery cell balancing

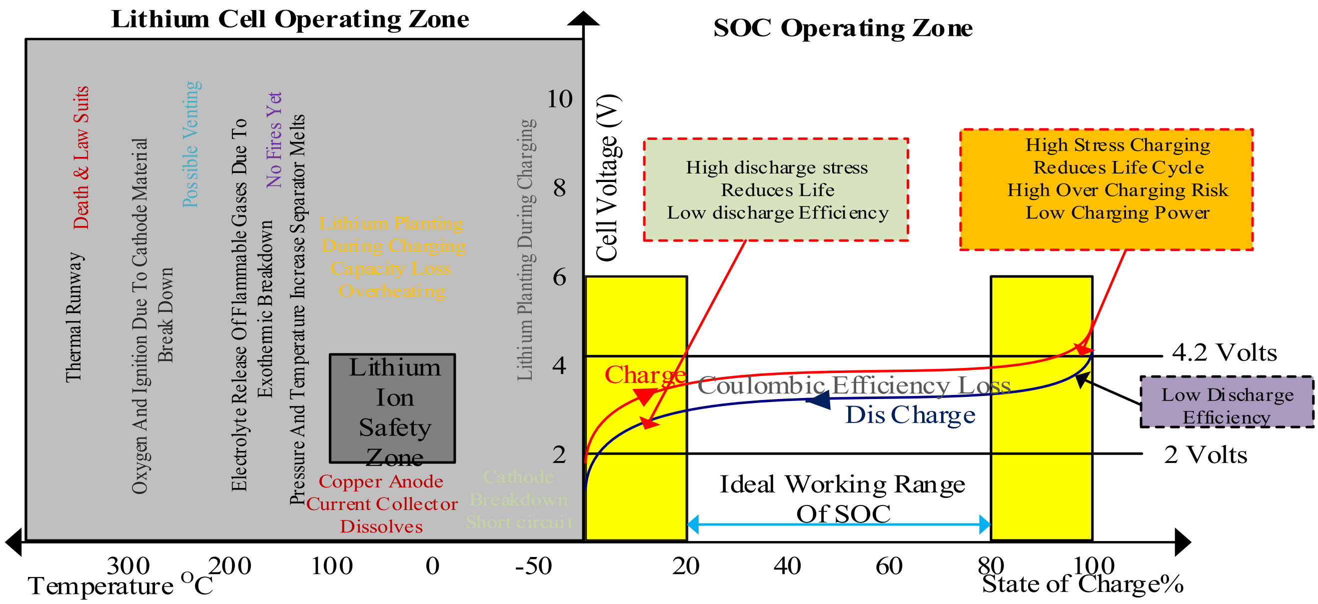


FIGURE 39. Lithium-ion battery operating and charging zones [280].

done by charge Equalization methods should be applied to enhance the life of batteries and overall performance when situation like peak current, over voltage and overheating occurs BMS activates protection circuits. Cutoff Field Effect Transistors (FETs) used for connection and disconnection of the battery. Cut off FETS is completely detached from other circuits as a protection measure. BMS regulates the voltage current level of each cell. That means it controls the charging and discharging process of the battery. It also monitors the cells to balance the parameters to increase the battery life span.

BMS controllers are of two types:

i. Passive or resistor based controller
ii. Active based controller.

Passive or resistor-based controller: in this controller when excess voltage occurs it will be dissipated through resistor. Because of simplicity this implementation is low-cost solution. One of the main disadvantages of this controller is the loss of energy that occurs during the cell balancing process and also it is time consuming process. Active based controller: in this process the energy is dispersed among the cells. Normally EV BMS designed with active cell balancing. This is a complex operation.

VII. MISCELLEOUS INFLUENCES ON WPT

A. CYBER SECURITY

For an advanced transport systems needs an advanced vehicular applications. These advanced vehicular system depends upon Internet and communication devices. Due to that Cyber-attacks on these transport systems getting increased. Compared to Wired systems, Wireless systems are more susceptible to cyber-attacks, these system gives more ways to attack without forming physical connection.

Cyber-attacks are many types depends upon attacker intention such as damage equipment, access the data, destabilize the entire system and attack on the driver. To avoid these adverse effects due to cyber-attacks it is compulsory to apply cyber security at various levels in wireless charger and EV modules [281].

Other ways of cyber-attacks due to unauthorized access are

- Data theft during transferring data.
- Intention to overload network channel by false data and making service denial to authorized person.
- The steal IP addresses to capture data.

The main objective is to deliver security measures to attain the confidentiality, integrity, and availability (CIA) triad for safeguard of the overall system along with its peripherals. The triad CIA is as follows [281]:

- **Confidentiality**: main goal of confidentiality is to secure the data from unauthorized access and provide services to authorized persons only.
- **Integrity:** Securing the network system from manipulating or modifying data.
- **Availability:** it signifies the real availability system to authorized person only. All modules have to work efficiently to stop the data from unauthorized access.

In [282], authors categorized and analyzed different kind of security threats for wireless charging system compared with plug-in method and concluded that security measures which are applied plug-in vehicles are not appropriate for wireless charging system. Attack types, preparation methods and solutions analyzed in the article [283].

B. ECONOMIC ANALYSIS OF WPT

The WPT technology economic competition with other technology is influenced by different factors such as in

TABLE 21. Cost comparison of CNG and OLEV bus [285].

Energy cost comparison				
	Efficiency	**Energy cost**	**Cost/month**	**Cost /year**
CNG bus	1.7 km/litre	1.0$/litre	4411$	52,932$
OLEV bus	0.7 km/kWh	0.11$/kWh	1178&	14,136$
Life time cost comparison in dollars				
	Single Bus cost	**Government subsidy**	**Energy cost (10 years)**	**Total cost**
CNG bus	200,000	1,00,000	529,320	629,320
OLEV bus	450,000	3,00,000	141,360	291,360

current infrastructure, battery technology and electricity per unit cost. Compared to plug-in charging methods, the major difference SWC system consists of magnetic coupler, which brings an additional cost of US$400/8 kW charger [27]. Cost of contactless charging is quite acceptable considering the features provided [284].

In literature [286], the authors used a mathematical model to minimize the battery size and they compared total cost of both SWC and DWC systems. Comparison results shown that DWC system is 20% percent less cost than the SWC system. This analyzation is done based on 18 OLEV buses operated for 10 years. Furthermore, it is helps in the reduction of the battery size and extension of the battery life [286], this makes EV lighter and helps to improves performance and reduces cost. a similar kind of study was done in [89]. They showed that commercializing OLEVs gives cost-to-benefit ratio less than one by 2024 [89]. Considering lifespan a bus, wireless electric bus reduces fuel cost over 80% compared diesel bus [287]. The comparison of CNG bus and OLEV was done on GUNMI city −7 line road having 250 kms per day trip, as shown in Table 21. After 10 Years operation, compared to CNG bus OLEV bus saved 337,960$ (with government subsidy) [285].

For DWC on highways, In compared total road way infrastructure, DWC implemented road will be a small portion [288]. Meanwhile, as the number of vehicles increases the utilization installed infrastructure increases [289]. For that future demands need to be considered while deploying DWC system.

C. ISSUES RELATED TO CHARGING INFRASTRUCTURE

EV sales and road infrastructure development are the main tools for proper deployment of wireless charging. Incorporating wireless charging system into the existing infrastructure is a hectic job, especially road embedded systems. This complexity is reflected in several aspects: i) coil magnetic properties may be altered by infrastructure; ii) losses may be created by constructed structure, and iii) Road mechanical integrity shouldn't disturbed by coil integration.

In [290], the impact of the electromagnetic characteristics of the concrete on the road embedded WCS for electric vehicles has been investigated and given advices for implanting a coil and points taken care while designing a coil. The project like OLEV and SELECT used plastic and non-metallic materials in the construction [291], [292]. In [293], wireless power charging lane based on transmitter coils directly embedded under the road surface and how the EM parameters of the concrete affect the overall behavior of the embedded device discussed.

In conclusion, more research requires to be done in the area of road embedded coil design, there influence on mechanical strength of the road and loss due to different materials using on construction. Another issue which needs to be consider is high pressure and vibration. Furthermore, environment effects on wireless charging structure based on different conditions is to be done. Issues like shielding, material choice, packaging, and coil incorporation on the road should be evaluated. The Fig. 40 shows the architecture of WPT system with different modes.

D. HEALTH AND SAFETY

The first question comes to people's mind, when it comes to wireless charging "is it safe for health." Fear due to EM radiation created during wireless transmission. To reduce this dilemma among customers, these radiations should be restricted by following international standards in design procedure. In addition, must follow proper shielding to prevent exposure of radiation to the living bodies [294], [295]. There are limits set by international organizations, how much EMF radiation should absorbed by biological tissues.

In [134], these guideless are analyzed and their limitations discussed. However, further research on radiation levels and shielding methodologies for high power and DWC applications should be carried out by considering several factors such as FOD, people with implanted medical device, accidental leakage exposure and varying speed of vehicle need to be investigated thoroughly.

In CARTA project and Utah State University projects, comparison between ICEV and wireless EVs is done. Results shown that reduction of pollutants in wireless EVs compared to ICEV [287], [296]. Although DWC based EVs showed good eco-friendly performance compared to conventional powertrain vehicles, contactless charging vehicles with plug-in charging vehicles need to be compared.

E. ADVANCED MATERIALS APPLICATION IN WPT

Performance of wireless chargers is basically determined by the materials used. By using advanced materials in WPT system, it removes the fundamental limitations and gives better performance. Copper is the most common material used to design the wireless charger due to its conductivity and low price. To increase the conductivity in Litz wires are used in coil making Litz magneto-plate wire (LMPW). Litz magneto-coated wire (LMCW) are advanced techniques used in Litz wire manufacturing, which are giving better performance than Litz conductors [140]. Aluminum used as conductive shielding is less cost.

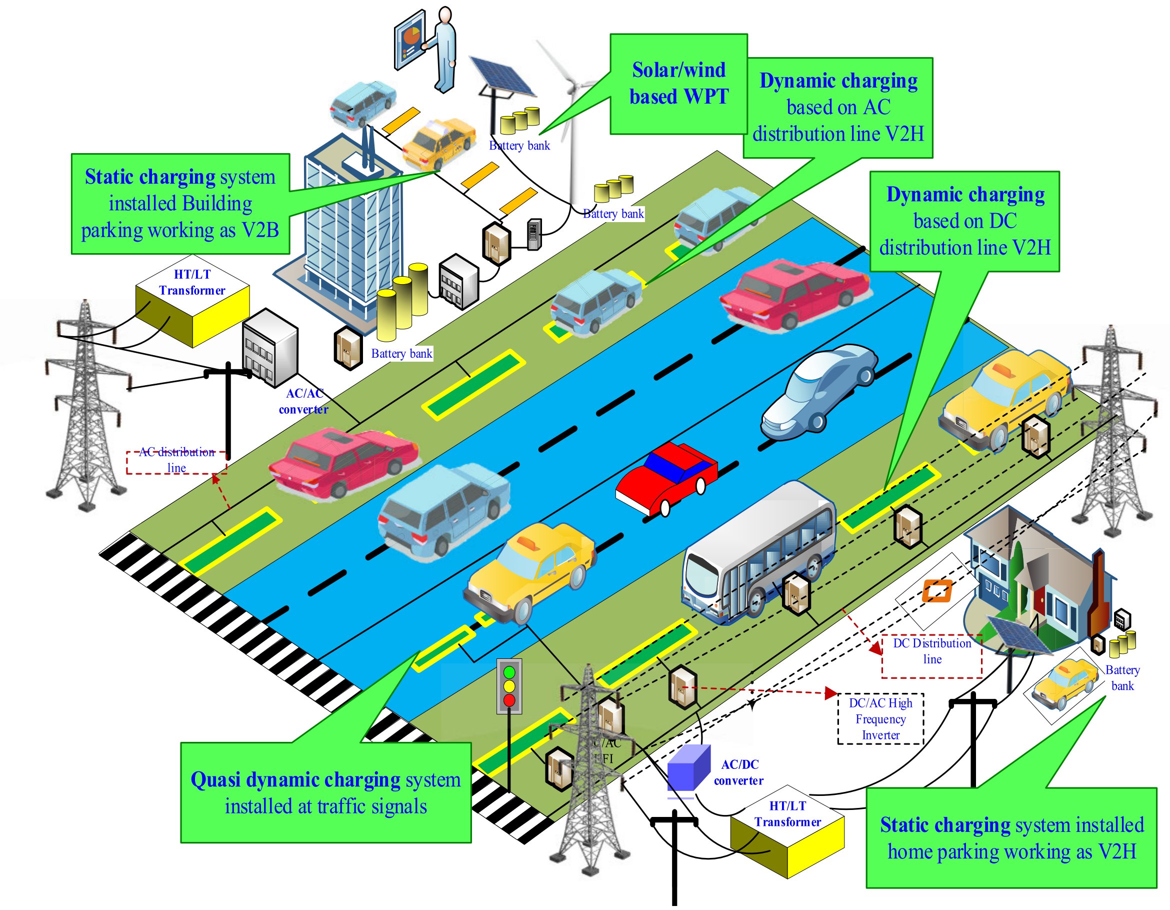


FIGURE 40. Roadway model of different modes wireless charging infrastructure.

The most commonly used magnetic materials to increase performance in IPT system are Manganese-zinc (Mn Zn) and Nickel-zinc (Ni Zn) because of their comparatively low losses at high frequencies [297]. They show high magnetic permeability coupled with low electrical conductivity, which help to minimize eddy currents. However, using ferrite makes the WPT system expensive, heavy, and fragile. For avoiding these limitations magnetic Nano particles-based core used, which is less weight but expensive and fragile. Other materials used as a core is flexible magnetic material-based, increases the system robustness against mechanical stress and vibration [116]. Still these materials are not optimum for road embedded transmitter pad. Any cracks in the road will damage the transmitter pad. Therefore, a magnetizable concrete was developed and proposed for a transmitter design, which is low cost and flexible and has good mechanical characteristics [116]. When it comes to power converters switches using WBG semiconductors such as *SiC* based power electronic devices have been proposed as alternative to silicon (*Si*) devices due to their superior material characteristics, allowing to improve thermal conductivity, increasing the achievable maximum switching frequencies and/or reduce power losses [298]. In DWC roadway it is charged with hundreds of kVA due to EVs high power demand. There are no semiconductor devices handle such power. SiC can handle low power at high frequencies. To make the system operate at safe, high power, large air-gap, good efficiency, high power density, high misalignment tolerance and future needs to be followed.

F. VEHICLE TO GRID (V2G)

In this technology power transfer happens between EVs to the distribution network (grid) and EVs used as energy storage system. Bi-WC utilized to transfer power between G2V (charging mode operation) and V2G (discharging mode operation). When there is off peak time's surplus energy production in grid, electrical vehicles will be charged. Similarly when peak load time charged electrical vehicles can give power supply to the grid. Subsequently, EVs can used as dynamic sources and dynamic loads. In the future the number of electrical vehicles is going to increase, and can be seen as reliable energy source. How wireless power technology simplifies the electrical vehicles connected to grid while charging and also during discharging (V2G) process when is connected to the grid is shown in [299]. This technology needs changes in grid infrastructure because it requires uninterrupted two-way communication between EVs and distribution system operator. Furthermore, smart meters

TABLE 22. Comparison of modified compensation topologies.

Standards	Substandard/Upgraded Standard	Area On Focus
SAE	SAE J2954/ J2836/6™ J2847/6-J2931/6,J1773	• Deals with EMF, safety, shielding and interoperability requirements. Requirement for wireless communication.
IEEE	IEC/IEEE 62704, IEEE P62704-2 IEEE C95-1234 P2100.1	• Specifies and provides the test for vehicle human body models and the general benchmark data for those models • Wireless charging system and EMF exposure to living objects
IEC	IEC 61980 (IEC TC 69), IEC TC 100, IEC 62827-1:2016, IEC PAS 63095-1:2017(E)	• General requirements for WPT, Communication, and Magnetic field power transfer and interface.
ISO	ISO 19363 ISO 15118-1 ISO 15118-2 ISO 15118-8	• EMF, safety and interoperability requirements. Requirement for wireless communication between Grid and vehicle
ICNIRP	ICNIRP 1998 ICNIRP 2003 ICNIRP 2009 ICNIRP 2010 ICNIRP 2020	• Guidelines for limiting exposure of EMF. Biological effects of exposure to EM fields.
European Telecommunication Standards Institute (ETSI)	ETSI EN 303 417 V1.1.0 (2017-9).	• Harmonized standards covering the essential requirements of article 3.2 of Directive 2014/53/EU.
CCSA China Communication Standard Association	CCSA TC9, YD/T 2654-2013	• Evaluation of EMF and EMC allowable limits and capacities. Requirements and test methods of EMC of WPT equipment.
JEVs	G106,G107,G108,G109	• Inductive wireless charging of EV: General requirements & manual connection • Inductive wireless charging of EV: Software interface & generally requirements
Broadband Wireless Forum(BWF) ARIB Association of Radio Industries and Businesses	ARIB STD-T113 (2015)	• Capacitive coupling for WPT, WPT using microwave two dimensional waveguide sheet. • Magnetic resonance WPT using 6.78 MHz for mobile/portable devices. • EMF of WPT for home appliances and office equipment. WPT for EV/PHEV.
TTA Telecommunication Technology association	TTAR-06.162 (19/11/2015)	• Efficiency measuring methods, wireless power transfer, and heavy duty EVs. MCR WPT. ICPT.

and advanced metering infrastructure required to keep track of the units consumed and sold at exact same day.

V2B (vehicle to building) and V2H (vehicle to Home) are similar to V2G. In this technology the vehicle communicates with the building or home. In this case instead of grid energy supplied to the building or home. Excessive energy produced by the small PV and wind applications can be stored in EV battery and can be utilized when required [300].

By using technology continuous charging and discharging the batteries (charging & discharging cycles) happens. This may head to shortening battery life and battery degradation. In literature [301], authors concluded that without battery degradation EV can participate in V2G transmission. The e-mobility pilot project in Malaga city, Spain will be the largest V2G pilot project.

G. WPT WITH GRID CONNECTION

High power unimpeded EVs charging may create adverse effects on the grid. The possible effects could be unacceptable voltage deviation, power system overloading, harmonics injection, phase unbalance and peak demand [302]. Several factors influence severity of impact such as EV battery capacity, time and location of charging, EV charger power rating, EV battery SoC, distribution system status and EV penetration level [302] These limitations can be overcome by controlling the charging and discharging states. The positive effects of EV on the grid are Reactive Power Compensation, Voltage Regulation, Improving Power Quality and Congestion Management [302].

Many researchers suggest that adopting proper scheduling and planning strategies are necessary to mitigate the aforementioned problems. Cost of charging and the level of the user's convenience are among the most relevant measures for assessing the suitability of charging and scheduling algorithms [303]. While there are several studies chose either convenience level or optimizing charging cost [304], [305], some of them consider both [306]. He et al, proposed locations and sizes of charging stations, to reduce the incremental investment costs by optimal planning strategies [307]. Another method is to find energy efficient routes, rather than just fast or short routes are studied in [308]. In [309], proposed a SoC prediction algorithm for balancing vehicle SoC and

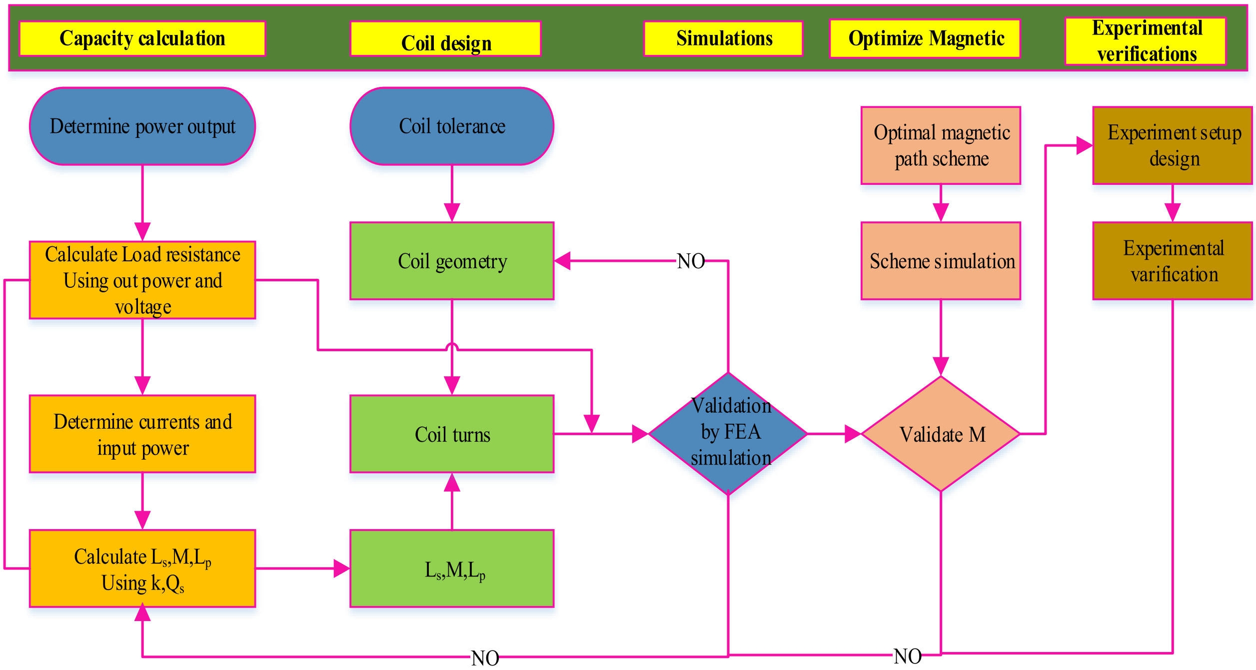


FIGURE 41. **Magnetic coupler design flow chart.**

load management utilizing historical data. In case of wireless technology makes the scheduling and charging problem even more complex.

Impact of dynamic charging method on demand cycle was studied in [310], and possible solution were given to smoothening the demand curve [310]. Variation of the grid voltage is mainly due to the operation of DWC systems studied in [311], by taking three different scenarios. Based on results, combination of good control system and energy storage infrastructure is enough to maintain the grid stability. A control strategy was proposed in [312], to limit the grid-side power pulsations for DWPT application without incorporating any additional converters.

In consideration of the WPT at Smart grids, the effectively implementing advanced charging techniques, resource optimization techniques, ensure the scheduling despite of limited computing capabilities and transmission delays and Irregular charging behavior of electric vehicle users. These challenges can be solved by smart grids. Smart grid is the futuristic grid for solves these problems by combining power infrastructures with artificial intelligence, smart sensors, advanced information, and automatic control technologies [313], [314].

Compared with the plug-in charging mode, WPT is easier to realize the interaction between the EVs and the power grid in the contactless charging mode. Through the joint construction of EVs and the smart grid, the SOC of every EV battery could be monitored and it is easy to guide the EV owner to reasonably charge by collecting the related information such as peak load, valley load and electricity rate. Human resources are significantly reduced by this technology [315]. The Qualcomm proposed 3G network based smart grid integration. Latency is main issue in the 3G telecom networks. This can be resolved by high speed internet 4G or 5G. Hybrid AI based 5G smart grid for EV charging analyzed [316].

Using electric vehicles to support the integration of the Renewable Energy is becoming a major research topic. The EVs connectivity with RES will highly support and enhance more penetration of the RES into the grid. However, this concept needs more research in view of cost-benefit justification. There are already some demonstration projects to assess the effects and possibility of the EV and RES connectivity [317]. A potential analysis to deploy PV solar on car parking in the Swiss city of Frauenfeld is extensively explored. Results reveal that the setting up of the PV system on parking lots can cover between 15% and 40% of the energy demand of the EVs in the future.

H. STANDARDIZATION

There are no particular universal standards for the operational principles of wireless chargers. The main issue is interoperability among the different coil structures, power converters and compensation networks by different manufacturers [318]. there are different recommendations.

Shown in the Table 22 China recently published their own standards for wireless charging systems. The SAE is leading one among them. It is currently working on finalizing a standard for high power applications, till now power range between WPT1 to WPT3 (22kVA) covered.

In [319], comparison among IEC, SAE and ISO is done, which have many common points. However, when it comes to EMC it is different. Similar kind of study done in [320].

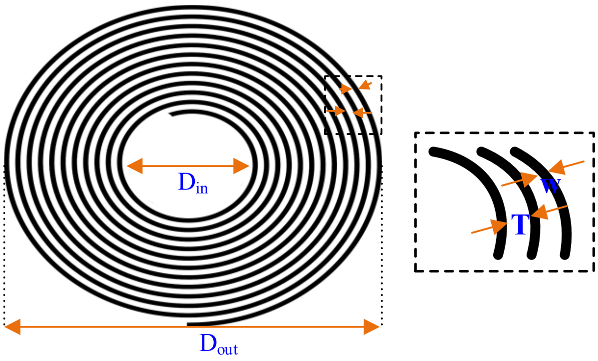


FIGURE 42. Circuit model of circular coil.

There is strong demand for further development of high-power WCS standardization. A similar effort needed in DCS.

I. QUASI DYNAMIC CHARGING

The application of a QWC technology at road traffic signals and parking bays might deliver a promising solution for EV charging. QWC method utilizes the features of DWC system and reduces the infrastructure cost compared dynamic charging system. In addition, easy control, and improves the efficiency by allowing effective alignment between couplers. In this method Primary pads (transmitters) are positioned on the roadway in each travel lane at traffic signals as shown in the Fig. 40 and driven by power converters. Thus, the transmitting pads are selectively excited based on the EV position such that the energized pads are covered by EV [27]. To determine the number of WPT coils to support each lane, can be decided by conducting a traffic flow analysis for the minimum coverage distance. QWC method can be used for bi-directional power transfer (V2G or G2V) while stoppage at traffic signals and it also used for the traffic detection [321]. The effect of implementing QWC over one driving cycle with different scenarios was briefly studied in the paper [322]. Normally, the change in State of Charge might be lower as it is likely that the charging pads are misaligned, and the vehicle will not spend 100% of the waiting time on the charging pad till it fully charged. In the paper [323] the effect of different transfer efficiencies and duration spent charging analyzed.

VIII. DESIGN PROCEDURE OF A COIL

Design and optimization of magnetic coupled system involves complex procedure. It needs power, frequency and voltage considerations, which determines the compensation, topology and magnetic coil geometry. The flowchart shown in Fig. 41 presents the methodology for a magnetic coupled system. According to application coil geometry needs to be chosen. Coil geometry determines the mutual inductance, self-inductance and tolerance of the design. The coil design parameters can be verified through Finite Element Analysis (FEA) for optimum efficiency. The mathematical calculations of the parameters becomes more complicated while designing the arbitrarily shaped coils (e.g., DD, DDQ).

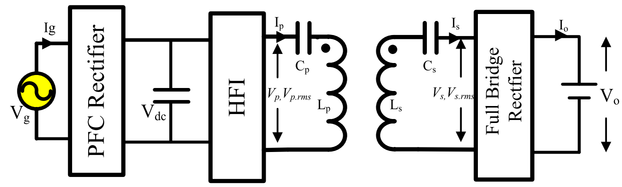


FIGURE 43. MATLAB simulation model diagram for SS compensation.

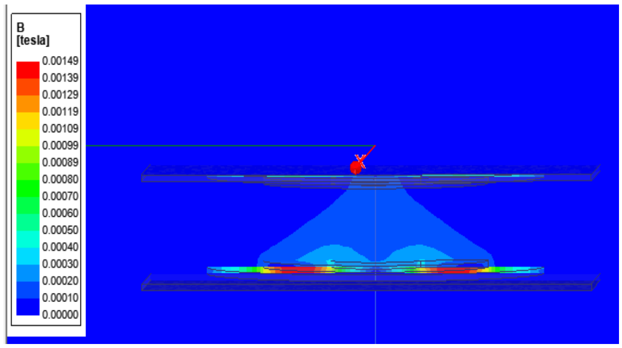


FIGURE 44. Flux distribution in the Ansys-Maxwell FEA model.

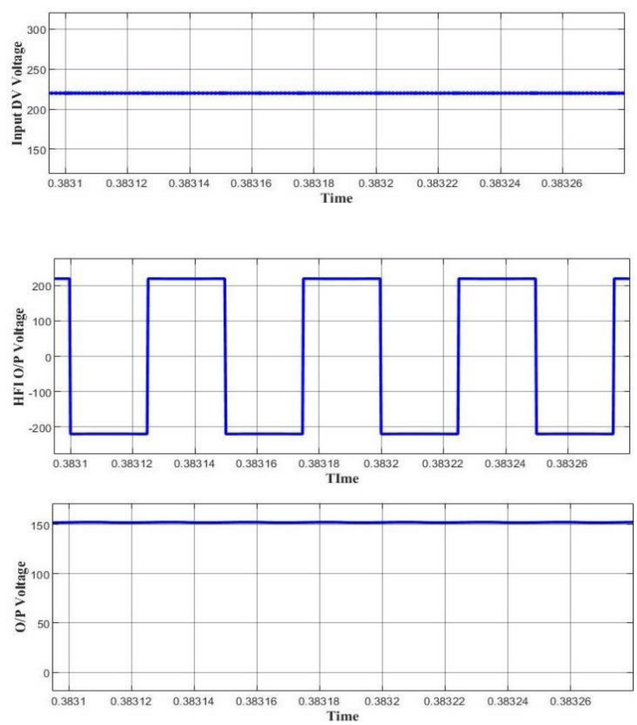


FIGURE 45. Voltage wave forms from MATLAB simulation.

These limitations may be overcome by using of finite element.

The coil design parameters can be verified through finite element analysis (FEA) for optimum efficiency. Mathematical Calculations of the parameters becomes more complicated while designing the arbitrarily shaped coils (e.g., DD, DDQ). These limitations may be overcome by using of finite element analysis.

TABLE 23. MATLAB simulation parameters.

Parameters	Values
Power	3.6kW
Frequency	20kHz
V_o	168V
V_{prms}	220V
V_{srms}	152V
I_{prms}	16.4A
I_{srms}	24.9A
R_o	7.84Ω
L_p	24.12μH
L_s	552.80μH
C_p	114nF
C_s	262nF

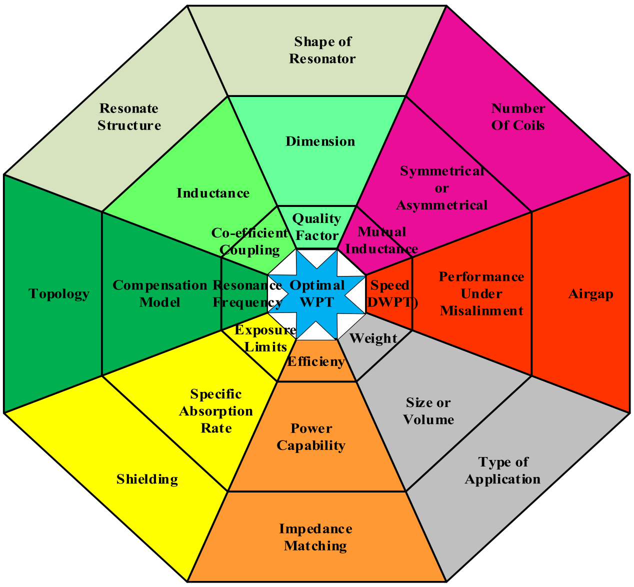


FIGURE 46. Summarized design constraints of WPT model.

Considering Circular coil design as an example: In a paper [324], authors made tested with several sizes of circular coil to determine the optimal shape of the coil for same power frequency. They suggested that the outer diameter of both coil should be kept equal and inner radius of the primary coil should be maintained lesser than the inner radius of the secondary coil to obtain the best coupling profile. The coil wounding can be divided into two types: Tightly Wounded and Loosely-Wounded. By tightly-wounded (width between coils turns less) the circular flat spiral coils are, increasing the coil turns in a certain extent, the coil-transfer efficiency can be improved, but too many turns will cause more losses due to parasitic resistance which limits the transfer efficiency. In other hand loosely-wounded (width between coils turns more), the coil-system transfer efficiency can be improved greatly compared to the tightly-wounded coils. Several researchers, scientists given equation for circular spiral coils. The sort design procedure example is as follows.

TABLE 24. Opportunities and challenges for development of WPT.

Area	Challenges and opportunities
Health and safety	There is concern about safe operation of the system regarding EMI. This requires more attention and research towards shielding and foreign objects detection methods (which are capable heating up).
Fast charging	As per present requirement and competition with plug-in charger. We need to design charger that are capable charging the vehicle within 15 minutes. Therefore exploring ultra-fast chargers (>200kW) is need to be done.
Construction and installation	Main challenge related DWPT system is integration with existing system. These areas are to be concentrate while developing 1.selecting materials which generate low losses.2.mechanical integrity 3. Mechanical structure. Another issue are optimization infrastructure and reduce the cost of the system societal impacts of large scale infrastructure deployment
Power metering	Another issue need to be concern is power billing which is accurate, trustworthy billing reliable and safe method from cyber-attacks. Another problem with metering is different companies charging companies charges different rates for per unit.
Cyber security	Due to the development IT and web technologies, now a days we are integrating transportation mechanism and communication mechanism with different devices to operate easily. This system can be easily targeted by miscreants to damage the system. There is need to develop a security system which is capable of handling such attacks.
Interoperability	Testing and evaluation of interoperability between different kinds of designs, which are more interoperable than others.
Pad design and Magnetic materials	There is a need of Novel pad designs that are capable of fast charging, low cost, misalignment tolerant, interoperable with many pads. To achieve that Search for new magnetic materials compositions and new designs are required for further development of WPT charging systems.
Durability	These WPT systems need to be installed outdoors and Dynamic and quasi-dynamic system installed on the roads. Robust system required developing, that handles the harsh environment, operating conditions, offers low maintenance and longer durability.
Standardization	There urgent requirement to develop global standardization which solves problems related to power supply adaptation, magnetic couplers designed by different manufacturers, interoperability, different levels of power, communication and more issues to be addressed.
Grid and distribution	When multiple vehicles on at a time or charging of vehicles at peak times of grid may create burden on distribution system. Issues regarding Power distribution management and charge sharing algorithms need to be developed.
Automated high way systems	In this method private owned vehicle capable of communicating on streets and highways in addition high speed operation on a automated guide way. With this concept, the high way carrying capacity and travelling time can be dramatically increased.
Economy	Need to find more innovative methods to reduce the cost of the materials of the system importantly DWPT Power rail construction.
V2G,V2V technology	Adopting these technologies are very difficult. These technologies helps the grid and customer and makes charging of the vehicle easier.

TABLE 24. *(Continued.)* **Opportunities and challenges for development of WPT.**

Scheduling algorithm	Have to find more reliable scheduling algorithm which supports more vehicles with proper navigation and communication. Technologies like 5G may be helpful.
Power electronic architecture	Need to reduce the power electronic architecture which reduce the size and cost of the system. Power electronic switches, which are capable of handling few hundred kW power at high frequency need to be innovated.
Smart grid	Adopting above mentioned technologies and integrating the grid with renewable power makes grid more reliable and helpful for create fully automated transportation.

The equation for coil inductance for circular coil is given below based on wheelers equation. The design model of circular coil is shown in the Fig. 42.

$$L = N^2 a^2 / (8a + 11c) \tag{21}$$

where,

$$\begin{aligned} a &= \frac{D_{out} - D_{in}}{2} \\ c &= \frac{D_{out} + D_{in}}{4} \\ D_{out} &= D_{in} + 2W + (T + W)(2W - 1) \end{aligned} \tag{22}$$

where, D_{out} is outer diameter D_{in} is inner diameter; T is the spacing between turns; and w is the diameter of the wire used for making the coil.

Based on above equation test model for 3.6 kW with resonance frequency 20 kHz WPT system was simulated in MATLAB software program for the SS compensation values considering the Circular coil having wire cross sectional area. Block diagram of simulated model is shown in Fig. 43. In the MATLAB-Simulink simulation model, instead of using PFC converter we used DC source for the HFI. The simulation results of the voltage waveforms for the different stages are presented in Fig. 45 the top wave shows the input DC voltage, middle wave form shows the voltage obtained from the high frequency and lower wave form is the output voltage from the secondary side rectifier. The simulation parameters used and obtained from the Ansys-Maxwell simulation tool are shown in the Table 23. Flux distribution via FEA analysis is also shown in Fig. 44.

In order to design optimal WPT system there are some factors to be considered during the design and manufacturing process, as depicted in Fig. 46.

IX. FUTURE CHALLENGES AND OPPORTUNITIES

Challenges and opportunities interrelated words, where every challenge is an opportunity and they co-exist for development of WPT for sustainable transportation. By reference in section 8 a series challenges and opportunities are pointed out in Table 24.

X. CONCLUSION

This paper presents the current technology in a WPT system. Wireless technology is currently undertaking intense research in both academia and industry, due to their reliable, convenient, and efficient charging with minimum human interaction. In our review paper and studied literatures there are different types of magnetic coupler designs for both static and dynamic methods and compensation networks, power electronics circuits and architecture, shielding techniques, control system, standards, and communication networks in stationary and dynamic wireless charging. This paper also highlighted miscellaneous features and causes of WPT technologies like batteries, effects of grid integration, V2G, and infrastructure. Furthermore this article addresses issues like cybersecurity, health and safety, DWC infrastructure installation.

Higher efficiency compared to plug-in charger is one of the main goals of the WPT charging systems. This paper lights on some major challenges and hurdles in the way of wireless charging system like health and safety, fast charging, cyber security, interoperability, economy, scheduling algorithm and more as shown in the Table 24. By overcoming these challenges, wireless chargers has ability revolutionize in commercial deployment. However some of the companies already introduced basic EV wireless chargers in the market, still it needs more efficient functionalities. While deploying DWC in real world, ecological, financial, and social impacts of full-scale implementation and performance in terms of efficiency, stability, and dependability must be carefully assessed. Using DWC track as distribution and communication line is to be further studied. Bidirectional integration with grid enables Vehicles to become dynamic energy storage system to support the control of the grid by storing excess of energy generated from renewable sources. Future improvements of WPT technologies are going to determine the full scale commercialization and automation of wireless charging system.

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