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TOPICAL REVIEW

An Empirical Survey on Wireless Inductive Power Pad and Resonant Magnetic Field Coupling for In-Motion EV Charging System

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ABSTRACT EVs are the recent emerging automotive technology in the transportation sector to reduce the CO_2 emission from the internal combustion engine. The issues in EVs technology development are battery tube capacity, heavy-size batteries, fast charging, and safe charging infrastructure. The dynamic wireless charging technology shows a suitable alternative to address the charging system-related issues in EV. However, a limited number of review studies are conducted to specifically address the wireless charging pad design challenges. The wireless inductive power pad and magnetic coupling circuit design are the main factors to decide the performance of the DWPT system. This review analyzes the current developments and challenges associated with wireless charging pad design. Further, this study investigates the potential parameters which improve the performance of a DWPT system to increase the distance traveled (mileage). First, this paper discusses WRIPT technology for DWPT EV charging application, and several parameters affecting the PTE are examined. Also, the aids factors considered for designing the DWPT power pad and different magnetic resonance coupling topologies are presented. In addition, the performance evaluation of the WRIPT power pad, with in-motion testing from the major findings in earlier studies is discussed. Finally, the challenges and opportunities of the WRIPT power pad for in-motion EV charging applications are also addressed. The current state of the art of DWPT and its future directions to make DWPT EV charging systems a full-fledged method are highlighted.

INDEX TERMS Electric vehicle, WRIPT power pad, resonant magnetic field coupling, interoperability, misalignment.

NOMENCLATURE

EVs	Electric Vehicles.
PCM	Phase Change Material.
EMI	Electromagnetic Interferences.
EMC	Electromagnetic Compatibility.
PNP	Power Null Phenomenon.
Tx	Transmitter coil.
Rx	Receiver coil.
Ls	Self Inductance.

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Lm	Mutual Inductance.
Φ	Magnetic Flux.
B	Magnetic Flux density.
J	Magnetic Current Density.
H	Magnetic Field Strength.
WRIPT	Wireless Resonant Inductive Power Transfer.
DWPT	Dynamic Wireless Power Transfer.
QDWPT	Quasi Dynamic Wireless Power Transfer.
S_{Tx}: S_{Rx}	Single Transmitter & Single Receiver.
D_{Tx}: S_{Rx}	Dual Transmitter & Single Receiver.
M_{Tx}: D_{Rx}	Multi Transmitter & Dual Receiver.
D_{Tx}: D_{Rx}	Dual Transmitter & Dual Receiver.
S_{Tx}: M_{Rx}	Single Transmitter and Multiple Receiver.
S_{Tx}: D_{Rx}	Single Transmitter & Dual Receiver.
M_{Tx}: S_{Rx}	Multi Transmitter & Single Receiver.
D_{Tx}: M_{Rx}	Dual Transmitter & Multi Receiver.
M_{Tx}: M_{Rx}	Multi Transmitter & Multi Receiver.
PTE	Power Transfer Efficiency.
K	Coupling Coefficient.
DD	Double D.
DDQ	Double D and Q.
DDC	Double D and Circle.
BP	Bipolar pad.
FEA	Finite Element Analysis.
LOD	Live Object Detection.
FOD	Foreign Object Detection.
MOD	Metal Object Detection.
FWD	Falling Weight Deflectometer.
MoRTH	Ministry of Road Transport and Highways.
ISO	International Organization for Standardization.
IEC	International Electrotechnical Commission.
SEA	Society of Automotive Engineers.
ORNL	Oak Ridge National Laboratory.
NREL	National Renewable Energy Laboratory.
ICNIRP	International Commission on Non-Ionizing Radiation Protection.
HMI	Human-Machine Interface.

I. INTRODUCTION

EVs are introduced into the market as retrofitted battery-operated vehicles with the integration of IC engines and regenerative braking systems. EV benefits society and the ecosystem to achieve a sustainable environment. EV technology is booming for light, medium, and heavy load-operated vehicles, traction, industrial lift trucks, and marine applications. EVs are recharged or reenergized through advanced power modulator topologies and charging methodologies for various power levels [1]. In addition, different onboard chargers with power factor correction topologies are discussed. EV has several benefits, but there were challenges in charging the vehicle and battery energy management. Charging duration of EV with respect to power capacity and range travel distance, addressed by fast charging system. Fast charging systems reduced the charging duration of the EV and raise power charging capacity, which will enhance the distance traveled (milage) by the EV [2]. EV charging system aids the advantage of the utilization of sustainable energy sources and is a promising approach to elevate society toward sustainability which addresses climate change actions [3]. Recently there was a lack of EV charging infrastructures, charging the battery (Energy storage unit) efficiently by developing a suitable energy storage unit, increases in charging duration, and a rise in power demand [4]. The wireless power transfer system has been developed to overcome the risk of handling plugin cables for high power transfer EV chargings. The requirement for battery and charging actions can be addressed by DWPT EV charging systems. Currently, other EV charging technologies available are; plugin static charging, in-motion contact charging, and in-motion wireless charging (Quasi-Dynamic and Dynamic) systems. this paper deals with medium distance contactless charging systems, contactless charging systems developed for EV applications from the faradays law of electromagnetic induction principle.

The historical journey of the WRIPT system with major events is shown in figure 1. In 1831 Michael faraday developed an Electromagnetic Induction experimental setup to derive the principle of electromagnetism [5]. In 1873 Maxwell and Heinrich hertz presented an equation for Electromagnetic energy transmission in free space and experimental verification with Maxwell predictions. In 1888, Heinrich Hertz established and detected Electromagnetic waves by using a spark gap connected to the induction coil and a spark gap on a receiving antenna [6].

In 1890 Nikola Tesla dreamed to transmit wireless power for global usage. In 1897 Nikola Tesla transmitted wireless power through microwave signals for over 48 km [7]. Again with trending history in 1963, WC. Brown transmitted microwave wireless power [8]. In 1976, DWPT technology was first introduced, and evolved its system feasibility at Lawrence Berkley National Laboratory (LBNL) [9]. In 1993, UOA patented a Non-Contact Power Distribution system. In 1996 General Motors introduced a magnetic coupled inductive charging system for EVs, side with the commercialization of stationary charging systems started between 1997 to 1998 by Conductix-Wampler [10]. In 2007 marin salfacia demonstrated the experimental model for a WIPT system to power the bulb [11]. In 2009 the Online Electric Vehicle OLEV project was conducted by KAIST (Korea Advanced Institute of Science and Technology) [12]. In 2011 Nissan Leaf Prototype inductive electric car charging system at the Tokyo Auto show [13]. In 2016 Bombardier manufacture the PRIMOVE up to 200kW for the first inductively charged EV Bus line. In 2017 WiTricity collaborated with Nissan corporation on Wireless charging for EVs. This charging the EV with WRIPT technology reduces the charging time duration, which is applicable for high-power power fast charging applications, but there will be a huge

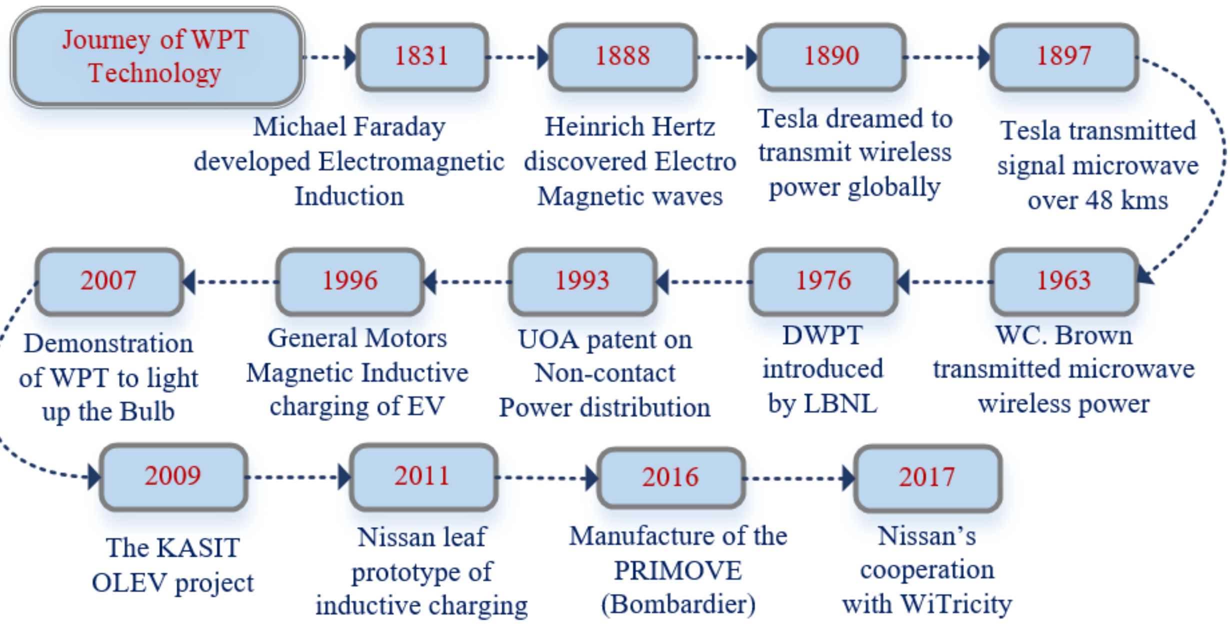


FIGURE 1. Historical journey of the WRIPT system.

raise in power demand. Especially charging the EV during inmotion (Quasi Dynamic / Static state of power transfer) has huge benefits.

In-motion stands for Dynamic and Quasi-Dynamic charging systems; it is also beneficial for static state charging. Another benefit of in-motion wireless charging is capable of fast charging applications. In-motion WRIPT charging system has the potential for carbon emission reduction [14]. In-motion WRIPT systems are classified into; primary wireless source power transmitter unit, secondary device pick-up unit, and magnetic resonance inductive coupling topology. The primary wireless source power transfer unit transmits high-magnitude inductive power with high frequency (79 – 90 kHz) as per international standards. The secondary pick-up device receiver unit moves above the primary Tx unit; it picks up the primary transmitted high-frequency magnetic flux from transmitter coils from the intermediate wireless region through inductive links [15], [16]. Efficient power transfer between Tx and Rx coil is achieved by establishing effective or strong resonant magnetic coupling links. The effectiveness of magnetic coupling links is enhanced by reducing the misalignment between the Tx and Rx coils. Primary Tx and secondary pickup Rx coils are inductively coupled through the wireless inductive medium with coupling coefficients of cross-couplings and trans-coupling links [17].

Primary coils are embedded on running e-roadways in adjacent sequences, and secondary coils are mounted underneath the moving EVs. Primary coils are energized through a high-frequency power modulator, and secondary coils pick-ups the established magnetic flux through inductive coupling links from the interleaved wireless region. Wireless power transfer has considerable benefits in various platforms for various applications. But, it inculcates a lot of technical challenges, which would slow down the technology enabling and advancement to exchange EV charging technology [18]. WRIPT in-motion EV charging systems are the most demanded technology nowadays to motivate EV users to charge user-friendly. In-motion EV charging involves dynamic charging in highways, traffic roads, and urban lanes [19]. The effectiveness of magnetic coupling is affected due to vertical distance variation or misalignments during the quasi-dynamic moment due to stretches in the roadways [20].

The most common challenge in WRIPT is misalignments (more significant air gap) between the Tx, and Rx coils will directly affect the coupling coefficients between coils. Minor misalignments are compensated and regulated using an inductive resonant compensator in primary and secondary units. A primary compensator was introduced to transmit adequate power toward the receiver coil. The ultimate duty of the Tx coil is to maintain higher flux density (B) in the intermediate airgap region. Also, the compensator unit regulates the square wave inverter output magnitude to the alternating sine magnitude. The equivalent circuit analysis and characteristics of an inductively coupled power transfer system, fabrication of resonant coil, leakage inductance analysis, and power enhancement techniques are discussed [21]. Static and dynamic WRIPT charging of EV's economic feasibility is analyzed, and WRIPT power pad layers with electromagnetic shielding. Also, it states the state of the art of the latest application in developing WPT systems to charge the EVs during static and in-motion applications [22]. The WPT energy efficiency, transmission distance, magnetic coupling architecture, benefits of the effective inductive couple, commercial journey, safety factors, emerging WPT topologies, and the latest communication techniques enable efficient technology investigated. Commercial benefits of WPT, electromagnetic safety analysis, and security operation is the critical enabler for accelerating the adoption of e-mobility to drive a greener future [23]. The analysis of influencing magnetic coupling factor is investigated, along with the physical geometry of the coil, physical dimensions, type of magnetic core, coil conductor, and the mutual position of Tx and Rx are analyzed on the properties of the WPT system [24]. WRIPT system is operated at high frequency, and Litz conductors are preferred to make WRIPT pad. Litz wire in high-frequency applications reduces the conduction losses depending upon the inner structure of the wires; frequency-dependent losses differ significantly. The influence of inner skin and proximity effects on the conductor in Litz wire affect the performance is investigated [25]. Magnetic ferrite cores are kept in an optimized potion to establish even flux distribution. The electromagnetic shielding layer in the power pad will enclose the coil and magnetic core and control the emission. The WPT guide provides practical development of the WRIPT system for EV charging applications, along with its safety standards and functionality of the power transfer system [26].

EV charging is classified into different power capacity ranges is classified into Level – 1,2, and 3 charging; Level – 1 charging with a low power rating (120 Volts) takes more time duration to recharge the battery, and Level – 2 charging voltage ranges between (208 – 240 Volts) benefits only for average distance and duration to recharge the battery. respectively, these charging system levels are applicable only to low and medium wireless inductive power transfer distance applications, preferred for WPT infrastructure development in domestic and office. Also, power transfer in these levels undergoes more system losses and affects the PTE. Level-3 charging voltage ranges between (400 – 900V) with high power capacity power transfer, transferring a high range of power will reduce losses and enhance PTE [27], [28]. This can be preferred for WPT infrastructure development for public use by constructing E-roadways.

WRIPT with higher power capacity EV charging systems is called fast charging or supercharging systems. In a wireless fast charging system, current carrying capacity is increased, and the size of the power pad, temperature, and weight are also increased. wireless fast charging benefits the EV charging system by reducing the need for a battery, and charging duration, increasing the range of vehicle travel, speed of the DWPT charging vehicle, and intermediate distance between Tx and Rx coils [29]. Due to the very high power capacity of the EV charging system, there was a challenge in designing components of EMI shielding, power semiconductor switches, and the selection of passive compensator elements [30]. Comparatively the cost of installation is higher for a wireless fast-charging system, which reduces the system losses and enhances the system efficiency [31]. Charging infrastructure development is the main challenge in EVs, it limits the driving distance, charging downtime, and cost of the battery. In-motion WPT charging system overcomes the above challenges by moving over the charging infrastructure remotely for public usage.

The main focus of developing the WRIPT system for EV charging applications is to address the challenges associated with static WPT and plugin EV charging systems. In DWTP, to achieve high power transfer at a lower level of misalignment, magnetic coupling is to eliminate the Power Null Phenomenon (PNP) and zero power angles, to enhance WRIPT efficiency. This paper describes concepts associated with DWPT technology and factors considered for developing inductive power pad coil design with the usefulness of soft computing optimization techniques. In addition, significant parameters were considered to develop the DWPT system, and finally, the challenges and future opportunities or research gaps with the DWPT EV charging system.

II. WRIPT TECHNOLOGY FOR IN-MOTION EV CHARGING APPLICATION

Dynamic WRIPT EV charging system operates for near-field magnetic resonance by the governing principle of Ampere's circuit law and Faraday's law. According to ampere's circuit law, an AC generates a time-varying magnetic flux established around the conductor. Then established flux is wirelessly coupled to the secondary coil through inductive coupling links; the Rx coil pick-ups the voltage from the magnetic field generated by the Tx coil current and the no. of turns of the Tx coil as governed by ampere's law equation (1). The magnitude of the induced emf voltage in the pick-up Rx coil is proportional to the coupled flux and no. of turns in the coil, which is governed by faradays law equation (2).

$$\oint_{C} \mathrm{B.dl} = \mu_{\mathrm{O}} \mathrm{N_1 I} \tag{1}$$

$$\mathrm{V} = -\mathrm{N_2}\frac{d\phi}{dt} \tag{2}$$

where N_1 and N_2 are the no. of turns on the Tx and Rx IPT coils. Magnetic field density is denoted as 'B', and 'C' is the denotation for the curve integration of the boundary. '$\mu_{o'}$ is the permeability of the air region, 'I' is the primary coupling current, V is the induced voltage in the secondary coil, and 'ϕ' is the magnetic flux coupled to the secondary pick-up Rx coil. WRIPT system contains a pair of Tx and Rx coils inductively linked and physically isolated from each other. So, it is referred to as a loosely coupled transformer [32]. WRIPT technology for in-motion EV charging benefits not only increases the travel range of the EV but also reduces the need for the battery or the size of the battery. DWPT can potentially address the charging issues in EVs, especially charging infrastructures, fast charging, and plugin challenges. Besides all these factors, it is more flexible, reliable, and robust in EV charging systems. But still, the WRIPT system introduces challenges in in-motion EV charging, such as; interoperability of different power pads, misalignments, EMI, leakage flux, low PTE, and high cost compared to the plugin charging system [33], [34]. These complexities should be addressed by further investigations on the component and system level of WRIPT technology. The block diagram of the in-motion WRIPT system is shown in figure 2, which can be classified into the primary transmitter unit and secondary pickup unit. The primary Tx unit was installed on the roadway's surface, and the secondary Rx unit was underneath the in-motion vehicle. The primary unit comprises the full bridge rectifier (AC-DC), high-frequency power modulator (DC- high-frequency AC), primary resonant compensator (regulating the HF AC power), and power Tx coils (Track) in an adjacent sequence. The secondary pick-up unit comprises the pickup Rx coil, secondary compensator (regulating the pick-up power), high-frequency power converter (HF AC to DC), and DC load or battery.

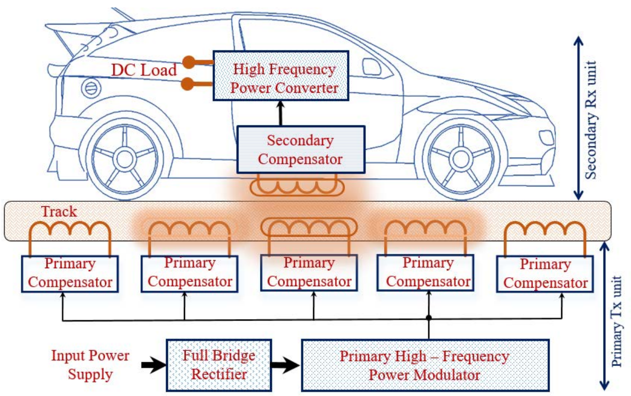


FIGURE 2. WRIPT Technology for In-motion EV charging.

WRIPT overcomes the challenges associated with the plugin and static charging systems; EVs' slow charging rate and travel range (mileage) issues must be avoided [35]. Instead of charging the EV at a static or rest position charging during in-motion along the track will benefit by reducing charging duration, which is called an in-motion charging system. Here the transmitter pads are embedded in the roadway surface, Rx pad on the EV. Embedding the transmitter pad on the road surface is a complicated process requiring more investigation to optimize the tracks for in-motion EV charging applications. The track or transmitter power pad is classified into two: stretched and lumped. Long track coil is suitable for highways, the length of the coils is limited by the range of inductance of the transmitter unit, and it evenly requires higher input voltage.

The construction of the tracks shown in figure 2 consists of many Tx coils embedded in adjacent sequences, which is feasible to implement on roadways. The benefit of this is that it can address any faults in the adjacent coil to supply power continuously [36]. But the cost of installation and PTE during in-motion magnetic coupling leads to misalignments are the challenges caused by lumped tracks. PTE efficiency is reduced to 50% in the middle of the two pads; it again starts increasing during coils effectively coupling directly and reaches max PTE.

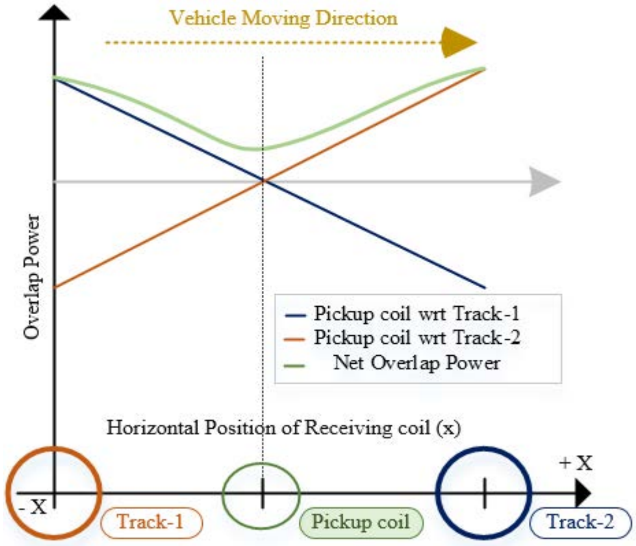


FIGURE 3. Power fluctuation along the DWPT EV charging.

The position of coils aligning during transients between two Tx coils is shown in figure 3. This in-motion charging system is also suitable for static charging applications, but the misalignment tolerance in the magnetic coupling region will result in power transfer capabilities. However, for in-motion cases, most of the single-geometry coils are not the best suitable to achieve maximum PTE; in some cases, it undergoes the PNP effect, also during the horizontal offsets exist, around 38% of the diameter of the power pad between Tx and Rx [37], [38]. To investigate the physical geometry of the coil, which does not undergo the PNP effect, DD is tested along the y-axis in motion and results well. For in-motion charging applications DD or DDQ coil in the Tx unit and DD in the Rx unit will perform well [39]. DD, DDQ, and BP pads perform better misalignment tolerances and are suitable for static and in-motion WRIPT applications [40]. Introducing online EV means deploying the EV with the WRIPT system on the roadways, which operates around 20 kHz to Tx power wirelessly in-motion charging system, which will address the battery capacity issue, weight, and cost of the battery in EV [41]. WRIPT coil works in the resonant frequency of operation by utilizing the Reactive Resonance Current Loop principle to cancel the effect of the unstable magnetic field [42]. WRIPT system is designed and installed through resonance frequency at 22kHz with pulse width modulation for the Online Electric Vehicle system. Various parts of the WRIPT system have been designed for maximum efficiency by considering structural coil design, wireless transmission system, power modulator, rectifier, regulator, and electromagnetic safety. The experimental model was designed for 100 kW and obtained an efficiency of 80% at an air gap of 26 cm. Electromagnetic shielding for the magnetic leaking to the surrounding areas was within the safety limit as per ICNIRP guidelines [43].

Various parameters which affect the WPT PTE are; interoperability, leakage flux, and misalignments. Interoperability in the WRIPT system means that any EV with a different physical geometry structure of IPT coil should be suitable to charge with selected Tx power pad coil geometry (e.g. Triple quadrature pad) from Tx coil [44]. To achieve interoperable features for WRIPT power coil with selected magnetic coupling topology at different air gaps with optimum efficiency is investigated [45]. Interoperable specifications of the Tx coil play a significant challenge among coupling systems in the WRIPT intermediate magnetic coupling units, which required more examination to ensure the coil will operate for universal geometrical structures. Magnetic leakage flux in the WRIPT system will get affected due to the frequency of a WRIPT system, which ultimately improves its efficiency. The resonant compensator network is integrated into a series-parallel combination to regulate the power transfer through an intermediate wireless medium [46]. Magnetic flux leakage has been minimized by optimizing or altering the structure of the magnetic ferrite core. It is one of the chief factors considered while designing the WRIPT power pad, also the selection of shielding to limit the leakage magnetic flux [47]. Misalignment is the case of primary and secondary power pad coils inductively coupled with each other; if the coupling is perfectly aligned for cent percentage directly, this position of magnetic coupling is a perfectly aligned position or ideal alignment position. From an efficiency point of view, this case will get affected due to vertical axis distance variation. If there is any misalignment is introduced during the magnetic coupling of coils will affect the PTE. During such misalignment cases, by establishing further magnetic links in the coupling region, a specific alignment limit is controlled through resonant compensator topology for minor misalignments [48].

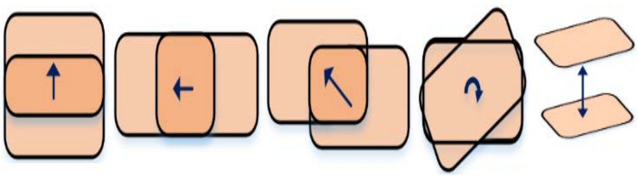

a) b) c) d) e)

FIGURE 4. Misalignments. a) Y-axis. b) X-axis. c) XY-axis. d) Rotational axis. e) Z-axis.

Figure 4 shows the various possible misalignment cases in the intermediate magnetic coupling region between primary and secondary power pads. Primary and secondary Rx will introduce misalignments in the horizontal and vertical axes. Horizontal misalignments undergo; Y-axis, X-axis, XY-axis, and Rotational axis. Vertical misalignments undergo in Z-axis. This misalignment will reduce the coupling between Tx and Rx, affecting the power transfer capacity due to misaligned couplings or uncoupled systems. Misalignments are spread in random directions with possible cases in figure 4, and flux will not get coupled in Tx and Rx. In these cases, flux spreads into the surroundings in a random direction and may cause danger to living beings by reaching above the threshold safety limit. The ICNIP standard magnetic flux limit is set to 27 μT for the high operating frequency between 10kHz to 100kHz [49]. These undesirable features of the magnetic flux leakage in IPT coils should be set to zero ideally [50].

Magnetic coupling coefficients factor ‘k’ is the distance between primary Tx and secondary Rx. Coupling factor k is calculated by using equation (3). The total impedance in the coupling IPT coils is calculated using equation (4).

$$M = K\sqrt{(L_1.L_2)} \tag{3}$$

$$L_{total} = L_1 + L_2 \pm 2M \tag{4}$$

Usually, the magnetic coupling ratio ‘k’ range between 0 to 1; it highly depends on the distance between Tx and Rx coils. The L_1 and L_2 are the self-inductance of the primary Tx and secondary Rx coils; the sum of L_1 Tx and L_2 Rx with tolerance factor 2 ‘M’ will result in total inductance of the IPT system L_{total}. Increased airgap distance between Tx and Rx will cause decreases in the ‘K’ value, affecting PTE. Various power pad coil geometry is compared based on the coupling coefficients. The optimal coupling range of ‘K’ for WRIPT ranges between 0.1 to 0.25 [51]. WRIPT output power transfer equations are given in equations (5) and (6), which will impact the importance of designing an efficient magnetic coupling structure.

$$P_{out,sec} = V_{sec,op} * I_{sec,sc} * Q_{sec} \tag{5}$$

$$\begin{aligned} P_{out,sec} &= \omega * \frac{M^2}{L_{sec}} * I_{pri}^2 * Q_{sec} \\ &= \omega * I_{pri}^2 * K^2 * L_{pri} * Q_{sec} \end{aligned} \tag{6}$$

where; $V_{sec,op}$ is the secondary Rx coil open-circuit voltage, $I_{sec,sc}$ secondary Rx coil short-circuit current, Q_{sec} is the secondary coil quality factor, ω is the angular frequency. The product of three parameters ($V_{sec,op}$, $I_{sec,sc}$, Q_{sec}) is known as uncompensated pick-up power across the secondary Rx coil. Q is the measure of the efficiency of a WRIPT power pad which should not be too low. The optimal value of Q range between 4 to 10 due to the stability and sensitivity factors [52]. Also, the Q factor depends on the type of resonant compensator topology.

A. PRIMARY AND SECONDARY WRIPT POWER PAD LAYERS

A WIPT system combines a primary power source transfer unit, a secondary pickup receiver unit, and a magnetic resonance coupling architecture. The primary power source transfer unit is a power transfer charging unit that establishes magnetic flux into the intermediate wireless region. It contains; a resonant coil, magnetic ferrite cores, electromagnetic shielding, and PVC encloser, as shown in figure 5 a.

Tx coils are embedded into the e-roadways to effectively establish the magnetic field over the surface of the roadways toward the receiver coil through intermediate inductive links. The main objective of the WIPT Tx coil is to transfer higher magnetic flux density (B) toward the receiver pick-up coil. The secondary pick-up receiver power pad contains; a coil that extracts the maximum magnetic flux from the

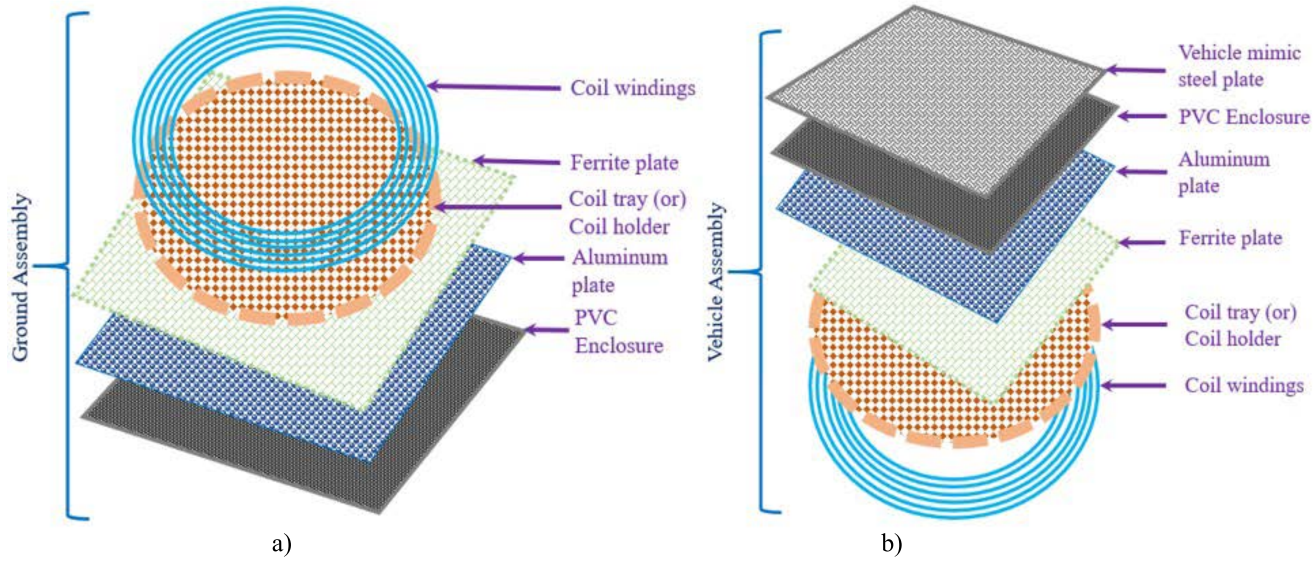


FIGURE 5. Exploded View of WRIPT power pad Layers. a) Primary IPT Pad. b) Secondary IPT Pad.

intermediate wireless region through inductive coupling links.

The secondary receiver unit, along with the coil tray, magnetic ferrite plate, electromagnetic aluminium plate shielding, PVC enclosure, and vehicle mimic steel plate, is shown in figure 5 b. It picks up the captured magnetic flux from the Tx coil through intermediate wireless inductive links. It picks up the current in the receiver coil and will be converted to direct current for powering the EV or recharging its battery [22], [53], [54]. The constructional arrangement of the power pad, material selection, and structural geometry design for the WIPT Power Pad is discussed [55]. Also, it generalizes the idea for material selection and modeling of the WRIPT coil power pad.

In the WRIPT EV charging application, the primary transmitter pad & secondary receiver pads are layered to achieve maximum power transfer efficiency by considering the safety standards of electromagnetic field emission. The transmitter and receiver power pads are constructed to establish effective coupling in intermediate wireless power transfer regions. Various power coil design geometrical structures and magnetic resonant couplings are discussed in the following sessions will empower the design plan of the Efficient WRIPT EV charging system.

B. MAGNETIC FLUX ESTABLISHMENT IN WPT INDUCTIVE COUPLING LINK

Magnetic flux is established between primary Tx and secondary Rx coils in the intermediate wireless region, ideally by linking inductively coupled systems. Magnetic coupling designs/ inductive coupling links/coil topologies/ identical or interoperable wireless coupling can be classified based on their direction of magnetic flux establishments. Magnetic flux established in the intermediate wireless region

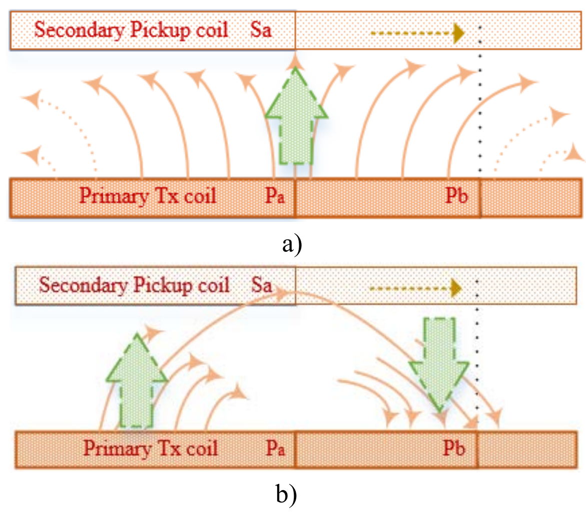


FIGURE 6. Magnetic Flux established in WIPT Power Pad. a) Perpendicular flux from Tx passing towards Rx. b) Parallel flux from Tx passing towards Rx.

(air) is susceptible to three categories; a) polarized, b) Non-Polarized, and c) Both Polarized and Non-Polarized [37].

Wireless inductive power Tx coil establishes magnetic flux is susceptible to vertical flux established in the vertical axis towards Rx coil. Power pads are coupled parallel or horizontally to transfer magnetic flux between the power pads. The magnetic flux established by the polarized pads and Non-Polarized pads is perpendicularly passing through the pick-up pad and parallelly passing through the pick-up pad. The types of polarized and Non-polarized pads can generate both types of flux patterns depending upon their phase currents. The classification of the polarized and non-polarized magnetic flux in Tx and Rx power pad establishments is shown in figure 6 [56].

Non-Polarized power pads establish magnetic flux, which is suspected to be perpendicular magnetic flux establishment.

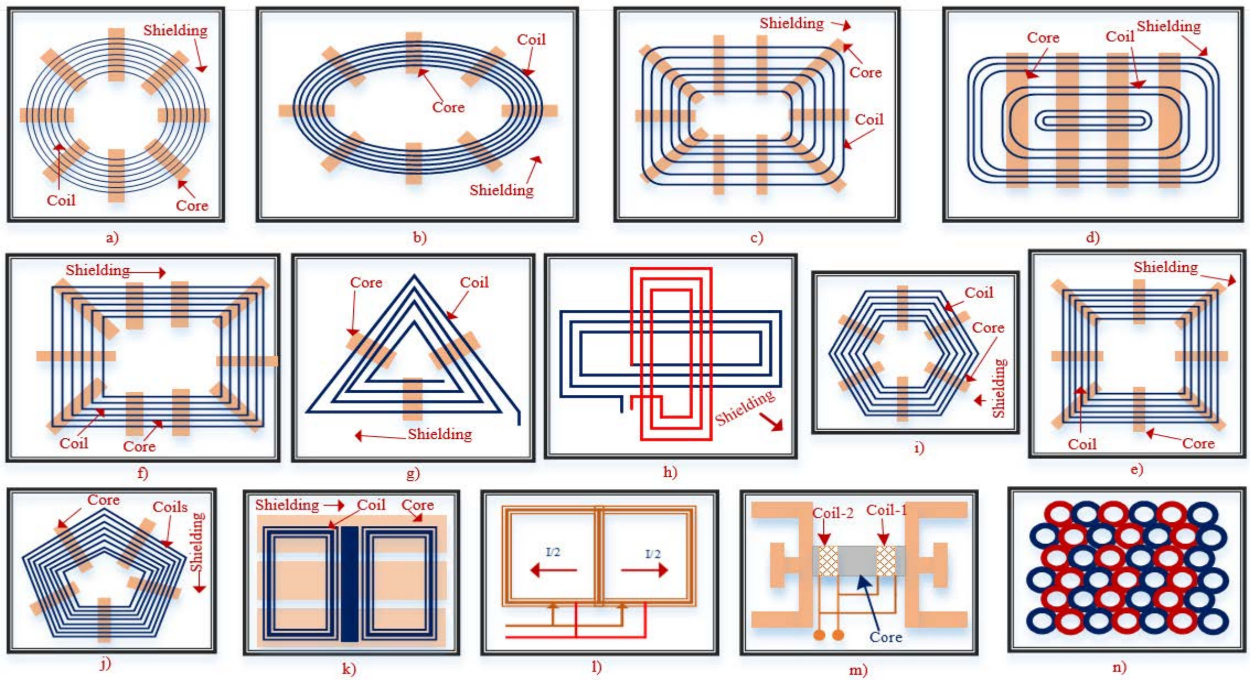


FIGURE 7. Geometrical structures of static WRIPT power Pads. a) Circular. b) Elliptical. c) Circular Rectangular. d) multi-Threaded. e) Square. f) Rectangular. g) Triangular. h) Cross-shaped. i) Hexagonal. j) Pentagonal. k) X pad. l) Segmented pad. m) Flux Pipe. n) Homogeneous Pad.

TABLE 1. Static WRIPT power pads.

Physical Geometry	Polarization	Interoperability	Misalignment	Efficiency (approx. %)
Circle [60]	Non-polarized	Very Low	Poor	85 – 95
Elliptical [61]	Non-polarized	Very Low	Medium	70 – 75
Circular Rectangular [62]	unipolar	Low	Medium	–
Multi-Threaded [63]	polarized	Low	Medium	65 – 70
Square [64]	unipolar	Low	High	85 – 90
Rectangular [65]	Non-polarized	Low	Medium	75 – 90
Triangular [66]	unipolar	Low	Medium	–
Cross-Shaped [67]	unipolar	Low	High	>90
Hexagonal [50]	Non-polarized	Low	High	>90
Octagonal [68]	Non-polarized	Low	High	>85
Pentagonal [69]	Non-polarized	Medium	Medium	–
X-Pad [70]	Bipolar	High	High	90 – 95
Segmented [71]	Bipolar	High	High	–
Flux Pipe [72]	unipolar	Low	High	>80
Homogeneous [73]	Polarized	Very Low	High	–

Various geometrical structure coils with the type of polarization are differentiated in tables 1 & 2 for static and in-motion applications. Most single geometrical coils are not much polarized with multiple polarization [57], [58]. Multiple polarization in the coil surface will solely address the misalignment issue by performing interoperability operations in the WIPT application. Multi-polarized coils are suitable for in-motion wireless inductive power transfer applications, and also, it is suitable for static WIPT applications. Non-polarized and polarized pads can also be categorized as single or double-sided magnetic fluxes based on the magnetic flux that passes through them. WIPT power coils establish magnetic flux based on the types of excitation of the magnitude of currents in their polarity.

TABLE 2. In-motion WRIPT power pads.

Physical Geometry	Polarization	Interoperability	Misalignment	Efficiency (approx. %)
Booster Module [74]	Polarized	High	Good	-
DD [75]	Polarized	Non-interoperable	Medium	>90
Layered DD [76]	Polarized	Non-interoperable	Medium	-
Crossed DD [77]	Polarized	Poor	Medium	80 - 90
DD Excitation [78]	Polarized	Low	High	-
DDQ [79]	Polarized	High	High	91 -95
DDC [80]	Polarized	High	High	>90
Meander Type [81]	Polarized	High	High	97
QDQ [82]	Polarized	High	High	85 – 91
Quadrupole [50]	Polarized	High	High	-
Bipolar (BP) [83]	Bipolar	High	high	90 – 95
Integrated Bipolar [84]	Polarized	-	High	-
Poly-phase [85]	Polarized	Medium	High	90 – 95
Tri-polar [86]	Tri polar	High	High	91 – 95
Integrated Tri-polar [87]	Polarized	High	High	-
Bipolar Double layer [88]	Polarized	-	High	90 – 95
Two pairs of auxiliary [89]	Polarized	Low	Medium	75 - 85
Three pairs of auxiliary [90]	Polarized	Medium	Medium	80 – 85
Repeater array [91]	Polarized	High	High	75
Rectangular central solenoid [92]	Polarized	Low	High	-
Triple Quadrature [93]	Polarized	Very High	Very High	-

The objective of combining more than coils (multi-coil geometry) is to get decoupled magnetically with each other. This phenomenon of decoupling of multi-coils is called mutual decoupling. The benefit of mutual decoupling is the reduced power requirement from the primary power modulator unit [51], [59]. But complete decoupling is challenging in most geometrical coils because there will always be a minimum amount of cross-inductive coupling within geometry.

C. PHYSICAL GEOMETRICAL STRUCTURE OF THE WRIPT POWER COIL

The physical Geometry of the WRIPT power coil is one of the main factors influencing in efficiency improvement of the WRIPT system. The previous investigations of the WRIPT coils and the physical geometry of the coils are listed in table 1 and table 2. It shows the physical geometry of the listed coil's performances compared with the type of polarization, level of interoperability, and misalignment. Wireless Power Transfer is classified based on its charging states are; static and in-motion (Dynamic and Quasi Dynamic) EV charging states. In the WRIPT system, power transfer efficiency is enhanced by selecting proper physical geometrical coils, considering the type of polarization, interoperability between coils, and misalignments. WRIPT system comprises Tx and Rx coils; the Tx coil has to perform high interoperability and maximum power transfer at low misalignments.

Static wireless power transfer systems charge the EV at the rest position. The efficiency of the inductive power transfer depends on the level of magnetic coupling alignments. Misalignment between Tx and Rx coils in the wireless intermediate region introduces the zero-phase angle issue, which leads to the PNP effect. These parameters affect the power transfer capacity in the WRIPT system. Also, systems will operate with variable frequencies and are subject to a Bifurcation phenomenon. The bifurcation phenomenon occurs with multi-zero phase angle resonant frequency, which makes the system operate in an unstable mode. However, table 1 helps us to identify the best geometrical coils to achieve higher power transfer efficiency for the static EV charging systems. Static WPT coil geometries are shown in figure 7 and dynamic or in-motion WPT coils are shown in figure 8.

Various physical geometrical structures were involved in previous investigations for static WRIPT EV charging systems [60], [73]. Most of the geometrical structures are single geometry coils, and the performance comparisons are listed in table 1 concerning their level of interoperability, misalignments, and type of polarization.

Physical geometries investigated for in-motion applications to find effective geometry of magnetic flux transfer

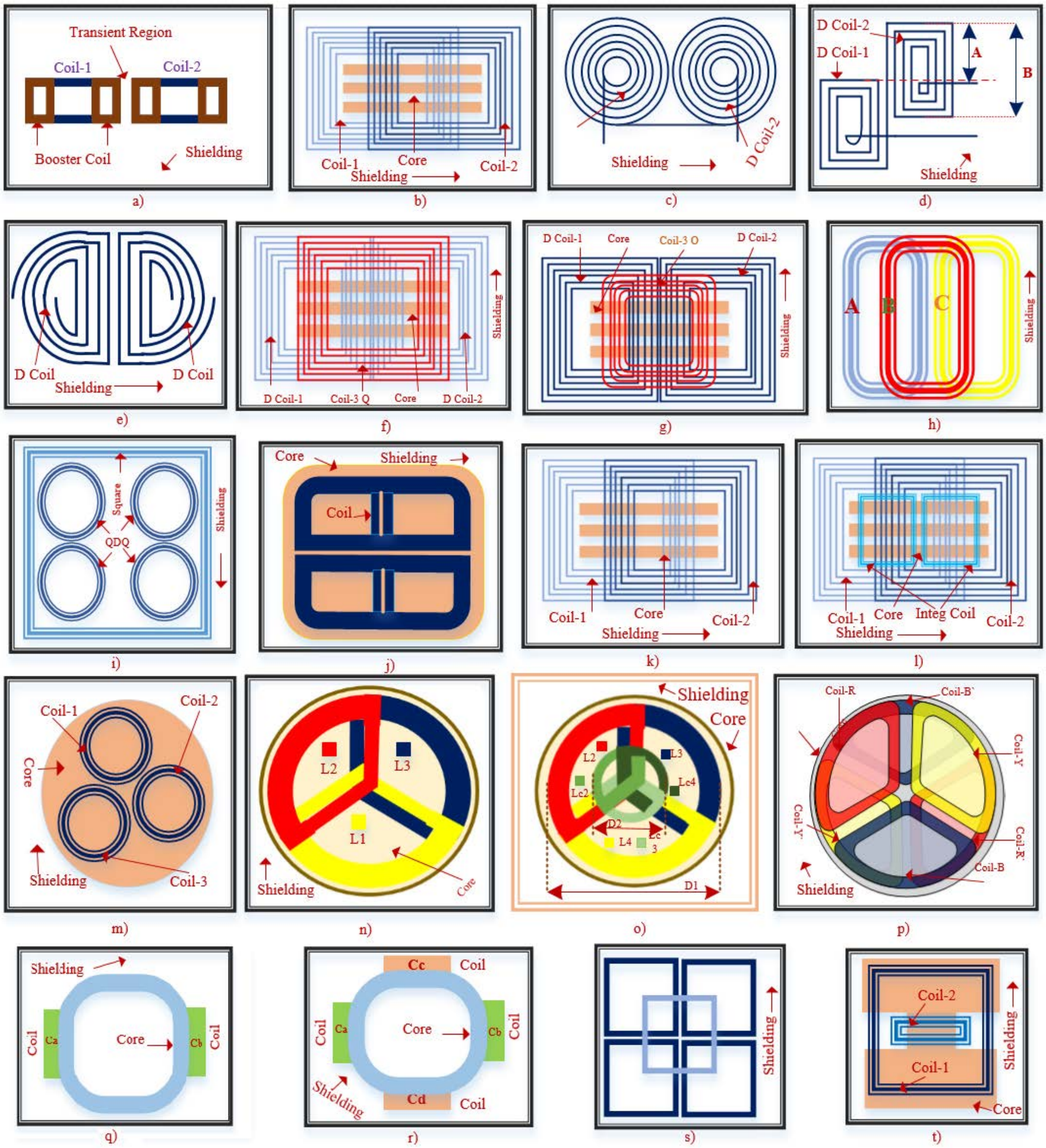


FIGURE 8. Geometrical structures of In-Motion WRIPT power pads. a) Booster module. b) DD. c) Layered DD. d) crossed DD. e) DD Excitation. f) DDQ. g) DDC h) Mender coil. i) QDQ. j) Quadrupole k) Bi-polar. l) Integrated Bi-polar. m) Poly-phase. n) Tri-polar. o) Integrated Tri-polar. p) Bipolar Double layer. q) Two pair auxiliary. r) Three pair auxiliary. s) Repeater array. T) Rectangular central solenoid.

across the intermediate region. The effectiveness of magnetic coupling in the intermediate wireless region, the Tx coil should uniformly maintain flux density to transmit power efficiently toward the Rx coil. Effective magnetic couplings reduce the PNP effect by reducing misalignment during in-motion charging. The objectives of the WPT power pad coil are coil geometry with minimum outer dimension, leakage flux, and PNP effect. The coil conductors should be suitable for high-frequency applications. Coil geometry should be interoperable or adaptable to any other different geometry shape in Tx and Rx. It should establish higher magnetic flux density over the coil surface region.

Figure 8 shows the physical geometries of the in-motion WRIPT system from previous investigations [74], [93]. The list of geometrical coil structures involved in in-motion EV charging systems is also suitable for static WRIPT charging

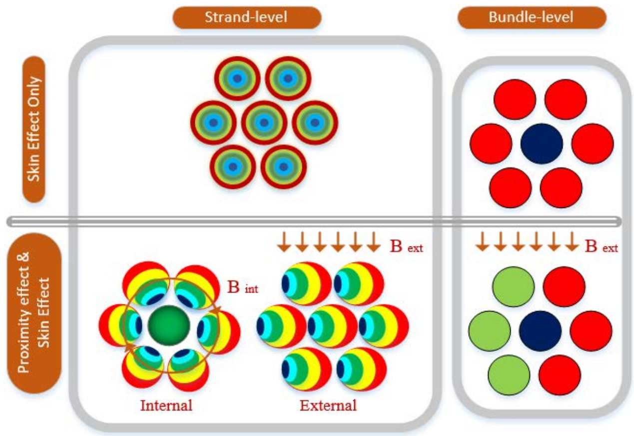


FIGURE 9. Ohmic losses in conductors.

states. The performance (polarization, interoperability, misalignment) comparisons of the in-motion WRIPT power pad coils are listed and compared concerning their operating performances in table 2. Most of the coils available for in-motion applications are combined geometrical coils, which have the potential to establish multiple polarizations with mutual decoupling. It reduces power requirements from the primary power modulator unit [51].

In the DWPT EV charging system, misalignment is the parameter that will affect the WRIPT efficiency. This misalignment undergoes various 3D axis, but it can be minimized by developing an effective coupling topology for in-motion applications. Magnetic coupling topology deals with Tx and Rx coils, and various physical geometries available for in-motion applications are reviewed from previous investigations and listed in table 2. It helps to identify the best physical geometrical coil, which is polarized better to transfer higher flux into the magnetic coupling region and perform high interoperability to transfer higher power at min misalignments.

D. SUMMARY

WRIPT technology for In-motion EV charging systems is discussed along with various factors affecting the PTE of the system are briefed with sufficient literature articles.

The construction of the primary Tx coil and secondary Rx coil for the WRIPT system power pad layers are represented in exploded view and are discussed with references.

The magnetic flux establishment in the interleaved wireless magnetic coupling region as per power coil geometry in three different aspects of polarization are discussed with its importance to enhance the coupling coefficients (coupling and decoupling) within coil geometry.

Then power coil geometrical design parameters is the main objective for effective inductive coupling are discussed with various geometry investigated as per static and in-motion WPT application.

Comparatively, power coil geometry is tabulated with parameters affecting PTE and efficiency of individual power pads from various literature articles calibrated for interoperable and identical cases with respect to various power and frequency ratings from the references.

III. DESIGN CONSIDERATION OF EFFECTIVE INDUCTIVE POWER PAD FOR WRIPT EV CHARGING APPLICATION

WRIPT power coil comprises an inductive power coil, magnetic ferrite core, and electromagnetic shielding. Inductive coils are designed for various geometries, the magnetic core is fixed beneath the inductive coil, and electromagnetic shielding encloses the inductive power pad coil with high-conductivity and low-permittivity metals. In coil design, optimization of the power pad's physical dimension, coil geometry, ferrite core placements, and distance between the core, coil, and shielding to enhance the efficiency of the power transfer pad with optimal design cost. Algorithms designed to optimize various soft computing techniques are discussed in upcoming sub-sections.

A. WIPT COIL

WRIPT power pad coils are designed for various physical geometries; it is selected based on the type of EV charging applications by considering the interoperability and misalignment tolerance level of the physical geometry coils. WRIPT coils are the main component of the DWPT system, where power transfer happens via a wireless time-varying magnetic field region [94]. A time-varying high-frequency magnetic field is established between the primary Tx and secondary Rx coils in the vicinity of the Tx coil to induce voltage. The intermediate air gap distance between the coils, no. of turns in each coil, the coil quality factor, the coupling coefficient, and the magnetic flux establishment over the time duration are the factors that determine the induced voltage. To maximize the power transfer capacity and limit the minor transients due to misalignment, Tx and Rx coils are integrated with a resonant compensator unit. The drop-in power transfer efficiency will result in ohmic losses and loss in magnetic core material with a rising thermal effect. For this high-frequency application, Litz conductors are used to limit the ohmic losses (skin effect and proximity losses) [95], [96]. The proximity and skin effects in standard-level and bundled-level conductors are shown in figure 9.

WPT community designed and proposed various novel power coils to enhance PTE in static and in-motion (quasi-dynamic and dynamic) EV charging systems. New shape power pad coils are listed as DD, DDQ, DDC, Bipolar, and Tripolar pads for static and dynamic EV charging applications [97].

B. MAGNETIC FERRITE CORE

WRIPT power pad comprises magnetic ferrite core/ bars/ sheet layered beneath the Electromagnetic coil along with the coil tray or holder. When the coil is excited with high-frequency power leakage, inductive current flow at the outer

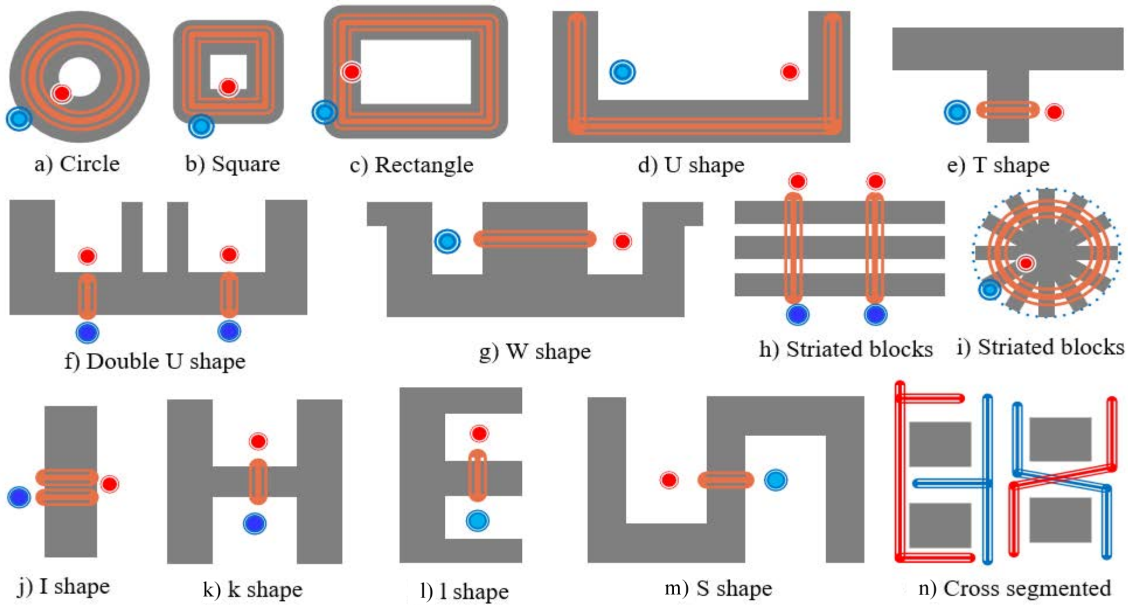


FIGURE 10. Magnetic ferrite core shapes for static and dynamic WRIPT system. a) circle. b) square. c) rectangle. d) U shape. e) T shape. f) Double U shape. g) W shape. h) striated blocks. i) striated blocks. j) I shape. k) H shape. l) E shape. m) S shape. n) Cross segmented.

diameter will link over the magnetic core, guiding the magnetic flux lines to flow and establishing a magnetic field. The main factor considered in the design of a magnetic ferrite core is physical dimension and geometrical structures, in-addition operating frequency, permeability, and optimal cost factor. A magnetic ferrite core is designed to link magnetic fluxes from Tx coils effectively toward the Rx coil side. Selected magnetic ferrite core significantly improves the self and mutual inductance of the inductive coils. The distance between the magnetic ferrite core and coil is maintained optimal in (mm) for effective parameter design of the power pad coils. The readily available magnetic ferrite cores are shown in figure 10 for the WRIPT power pad, and from this, suitable geometry is selected for coil dimensions. Core geometry is selected after optimizing the magnetic core's positions, geometry, and structures [98]. The ferromagnetic core electromagnetic field for selected ferrite geometry is investigated.

C. EMI SHIELDING

In addition to the inductive coil and magnetic core, the WRIPT power coil comprises electromagnetic shielding. The power pad is designed for high-power and high-frequency to transfer electric power from the primary Tx power pad coil to the secondary Rx power pad coil. Wirelessly for medium-distance application with the strengthened magnetic field around the coil region will establish a magnetic leakage field in the coupling region. To control and limit the level of emission shielding layer is then introduced in the power pad. The electromagnetic field emission around the coil is maintained within the safety limit reported by international standards and guidelines [99].

D. WRIPT POWER PAD OPTIMIZATION

WRIPT Power pad optimization was performed for the designed WRIPT power pad for selected geometry structure and physical dimension. Power pad optimization parameters are wire position, spacing between turns, the no. of turns, type of ferrite, and spacing between core, coil, and shielding. Power pad optimization involves three considerations they are classified as; Parameter sweep, Flow chart design, and evolutionary algorithms. Researchers are working and proposing design flow charts to optimize the best magnetic power pad structure. WRIPT Power pad module design is proposed for the entire system by investigation on magnetic pad [100], [101].

The systematic optimization procedure for magnetic power pads is investigated for better PTE [102]. Parameters are identified for all possible configurations to simulate optimal power pad design. Many parameters can affect the power pad performance with an acceptable range of selections, and selected parameters should significantly impact power pad performance [103], [104]. Also, many researchers are proposing evolutionary algorithms to identify the optimum solution for WRIPT power pad design. Soft computing algorithms are developed to enhance efficient optimization solutions of several problems associated with power pad design by considering several parameters investigated [105].

E. SOFT COMPUTING TECHNIQUES

Soft computing techniques convert the input signal to some expected output signal using specific control techniques or actions with the mapping function. In soft computing techniques, the input signal is called an antecedent signal, and the output signal is called a consequent signal. Soft computing approaches address the computing solutions to the

TABLE 3. Various soft computing techniques contribute to the WRIPT system development.

COMPUTING TECHNIQUES	PARAMETERS	OUTCOME
ML strategy based on the NN algorithm for Automatic resonance matching [106]	• Resonant Parameters • Radius, no. of turns, and pitch of Power coils.	• Efficiency 90% • Air gap 100mm - 250mm.
ML-based Reinforcement Learning algorithms, including RF and DNN for Rx coil Position Prediction [107]	• The physical dimension of the Tx and Rx coil, • Position of the coil by; online & offline detection.	• Achieve accuracy of around 95% of prediction. • Air gap distance 980 mm, • Results around 700 at a time duration of 800 sec.
ML-based Reinforcement Learning for magnetic ferrite core optimization using a Q-Learning algorithm. [108]	• Magnetic coefficients, • No. of trialled data, • Target network update period, Learning rate, • initial exploration, • Final exploration, • No. of hidden layers 1, 2.	• Trained data is around 2.3 % out of the total possible cases. • Magnetic coupling co-efficient is also 7% higher than the Air gap distance of around 98cm.
ML-based Reinforcement Learning proposed an algorithm for ferrite core optimization. [109]	• No. of trialled data (Ls, M, K) • Learning rate, • Initial exploration, • Final exploration, • No. of hidden layers-1,2.	• Air gap around 15cm. • Trained data of 0.011% out of possible cases. • Lm is 0.6 % higher than the conventional method. • The volume of the core was reduced to 90 %, and costs were reduced to 90%.

existing complex problems and are an adaptive process that does not affect the environment. Soft computing techniques involve biologically inspired methodologies. It is classified into the following types; Artificial Neural Networks (ANN), Artificial Intelligence (AI), Machine Learning (ML), Genetic Algorithms (GA), Deep Learning (DL), and Fuzzy Logic (FL). Generally, like human nervous systems, genetics, particle swarming, and evolutionary computational techniques.

Soft computing techniques proposed for WPT systems for various components optimization of the system are; coil, magnetic ferrite core, electromagnetic emission shielding, resonant compensator, and magnetic coupling system. High-frequency power modulators are the nervous research gaps in developing machine learning algorithms to simplify system planning, development, and operation. They are implementing a soft computing Machine Learning (ML) strategy algorithm based on soft computing (NN) Neural Network algorithm for the real-time range adaptive automatic resonant impedance matching of the WRIPT system. This proposal aims to effectively predict the resonant parameters to perform automatic tuning operation of resonance parameters in a compensation network for balancing resonance controlled by trained NN models. This model experimentally verified the efficiency for WPT and obtained around 90% for the variable range limited from 100mm to 250mm [106].

The machine learning algorithm applies the multi-coil transmitter power transfer pad to one or more single-coil receivers. In this case ML algorithm involves the online and offline prediction of receiver position using Random Forest (RF) and Deep Neural Network (DNN) for effective position prediction to charge the receiver coil in the WIPT system efficiently. Simulation results show that the proposed RF and DNN perform well for the single Rx coil topology, and for two Rx coil cases, DNN performance is better than RF [107].

The reinforcement learning algorithm is one of the Machine Learning techniques applied to find the suitable ferromagnetic core positions for an effective or high magnetic coupling coefficient between the Tx and Rx inductive power Pads. Also, the selected pad experimentally verified that the core structure has a higher coupling coefficient for a distance of 980 mm between the Tx and Rx Pad [108].

ML algorithm is applied for the WRIPT pad to analyze a core structure to perform effective magnetic coupling between the Tx and Rx pad of the EV wireless charging unit. The proposed design is experimentally verified using Finite-Element Analysis (FEA) simulation-based data mining, and higher magnetic coupling data are trained. A prototype model of a 3.0 KW stationary or static EV wireless charging system was implemented and performed slightly better than a conventional case. Since formula-based theoretical design is not available due to the Non-Linear magnetic field distortion in the ferromagnetic core [109]. The contribution of various computing techniques on integrated WRIPT systems and their outcomes are discussed in table 3.

Furthermore, to improve the WIPT efficiency by applying soft-computing techniques with multi-domain aspects, each block component of the WIPT system is advanced by collaborating with recent technologies. The magnetic coupling architecture of the WIPT system is advanced in selecting the conductor for coil design, the coil's shape, core structure, magnetic coupling alignment of pads, automatic tuning of compensator network for resonance balancing, and control strategies for power modulator unit. Also, in concentration with dynamic moving vehicles, minimum coil misalignment positioning for a certain distance main aim of the pad must be the minimum size with maximum surface flux density with minimum misalignment tolerance between transmitter and receiver pad.

F. SUMMARY

This section deals with the design consideration of an effective inductive power pad for the WRIPT EV charging application. The effectiveness of an inductive power pad depends on the design parameter selection for the WPT system. WPT power pad design parameters are inductive power coil, magnetic core, and EMI shielding. Along with power pad parameters optimization techniques are discussed with various literature articles, to enhance the quality of content in this present article.

WRIPT coils are the main component of the DWPT system, where power transfer happens with higher frequency time-varying magnetic field region. So, the selection of high-frequency Litz with desired skin depth for minimizing conduction losses is discussed in this literature article.

The magnetic ferrite core conducts the magnetic flux lines to well establish the magnetic field in the wireless region. The magnetic core shapes are selected as per the geometrical shape of the coil, core materials are selected as per the frequency range in order to avoid core saturation. Such a way that the magnetic ferrite core should have less magnetic resistance (reluctance) for high-frequency and high-power applications is discussed.

EMI shielding limits the emission from the magnetic field region to nearby regions. Also, it reflects the leakage flux after hitting the shielding and emits it back into the intermediate wireless region to enhance or strengthen the coupling region's magnetic field flux.

Along with this design, various parameter optimization techniques are discussed. The importance and contribution of soft computing techniques are the highlights of the design and development of the WRIPT power pad coil are discussed in several literature articles.

IV. MAGNETIC RESONANCE COUPLING TOPOLOGIES

In Dynamic WRIPT EV charging systems, resonance is the main factor. It must be maintained at resonant conditions to achieve effective inductive coupling between Tx and Rx coils in the interleaved contactless region. The effectiveness of magnetically coupled architecture depends on geometrical structure, physical dimension, and type of magnetic resonant coupling to transfer highly efficient power for in-motion EV charging applications. The intermediate air gap increases between Tx and Rx coils may cause higher magnetic field leakage, which affects the efficiency of wireless power transfer (PTE). Geometrical structure coils are proposed to operate highly interoperable, with low magnetic leakage flux and low harmonics current [110]. Physical dimensions and geometrical coil structure deals with the Interoperability performance, level of magnetic coupling coefficients, and power transfer efficiency [111]. Figure 11 shows the tree of WRIPT power pad magnetic couplers.

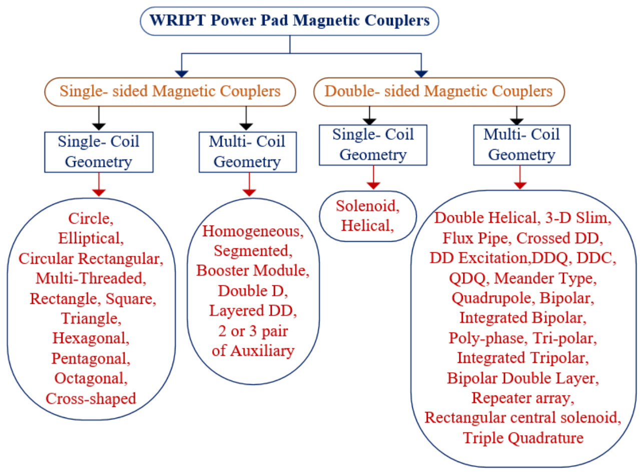
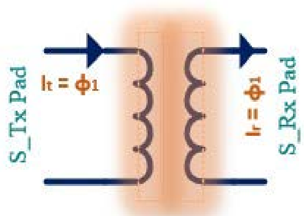
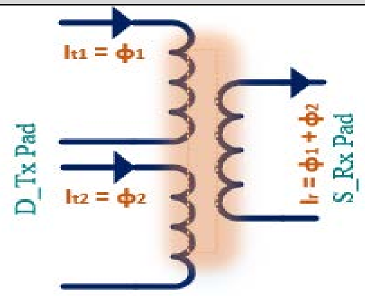
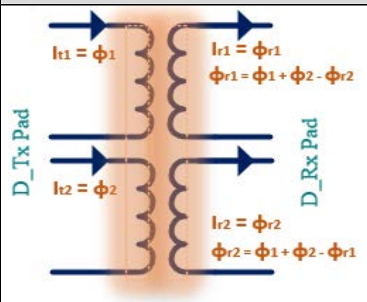


FIGURE 11. Tree of WRIPT power pad magnetic couplers.

The classification of single-sided and double-sided magnetic couplers is listed in the tree. Dynamic WIPT magnetic coupling architecture contains Tx & Rx combined with single-coil geometry and two or multi-coil geometry arrangements investigated for EV charging applications. Two or multi coils indicated more than one coil connected parallel with adjacent sequences combined to construct Tx or Rx pads. These combined coil constructions are; DD, Bipolar, Tripolar, booster pad, X-pad, and segmented coil. Single coil geometry is; square, circle, rectangular, pentagonal, hexagonal, and octagonal. Comparatively, combined coil performance is better for performing Dynamic WRIPT EV charging; single geometry and combined two-geometry coils were also investigated for identical and interoperable cases. The results show that combined coil performance is better than single-coil geometry in identical, interoperable cases [112].

Cost and Efficiency are the most crucial parameters for system design; combined coil cost reduced with core optimization is investigated, and the desired result is obtained [113]. The mutual inductance L_m is an essential parameter in magnetic couplings that can be defined in equation (3). The total inductance of the coil is the sum of the

TABLE 4. Comparison of S_Tx: S_Rx pad, D_Tx: S_Rx, and D_Tx: D_Rx power pad magnetic coupling architecture.

TYPE OF COUPLING	PARAMETERS	PARAMETERS	PARAMETERS
Architecture			
No. of Tx pad	Single ($S_{\_Tx}$)	Double ($D_{\_Tx}$)	Double ($D_{\_Tx}$)
No. of Rx pad	Single ($S_{\_Rx}$)	Single ($S_{\_Rx}$)	Double ($D_{\_Rx}$)
Misalignment	Poor	Medium	Good
Coupling Co-eff	Medium	Good	Good
Application	Static mode	Static & Quasi-Dynamic mode	Static & Quasi-Dynamic mode
Presented in	[115] [116] [117]	[118] [119] [120]	[121] [122] [123]

self-inductance of the Tx coil, and the Rx coil is described in equation (4).

In previous research, various magnetic coupling architectures are investigated for various combined topologies like; S_Tx: S_Rx, D_Tx: S_Rx, D_Tx: D_Rx, M_Tx: S_Rx, S_Tx: M_Rx, M_Tx: D_Rx, M_Tx: M_Rx, D_Tx: M_Rx, S_Tx: D_Rx are discussed in performance comparison tables 4-6 for various magnetic coupling architecture, in-motion WRIPT applications [114].

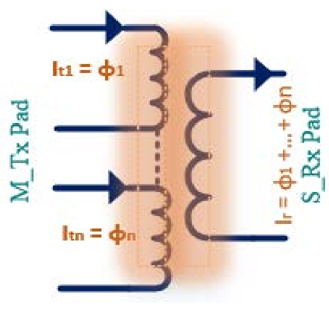
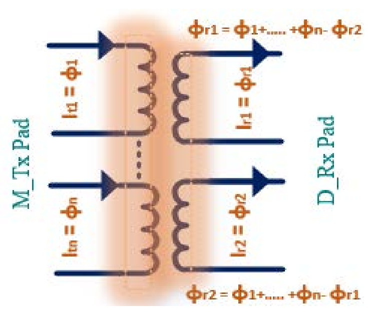
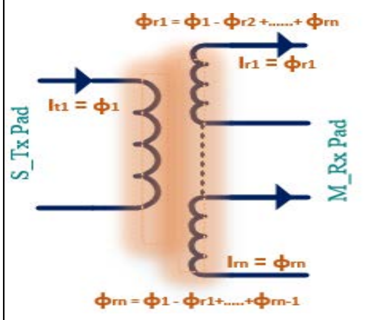
In table 4, S_Tx: S_Rx magnetic coupling architecture combines a single transmitter coil geometry with a single pick-up Rx coil power pad. Current (I_t) in the primary transmitter coil establishes magnetic flux (ϕ_1), and it is inductively linked with the secondary pick-up coil (I_r) and induces emf by linking with the transmitter coil leakage flux in an intermediate contactless medium.

In table 4 D_Tx: S_Rx magnetic coupling architecture, two coils are kept adjacent, enhancing the coil's voltage gradients and ensuring effective coupling coefficients between dual transmitter and single receiver coils. Double Transmitter coil currents (I_{t1} & I_{t2}) will establish magnetic flux (ϕ_1& ϕ_2). It is inductively linked with a Single pick-up coil receiver that will induce receiver current (I_r) due to cumulative magnetic flux (ϕ_1& ϕ_2) is receiver magnetic flux (ϕ_r). This type of magnetic coupling is suitable and performs better for static WRIPT & In-motion WRIPT EV charging applications.

In table 4 D_Tx: D_Rx magnetic coupling architecture, two transmitter coils are embedded in a power pad to transmit magnetic power. Two coils are connected in parallel and excited with a high inverter output power supply. Current through Tx pads (I_{t1} & I_{t2}) will establish magnetic flux (ϕ_1& ϕ_2) over the receiver coil in a contactless air region. The receiver coil will induce the current (I_{r1} & I_{r2}) with the sum of the Tx coil trans-coupling inductance coil magnetic flux (ϕ_{r1}& ϕ_{r2}) through inductive coupling links. Magnetic flux in receiver coils-1 (ϕ_{r1}) is the sum of the magnetic transmitter flux with differential to adjacent receiver coil magnetic flux (ϕ_{r2}). Correspondingly vice-versa for receiver coil-2 (ϕ_{r2}). Dual receiver coils' advantage will enhance pickup coils' voltage gradient through the received flux of cross-coupling inductance between adjacent coils.

In table 5, M_Tx: D_Rx magnetic coupling architecture, more than two coils are constructed in adjacent sequences to transmit higher magnetic flux into the intermediate contactless medium will ensure magnetic solid flux density over the transmitter coil's surface. Current (I_{t1}, $I_{t2} \ldots I_{tn}$) supplied to the transmitter coils will establish magnetic flux ($\phi_1, \phi_2 \ldots \phi_n$) is linked over a single receiver secondary coil will induce receiver coil current (I_r) to collect the transmitted power from the Tx coil. The Pick-up current results from the cumulative combination of multiple transmitter magnetic fluxes. It depends on the coil alignment position over the multiple transmitter coil flux links. Multiple transmitter coils will enhance the effectiveness of power transfer and reduce horizontal misalignment tolerance. Here the multi-transmitter ensures the effectiveness of coupling to transmit efficient power to the pick-up coil. This topology can be preferred for constructing effective e-roadways for In-motion wireless EV charging applications.

TABLE 5. Comparison of M_Tx: S_Rx, M_Tx: D_Rx pad, and S_Tx: M_Rx pad magnetic coupling architecture.

TYPE OF COUPLING	PARAMETERS	PARAMETERS	PARAMETERS
Architecture			
No. of Tx pads	Multiple ($M_{\_Tx}$)	Multiple ($M_{\_Tx}$)	Single ($S_{\_Tx}$)
No. of Rx pads	Single ($S_{\_Rx}$)	Double ($D_{\_Rx}$)	Multiple ($M_{\_Rx}$)
Misalignment	Good	High	Good
Coupling Co-eff	High	High	Good
Application	Static, Quasi-Dynamic & Dynamic	Static, Quasi-Dynamic & Dynamic	Static, Quasi-Dynamic & Dynamic
Presented in	[115] [124] [125]	[126]	[115] [127] [128]

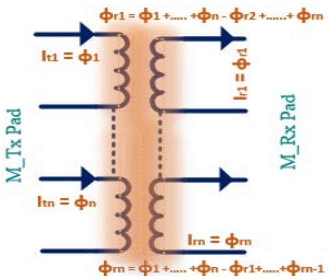
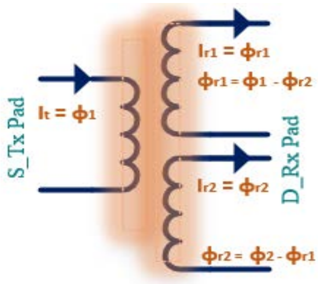
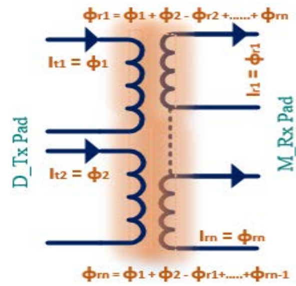
In table 5, M_Tx: D_Rx magnetic coupling architecture, multiple transmitters are embedded on electric roadways to transfer efficient power into the intermediate wireless region. Multiple coils mean more than one coil is mounted adjacent sequence in the transmitter unit, enhancing the inductive link through cross-coupling links within transmitter coils. It will improve voltage gradients between the multiple transmitter coils. The currents ($I_{t1}, I_{t2} \ldots I_{tn}$) flowing through multiple Tx coils produce magnetic flux lines (ϕ_1, ϕ_2, $\ldots \phi_n$), Which are linked with double Rx coils. These magnetic flux linked with Rx coil pickups the current (I_{r1} & I_{r2}) through magnetic coupling links (ϕ_{r1} & ϕ_{r2}) in the intermediate wireless region. Magnetic flux ϕ_{r1} is the cumulative sum of multiple transmitter coil flux differential with adjacent coil flux ϕ_{r2}. This combined architecture has several benefits compared to other types of magnetic coupling architecture.

In table 5, S_Tx: M_Rx magnetic coupling architecture single transmitter coil transmits magnetic flux into the intermediate wireless link. Exciting the high-frequency current (It1) to the primary coil will establish magnetic flux (ϕ_1) linked over the secondary multi-receiver coils. It will pickups the secondary current (I_{r1}, $I_{r2}, \ldots$, I_{rn}) in multiple coils concerning primary coupling inductive links. The receiver coil's current ($I_{r1} \ldots I_{rn}$) and linked magnetic flux is ($\phi_{r1} \ldots \phi_{rn}$). Secondary coil position alignment over the primary multiple coils cumulative flux is linked and differential to adjacent receiver coils. If the secondary receiver coil current (I_{r1}) is induced, its magnetic flux (ϕ_{r1}) magnitude is proportional to (ϕ_1) and the differential sum of the adjacent coil's magnetic fluxes. It is not better suited for an In-motion EV charging system, but it can be preferred for long-range biomedical or telecommunication power transfer applications.

In table 6, M_Tx: M_Rx magnetic coupling architecture, multiple transmitter coils are embedded in the primary and secondary unit, no. of primary & secondary coils that depends on the application. Multiple coils will enhance the effectiveness of the magnetic couplings to improve the power transfer efficiency. Current through multiple transmitters (I_{t1}, $I_{t2} \ldots$, I_{tn}) will establish magnetic flux (ϕ_1, $\phi_2, \ldots \phi_n$) over the intermediate wireless medium. When the secondary Pick-up coil is linked over the transmitted magnetic flux, current ($I_{r1} \ldots I_{rn}$) is induced as per the secondary coil position alignment. correspondingly, magnetic flux (ϕ_{r1}, $\phi_{r2}, \ldots \phi_{rn}$) induced in multi-transmitter receiver coil concerning coil positional alignment. This topology is best suited for in-motion and high-power applications, but this architecture topology is economically expensive.

In table 6, S_Tx: D_Rx magnetic coupling topology has a single transmitter coil with a double receiver coil unit, the current (I_t) through the transmitter coil induces the magnetic flux (ϕ_1) and is transferred over the dual receiver coils. Dual receiver coils will induce the pick-up current (I_{r1}& I_{r2}) with corresponding magnetic flux (ϕ_{r1} & ϕ_{r2}); ϕ_{r1} is proportional to ϕ_1 and the differential magnitude of adjacent receiver coil

TABLE 6. Comparison of M_Tx: M_Rx pad, S_Tx: D_Rx, and D_Tx: M_Rx pad magnetic coupling architecture.

TYPE OF COUPLING	PARAMETERS	PARAMETERS	PARAMETERS
Architecture			
No. of Tx pads	Multiple ($M_{\_Tx}$)	Single ($S_{\_Tx}$)	Double ($D_{\_Tx}$)
No. of Rx pads	Multiple ($M_{\_Rx}$)	Double ($D_{\_Rx}$)	Multiple ($M_{\_Rx}$)
Misalignment	Good	Medium	Medium
Coupling Co-eff	Good	Medium	Good
Application	Quasi-Dynamic & Dynamic	Static, Dynamic	Static & Quasi-Dynamic
Presented in	[115] [129] [130] [131]	[132]	[133]

flux ϕ_{r2}. Pickup coil-2 receiver magnetic flux ϕ_{r2} is vice versa of ϕ_{r1}.

In table 6 D_Tx: M_Rx magnetic coupling architecture, two transmitter coils transmit the power toward the secondary pickup coil into the interleaved wireless region. Two transmitter coils are excited with current (I_{t1}& I_{t2}), Tx coil establishes magnetic flux (ϕ_1 & ϕ_2) correspondingly. Transmitted magnetic flux establishes magnetic flux lines on the intermediate air region. Multi Receiver coil picks up the magnetic flux from the interleaved wireless region and induces a current in the secondary side ($I_{r1}\ldots$ I_{rn}) concerning the pick-up coil position alignment. Magnetic flux magnitude in secondary coils is the cumulative component of two transmitter coil's inductive links and differential to the sum of secondary adjacent cross-coupling inductive links.

A. SUMMARY

WRIPT through various different magnetic resonant coupling topologies is discussed with peer investigation on the effectiveness of magnetic coupling architectures. The effectiveness of magnetic coupling architecture is ensured by identifying the level of misalignment coupling between Tx and Rx coils.

Strong or effective magnetic coupling between Tx and Rx is necessary to ensure higher PTE in the WPT system. The effectiveness of magnetic coupling is enhanced by improving the possibility of coupling coefficient parameter participation. So, the PTE efficiency is improved by introducing effective coupling coefficients between Tx and Rx coils, which reduce the level of misalignment affecting the PTE of the WPT system.

This investigation is an important parameter that should be considered for developing or establishing a WRIPT EV charging infrastructure with static, quasi-dynamic, and dynamic states.

Along with this WRIPT power coils (single & multi-coil geometry) are classified according to their magnetic couplers (single-sided or multi-sided).

V. PERFORMANCE EVALUATION OF WIPT POWER PAD

WRIPT power pad operating performance is evaluated after developing the power pad coils with several parameter optimizations. The parameters of the wireless inductive coils are; self-inductance, mutual inductance, coil impedance, coupling factor, quality factor, frequency, and power ratings are considered while designing the wireless inductive power coil. For the design calculation of primary and secondary inductive coils, parameters along with the compensation parameters are analyzed for the design. A combination of inductive Tx & Rx coils and suitable resonant compensator topology determines the PTE in the wireless intermediate region [134].

Several optimization algorithms are developed to economically benefit high-performance coil design to design efficient wireless power with cost optimal. The power pad design optimization makes the WRIPT system more efficient, lightweight, and cost-effective. Also, to achieve maximum power transfer at low misalignment coupling, ferrite core placement, geometrical coil structure, and placements are investigated for WRIPT EV charging application [135]. While operating the Inductive power transfer Power coil with high power and frequency, its performance is affected by the heating effect. The coil temperature rising above the threshold limit will introduce a loss in the power coil and undergoes thermal breakdown. To protect against thermal effects, the coil's performance is calibrated and operated within a safer threshold limit [136]. After the wireless inductive coil is fabricated, it is embedding it into the concrete slab to construct the surface of the e-roadway lane. Transmitter coils are embedded to transfer power from the roadway surface.

After the embedment, the Inductive power coil behavior change to unexpected phenomena, which strongly affect the behavior of the coil. To reduce the above limitation, a numerical approach to handling the compression materials to optimize the parameters of the transmitter coil on concrete roadway [137]. In addition, the concrete-embedded inductive coils undergo various tests; compression strength analysis, fatigue analysis, and component test are investigated for WPT coil roadway integration [138]. EMI safety limits as per international standards and proper shielding designed. Operating the electric road safely, concerning live being health, algorithms related to foreign object detection, live object detection, and metal object detection are developed to ensure safety and security [139]. Finally, the developed WPT coil was tested for In-motion (various speeds) applications by positioning the wireless receiver coils for various alignments [140], [141]. Performance evaluation involves various parameters: thermal analysis, roadway embedding, Electromagnetic field safety analysis, and in-motion testing of the designed WRIPT system, as shown in figure 12.

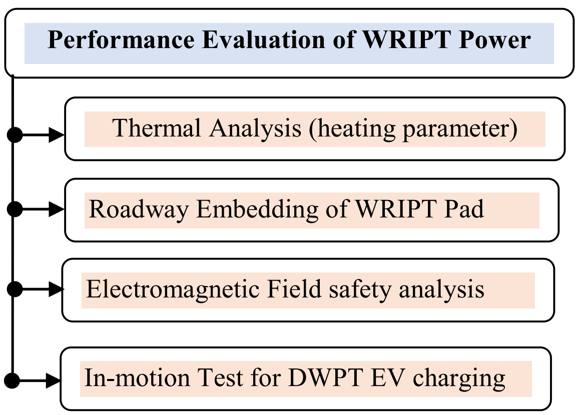


FIGURE 12. Performance Evaluation of WRIPT power pad.

A. THERMAL ANALYSIS FOR WRIPT COIL

Thermal energy is generated in the coil when it is operated for a long-time duration with a pulsating high frequency & current magnitude. Also, the environment causes a variation in temperature parameters due to seasonal effects. These are the factors that cause increases in coil temperature. This temperature raises the operating performance of the coil, or the coil is damaged due to overheating. Technical parameters have certain limitations in withstanding temperature concerning materials (Conductor, Magnetic core, Shielding, Coil holder) used to design power pads. Due to heat generated in WRIPT, power pads will transfer to the multi-part assembly of the EV, leading to several thermal management challenges. Power pad components and system-level behaviour are investigated using hardware-in-the-loop for the WRIPT system to address this thermal challenge. Power losses are taken for temperature dependency. Also, a comparative analysis of thermal behaviour in the space-frame concept shows an improved thermal behaviour compared to sandwich concepts [142]. The thermal pattern of the Magneto-thermal simulator is used to map the calculated powerless directly into the fluid dynamic solver. It is suitable for both transmitter and receiver WRIPT power pad to operate within the threshold safety limit at the roadway lane to the acceptable magnetic flux density (B) 123 mT for a 200kW power-rated system [136]. Thermal management is essential for designing compact wireless EV charging systems, especially for higher power ratings. Thermal sources in WIPT power pads are; the power thermal conductivity Litz wire coil, magnetic ferrite core, and EMI shielding; among these all, the magnetic core causes higher heat loss than the coil. The thickness of the ferrite core is 5mm, for a 50 kW WRIPT power pad, which causes a temperature of 150° C at a coil temperature of about 65° C for an operation of 10 minutes. This temperature rise is addressed by increasing the core thickness or using advanced thermal designs. When the thermal range is 150° C at the magnetic core, the temperature at the back case is 57° C, and conducting parts around the coil within 2-3 inches reach hazardous temperature [143]. So, shielding is necessary to maintain or control the temperature within the limit. The shielding must be low-permittivity, high-conductivity metal, such as copper or aluminium. This thermal parameter is simulated using 3D Finite Element Analysis (3D-FEA) by considering the magnetic and non-magnetic materials of charging power pads. One of the advanced methods of thermal energy management is introducing Phase Change Materials (PCM) with Power Pad construction, which will balance the severe thermal issues. Nowadays, PCM is widely used for thermal energy management and has a good performance in thermal management. PCM aims to set the thermal level within a limited space using a special aluminium alloy with permittivity and high thermal conductivity. The thermal conductivity of the Tx coil in an EV charging system ranges between 0.5-0.75 W/cm2 [144]. Thermal analysis of three single-sided flux power pads for the WRIPT system comprises Tx and Rx pads, EM shielding, and magnetic cores. Here various geometrical structure coil's thermal levels are analyzed by considering material characteristics using electromagnetic field elements and finite volume computational fluid dynamics. by considering the ferrite core's average permeability, the component's temperature is maintained below 200° C [145]. The temperature is tested for a qualitative measure of the distributed components

TABLE 7. Thermal Energy Management in WRIPT Power Pad.

PARAMETERS	THERMAL CHALLENGE	ANALYSIS	OPTIMIZATION TECHNIQUES
• Power 11kW, • Airgap (110–160 mm) [142]	• A sandwich and space frame concept that undergoes thermal heating.	• hardware- in -loop • For component, & system levels.	This space-frame concept has improved thermal management compared to the sandwich concept.
• Power 200 kW [136]	• Thermal heating patterns of the coil undergo different field densities in the ferrite core.	Thermal heating patterns of the coils are analyzed using Magneto-thermal simulation.	By mapping the power loss directly into the computed fluid dynamics solver concept.
• Power 50kW [143]	• WRIPT power pad undergoes heating challenges due to core losses. • High power-rated WRIPT Power pad undergoes more heating losses.	• Analyzed using finite element analysis and is tested for 10 min. • Obtained 65° C in the core, & 57° C in the cover.	Controlled by shielding materials. (high conductivity, low-permittivity metals)
• Heating plate power 0.5–0.75 W/cm2 • Heating plate size 20 cm × 20 cm, • Thermal conductivity coefficient 160 W/(m °C) [144]	Concerning thermal effects due to magnetic leakage losses established in the WRIPT power pad.	The study experiment tests the temperature changes at the Tx units under different heating conditions.	• The PCM-based system is designed using a special aluminium alloy. • Introducing PCMs will perform well in thermal management.
• power 6.6 kW [145]	• The temperature in the Tx, Rx coils, EM shielding, and cores of the WPT system under various coupling levels.	by considering material characteristics using electromagnetic field elements and finite volume computational fluid dynamics.	The core's average permeability maintains the component temperature below 200° C.
• Power 6.6 kW [146]	The thermal model for heat transfer in magnetic coupler intermediate region and the coil, core, and shielding heating mechanism.	The thermal parameter is calculated for coil, core, and shielding and operated for 30 min.	The system is operated for power rating and obtains a temperature in the coil, core, and shielding.

in WRIPT system. A prototype model is developed to experiment with a power level of 6.6 kW, then calibrated coil loss of around 48.3 W, core loss of around 2.6 W, and aluminium shielding losses of 10.9 W.System Operated for 30 min, the temperature of the distributed component is coil temperature is 34.6° C, core temperature is 31.2° C, aluminium plate temperature is 28.6° C, and the coil base temperature is 24.5° C [146].

Table 7 temperature or thermal Effect in WRIPT power pad is optimized by analyzing the distributed parameters. Various thermal distributed parameters in the power pad are; coil, magnetic ferrite core, and EMI shielding. This thermal energy is analyzed and optimized using various techniques: PCM phase-changing materials, increasing the thickness of the core as per power rating, and using advanced thermal management system designs for optimizing the core heat.

B. EMBEDDING WRIPT PADS ON ROADWAY

Embedding WRIPT pads on the roadway for inductive charging of EVs during dynamic or quasi-dynamic In-motion moments. Also, the static charging system is possible with an in-motion charging arrangement. Surface mounting is done by direct embedment of power transmitter coils on the road Pavement; in the adjacent sequential arrangement to establish E-roadways. Constructional design materials characteristics must minimize the occurrences of parasitic couplings of the magnetic coil flux with the ground. Parasitic coupling phenomena will affect the performance of electromagnetic field behaviors of the WIPT coils composing the charging process for wireless EVs. These parasitic coupling phenomena can become evident for the frequencies at which the power transfer is performed.

The parasitic effect in high-power WRIPT systems is investigated, and the impacts on standard mode conductive Effects are identified. Both analytical and FEM simulations are used to experiment with the parasitic values and Common mode noise model of the WIPT system. The stray capacitance between the WRIPT power coil and metal shielding layer is significant and plays a dominant role in the CM noise propagation path. Simulation analysis and experimental validation with an 11 kW WIPT system are conducted to verify the model's accuracy. Also, it provides guidelines for standard mode EMI design for high-power IPT systems. For the 11kW WIPT coil, the capacitance value is up to the nF level, which will significantly impact CM noise. Series compensation is designed along with the proposed CM noise model, and it aims to identify the relevance of CM noise propagation with different parasitic capacitances. The result shows that the stay capacitance between the transmitter Litz wire coil and shielding layer plays the dominant role in common mode noise, leading to 30∼45 dB noise magnitude. Common Mode (CM) noise increases drastically when the shielding layer of the transmitter coil is grounded [147].

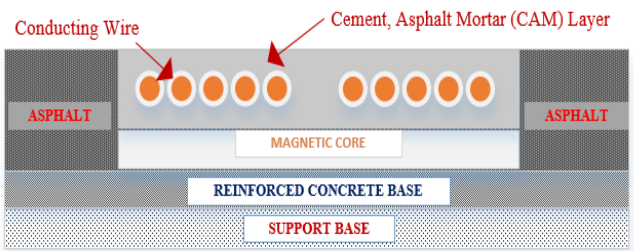


FIGURE 13. Constructional Arrangement of Roadway Embedded WPT coil.

Figure 13 shows the constructional arrangement of on-roadway embedding of the WRIPT power pad. Describes a prototype transmitter pad embedded on the roadway for experimentation of its performance and characteristics; five transmitter pads have been mounted on the roadway surface for experimental analysis. Cement asphalt mortar is a roadway construction material used to construct the roadway to avoid damage to the transmitter power pad; while operating at high temperatures and during construction. It results in more than 90% of 1 KW of electric power [148]. Electromagnetic parameters are the challenges in embedding the power coil on roadways and analyzing the concrete and the geometrical parameters of WPT overall behaviors. The turns spacing between the coil, insulation thickness of the wire, concrete resistivity, and the embedded coil's relative permittivity concerning the power pad's physical dimensions are studied in the article [149].

The development of DWRIPT technology for EV charging is deployed for public usage by embedding the coils on roadways by ensuring the system properties, both electrical and mechanical properties required for DWPT, for coils produced using synthetic resins. This coil without ferrite is an open-type coil with a different design structure, and it is constructed using four different Methods. The electrical characteristics of the WRIPT Power Pad were evaluated before and after burying the coil using Falling Weight Deflectometer (FWD) test. Also, evaluated the mechanical design strength, thermal, or temperature of the road before and after the coil or Power Pad was measured. The experimental test results show that the reflection crack suppression sheet method is currently the best construction method, and residual strain is reduced by injecting cement grout to protect the Electromagnetic coil [150]. In-motion WRIPT system for EVs charging on the snow-piled road is investigated. Tx co-efficient S21, one of the scattering parameters from Tx coil to Rx coil, is degraded due to misalignment coupling due to increases in distance between Tx & Rx coils, which is affected by ice or snow. This investigation proposes the parasitic coil will enhance the reception power in the parasitic coil between Tx and Rx coils. The outcome of the analysis shows the value of s21 by 15 dB using a mutual coupling, which can supply power to the Rx coil at an intermediate distance of 150mm [151].

C. ELECTROMAGNETIC FIELD SAFETY ANALYSIS

Electromagnetic field safety tests are conducted for the in-motion WRIPT system to qualify the standards before implementing them into the real-time application. QDWRIPT or DWRIPT system is a process of charging the EVs during in-motion by the WRIPT system. Before deploying this system in real-time practices, EMI Safety must be ensured by qualifying all global standards under all circumstances while the EV is moving over the charging Pads. EMI emission is controlled by fabricating the shielding for the WIPT coil, shielding is necessary to maintain and control the EMI emission limit, and shielding must be low permittivity, high-conductivity metal, such as copper or aluminium sheet [152]. The available electromagnetic shielding techniques for the WRIPT system for charging unmanned aerial vehicle application is investigated. As a result, EMI is experimentally analyzed and simulated to confirm the shielding method significantly reduces the magnetic field by almost 85% for the WRIPT system [153]. To evaluate the EMI safety of multiple WRIPT EV charging systems and to explore simple, effective EMI protection methods, the simulation analysis was made using COMSOL Multiphysics software. The various relative positions of wireless chargers on magnetic field parameters are investigated. It results in the maximum magnetic field density when two wireless charger works simultaneously 1.30 times. The aluminium alloy on the car body could reduce the maximum value of EMI emission over the surrounding [154]. To mitigate the magnetic field around an EV during a WRIPT system is charging the battery, an active coil is designed to increase the safety of humans with a pacemaker. The calculated magnetic field which exceeds the safety limit of EMC and EMI standards for human exposure is mitigated by active coils [155]. Electromagnetic field safety analysis is

TABLE 8. Electromagnetic field safety standards.

CODE	STANDARD
IEC 61980-3 [156]	EV WPT system Part-3 Requirements for the WRIPT magnetic field.
IEC 380 [157]	Safety of Machinery in the office, which is Electrically Energized.
IEC 61010 [45]	Safety of Electrical Equipment for measurement, control, and laboratory
SAE J1773 [158]	EV Inductively Coupled Charging
ISO 14117:2012 [159]	Biomedical Active implantable devices, Implantable cardiac pacemakers, EMC testing protocols & cardiac resynchronization devices.
ISO 19363 [160]	Electrically powered roadways vehicle - Magnetic fields of WRIPT – General Safety and Interoperability needs.
ICNIRP 2010 [161]	ICNIRP general Guidelines for EMI Exposure Limitation for Time-varying Magnetic & Electric Fields range Between 1 Hz to 100 kHz Frequency.
IEEE P2100.1 [90]	WPT and Charging system standards

conducted by considering the international standards on EMI safety measures listed in table 8.

In DWRIPT system safety and health concerns, electromagnetic field, electric shock, and fire hazards are the three main potential parameters [162]. DWRIPT system is capable and has the potential to transfer high or medium power through wireless coupling links. The frequency of WRIPT ranges between kHz to GHz, EV wireless charging level 1 ranges up to 3.7kW power, and level 2 ranges up to 7.7kW. These rated power capacity charging systems are installed in houses, parking yards, shopping centers, traffic zones, and other slow-moving areas. Design parameters of the WIPT power pad inculcate; accidental damages due to electric shocks risk and seasonal changes in hot and cold weather. Other temperature-changing parameters are considered for the design and commissioning of the system. EMI and EMC are the factors that need to be considered for the WRIPT EV charging system.

Electromagnetic exposure boundaries of a high-power WRIPT system are shown in figure 14. The Electromagnetic exposure boundaries are classified into three regions as per magnetic field establishment. Their classifications are;

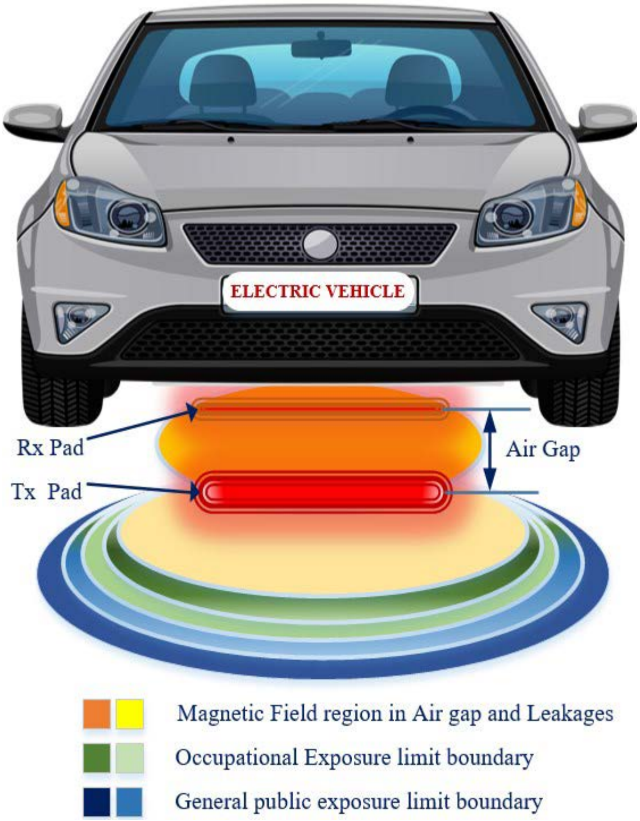


FIGURE 14. Electromagnetic exposure boundaries of a high-power WRIPT system.

magnetic field regions between Tx and Rx coils and leakage fluxes (light yellow and light orange), occupational exposure limit (light green and dark green), and general public exposure limit (light blue and dark blue). According to the ICNIRP standard guidelines, at the frequency range between 0.8 to 150 kHz, the general public exposure limit is 30.7 micro Tesla [161]. ICNIRP (International Commission on Non-Radiation Protection), the whole-body exposure has to be less than 27.3 micro Tesla at the time of EV charging to protect the nearby human beings.

D. IN-MOTION TEST FOR DWPT OF EVS

In-motion (Quasi -Dynamic or Dynamic) testing of the WRIPT system is indeed necessary for experimenting with the concept before deploying it into the market. Testing a dynamic WRIPT charging system is possible for indoor and outdoor environments. Indoor testing will be performed chiefly using a test bed for experimental verification, and outdoor construction will be in the form of roadway construction; wireless power pads are buried under the roadway Lane. The outdoor construction is a real-time implementation; power pads are mounted on the surface under the roadway lane with novel pavement for WRIPT Pad. Outdoor construction needs more experimental analysis concerning climate or environmental factors. Contamination of water moister or dusty particles quickly enters the road pavement between the coils, so it is necessary to verify whether this contamination affects the DWRIPT system's overall efficiency The parameter of the coil and theoretical efficiency can be measured by using metering instruments. Efficiency is evaluated by a power transfer experiment. Finally, experimental results clearly show how the efficiency is affected with iron sand, rainwater, and seawater and changes in resonance frequency of the DWPT system. WRIPT system is developed for a 20kW power rating for experimental verification of speed between (0 to 100 Km/h) with sequence order of sequential of EVs [163].

For this, the system electro-magnetic emission test was experimented on inside and outside the car with the help of a direct smaller range of communication antenna. The data is monitored in the control room also inside the vehicles for Human-Machine Interface (HMI). Dynamic air gap variation during fast-moving EVs is analyzed using laser measurement instruments for measuring the real-time distance between the ground of four corners and the ground [164]. DWPT for EVs is the main focus of researchers nowadays. After designing and validating the system, testing the system in real-time requires an effective test setup. For effective testing and calibrations of the designed experimental prototype model Electric Vehicle charging Research Centre depended on the Testing Bench or track. This technology transfers various power-rated high-frequency power between electric transport and power supplier in the DWPT system for charging the EVs during dynamic or quasi-dynamic moments. Safety is the main constraint for various power-rated systems, while power transfer happens with higher system efficiency. Testing of DWPT mainly investigates the "Interoperability operation of DWPT system power pad" different supplier systems also at different power levels and misalignment tolerance of the magnetic coupling architecture.

Table 9 shows the currently available testing bench at Idaho National Lab (INL) constructed by coordinating the SAE J2954 team and the US Department of Energy. SAE TIR J2954 contains a normative specification for constructing different power levels for WPT-1 up to 3.7 kW and WPT-2 up to 7.7 kW [140]. It results in the system working very well to safely power transfer at high efficiency (85% - 95%), with the participation of US DOE, Toyota, Ford, Nissan, Daimler, Jaguar, Qualcomm, and WiTricity.

Further panned for SAE Standard Taskforce WPT power classes; WPT 3 up to 11 kW and WPT 4 up to 22 kW with all recommended minimum target efficiency greater than 85% alignment to defined in SAE Standard [165]. Also, constructing "One Common Standard" inculcating SAE J2954 and ISO 19363 to standardize Wireless Charging is working together. In the US, the researchers at the ORNL research team are exploring DWPT for EV charging systems using a linear dynamic testing Bed at the Grid Research Integrated Research and Development Center to analyze the DWPT system and to support researchers in advancing smoothly integrating into the power grid.

TABLE 9. Test Bench and their Specifications.

TEST BENCH	POWER RATING	PERFORMANCE
Idaho National Lab [140]	Up to 3.7 kW	SAE J2954, Efficiency (85% - 95%) (WPT-1)
Idaho National Lab [140]	3.7–7.7 kW	SAE J2954, Efficiency (85% - 95%), contribution with US DOE, Toyota, Ford, Nissan, Daimler, Jaguar, Qualcomm, & WiTricity (WPT-2)
SAE Standard Taskforce (WPT-3) [165]	Up to 11kW	SAE J2954 and ISO 19363, minimum target efficiency greater than 85% alignment to defined in SAE Standard.
SAE Standard Taskforce (WPT-4) [165]	Up to 22 kW	

ORNL Researchers have already proven their static charging system for various power ratings for light-duty Electric vehicles with minimum charging time. But scientists and researchers at ORNL aim to dynamically charge the EV for Very high power by charging vehicles at highway speeds. This study helps us to visualize the future demonstrator of a real-world DWPT system for public utilization of DWPT technology to electrify Transportation after addressing potential challenges associated with Dynamic or Quasi Dynamic Power Transfer. The main goal is to establish a Track for Bench Testing the Moving Receiver coil with misalignment control in Research Centre for DWPT and to confirm operating performance, the safety of the system, and Interoperability.

E. SUMMARY

WRIPT system is operated with high frequency and high power magnetic coupling topology to enhance higher PTE. Due to the high frequency and high power resonance, inductive coupling performance Tx & Rx coils in magnetic coupling topology undergo power losses will result in reduced PTE. Power losses take place in the WPT system due to thermal losses in the inductive coil, EMI emission in the intermediate coupling region, and seasonal factors.

All these factors are considered in this present review article to define the reader understand the challenging factors and optimization techniques implemented to overcome challenges are discussed. EMI safety limit is maintained within the safety margin as per global standards included in the discussion, along with the roadway embedment process.

Finally, the in-motion WPT EV charging testing procedure and standards for the test bench are discussed in this section.

VI. SIGNIFICANT PARAMETERS OF DWPT

Electromagnetism and the basic principles of operation based on current commercial systems serve the technology of magnetically induced current wirelessly to recharge EV batteries. The research investigations involved the working of the existing systems in follow, and different EV charging methods were discussed. This survey led to the fundamental ideas of the in-motion EV wireless charging system, which listed several responsible parameters and focused on the DWPT EV charging system. It also follows the significant parameters affecting EV wireless charging and roadway expandable WRIPT systems; Positioning of wireless coils, speed, the distance between Tx and Rx coils, traffic, road gradients, number of charging stations and coils, slow-moving zones and impact of daytime in-motion wireless EV charging system. All the significant parameters of the DWPT systems are interlinked and depend on each other which are represented with a logical set diagram to relate the dependence of the parameters shown in figure: 15.

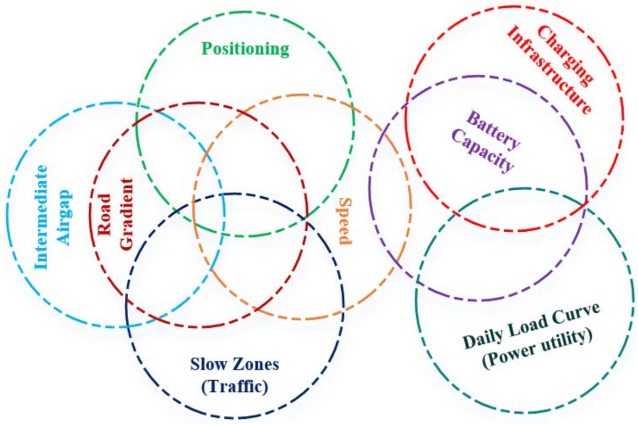


FIGURE 15. Significant parameters of the DWPT EV charging system set diagram.

The significant parameters of the DWPT EV charging system deal with the parameters affecting PTE. The parameters are the challenging components to be studied to find insight to address while constructing and operating the DWPT system to achieve higher PTE. The various different parameters are represented in figure 15 and every significant component is discussed in detail in the following subsections from 6.1 to 6.8.

A. SPEED

The primary transmitter coils are arranged in adjacent sequences and are energized as per the receiver Rx pick coil alignment. Here, the speed of the EV is a significant and crucial factor considered for in-motion EV charging [166]. Investigating this parameter will help us address challenges using advanced technologies and control the EV in-motion speed to achieve PTE by considering the effect of vehicle speed [167]. Qualcomm introduced transmitters embedded on the roadways to charge the in-motion EVs wirelessly. This roadway-constructed system inculcates; BAN blocks, power supply units, power distribution backbone, and long-distance charging units (100 m). with this construction, EVs could move forward or backward with 120 Km/h speed by picking receiver power of 20kW. But the limitation of this design is the initial cost required to construct or install the EV charging system on roadways [168]. The WRIPT EV charging technology of PRIME reduces the challenges in developing infrastructure for charging EVs. It benefits EV users to charge fast charging, by providing a power output between 100kW to 500kW depending on length, number of EVs, road condition, and application range. The system was designed with a Bombardier MITRAC energy saver system, which optimizes power for peak performance and energy storage during the breaking in a double-layer capacitor. It is a typical light rail vehicle with a length varying between 30m to 42m, which can speed up to 50km/h running on 270kW power [169]. Speed is one of the significant parameters in the WPT system affecting the PTE, the parameters are represented in figure 16.

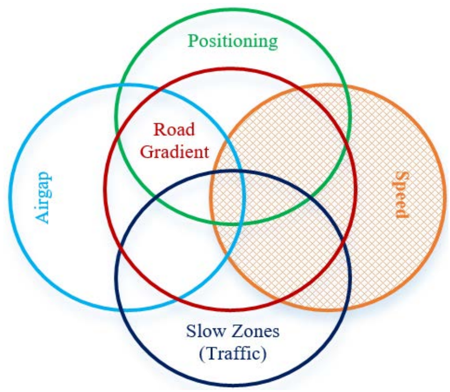


FIGURE 16. Impact of EV speed set diagram.

EV charging with the DWPT system has a challenge with respect to the speed of the EV dynamic moment. Speed is the significant parameter affecting the positioning of the coil and introducing misalignments will impact PTE. Speed is the significant parameter affected due to slow zones and road gradients, which will also impact the PTE of the DWPT EV charging system.

B. POSITIONING

WRIPT charging of EV parameters is affected due to misaligning position between Tx and Rx coils, especially during in-motion charging applications parameters are shown in figure 17. Wireless power can be transmitted efficiently by proper alignment to achieve maximum PTE. Positioning the EV accurately is a significant factor in achieving effective power transfer charging in the WRIPT system. Here, the position of the charging pad, the distance between charging pads, ground clearance, and speed during in-motion are the

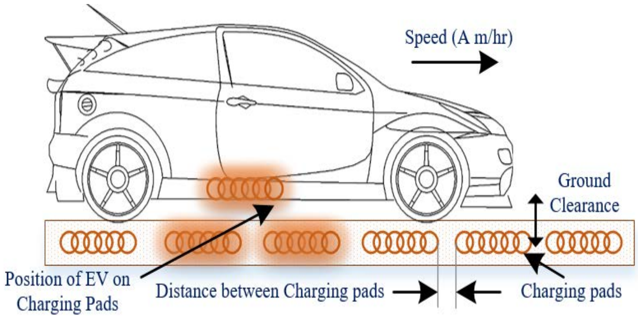


FIGURE 17. Parameters for positioning the WRIPT charging system.

factors considered to design the WRIPT coils positioning system.

The dynamic in-motion charging system can also benefit from charging the EV in a static state. Researchers are investigating Rx power pad positioning aligning to the maximum PTE to achieve maximum power transfer. Rx power pad positioning algorithms are developed to examine the performance of IPT for various misalignment cases [170]. The maximum power transfer point is sensed by achieving the secondary impedance when the load resistance varies. A dynamic WRIPT coupling coefficient is affected due to variations in airgap distance. Suitable compensators are designed to match the impedance according to the minor misalignment to limit this issue. For the more significant levels of misalignment couplings, identifications of coupling co-efficient, load resistance, and maximum power are tracked by impedance parameter [171]. Maximum power tracking of the WRIPT system based on critical coupling point identification is investigated, and another relation between critical coupling point and load resistance is analyzed [172]. For maximum PTE under any load condition, a DC-DC impedance circuit is added at the receiver side to achieve maximum power tracking by adjusting load resistance dynamically. Significant parameters were affected due to EV positioning which affected due to position is represented in figure 18.

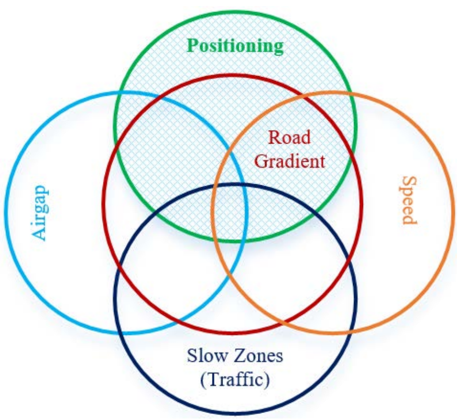


FIGURE 18. Impact on EV positioning set diagram.

EV positioning above the charging pad is one of the considerable factors that will affect the DWPT EV charging system PTE. Positioning is the parameter getting affected due to significant parameters' speed, road gradient, and slow zones. Positioning is the significant parameter that will affect the intermediate air gap distance between Tx and Rx WPT systems.

C. INTERMEDIATE AIRGAP DISTANCE

The intermediate air gap distance between the Tx and Rx is pivotal to the charge rate for p.u time. Airgap distance is also one of the significant parameters affecting the PTE, especially during in-motion EV charging applications. Transmitter coils are embedded on the roadway surface or Tx source for the WRIPT system, and Rx coils are fixed underneath the EVs. This intermediate distance is one of the parameters that must be maintained as close as possible above the source Tx coil. To achieve maximum PTE, the intermediate distance between Tx and Rx is a significant challenge that has to address to improve the power transfer rate. PTE can also get affected due to various types of road conditions with controlled speed limits. Hence the EVs are operated for different speed limits based on the road conditions. Moreover, vehicles above the road will maintain a minimum air gap distance of 0.5 meters [173]. In addition, the EV management system is designed effectively by considering the significant parameters affecting the Intermediate airgap distance between Tx and Rx coils. The intermediate air gap between the Tx and Rx power pad of the DWPT system is the significant parameter affected due to parameters like road gradient, speed, slow zones, and positioning of the magnetic coupling coils.

This parameter is the most challenging parameter in the WPT system and has to be maintained within the standard limit described by power and frequency ratings to achieve higher PTE. Controlling the air gap during the inmotion moment is the critical parameter that needs more control advancement for a better DWPT system. the logical set diagram represents the interconnection and dependence of parameters with each other represented in figure 19.

D. SLOW ZONES (TRAFFIC)

An important note is that EVs can operate in various road conditions; many are stuck in traffic zones along the road. We can monitor through navigation systems to locate low, high, and average traffic zones [174]. If WRIPT EV charging systems were deployed in such cases on roadways, a charge controller system would undergo many distractions due to traffic. If WRIPT EV charging systems were deployed in such cases on roadways, a charge controller system would undergo many distractions due to traffic. DWPT charging system en routes and makes electric bus systems more flexible charging for a multiline transit system with a good number of trips by incorporating optimal level information [175]. WPT charging infrastructure locations are restricted to bus stops and traffic zones. Also by determining the location, the charging lane

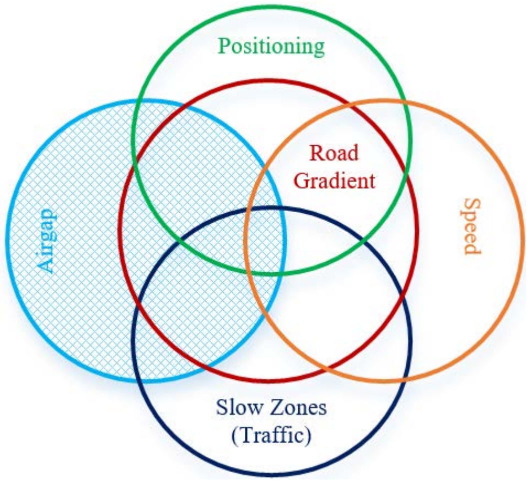


FIGURE 19. Impact on airgap set diagram.

area, and load (no. of buses and battery capacity). The impact of the slow zone significant parameter is represented with a set diagram in figure 20.

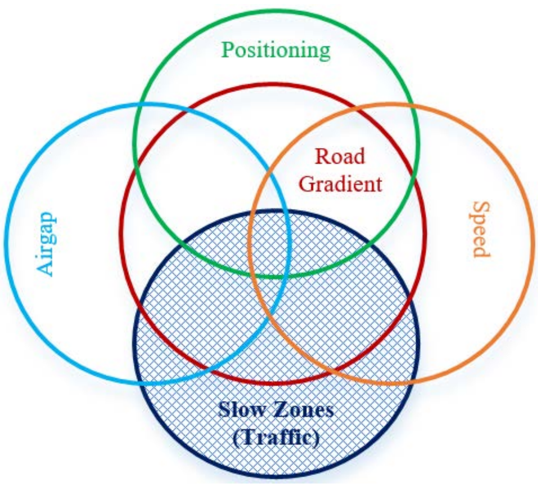


FIGURE 20. Impact of Slow Zone (Traffic) set diagram.

Slow-moving zones like traffic areas will affect the speed of the vehicle with changes in the speed of quasi-moment or static charging states. This significant parameter will also affect the road gradients in some cases and will influence the positioning misalignment issue, changes in intermediate airgaps will directly affect the PTE of the DWPT system.

E. CHARGING INFRASTRUCTURES

Charging infrastructures is another significant parameter to be considered to charge the EV user-friendly; nowadays, charging infrastructure is one of the major challenges in the EV domain. To address this issue, quickly identify the EV charging stations available in particular locations. Researchers are working to make them available through internet protocols (IoTs), the availability of plugins, or wireless EV charging systems [176]. Further, developing the charging zones in various locations by correctly mining traffic data for specific geographical locations [177]. The required charging unit is planned accordingly, depending on the level range and area. More no. of coils is placed in high-traffic zones correspondingly for other traffic or slow-moving zones. The construction of the charging zone also depends on the environmental condition and leakage flux establishment possible for medium (air, vacuum, snow, or water). Correspondingly to eliminate power losses and type of receiver coils is classified into 'n' groups [178]. This analogy is similar to a coaxial cable carrying electrical signals to transfer signals from one end to another. For example, there were five coils groups for the transmitter coil of 20kW, each with a capacity of 4kW. However, the no. of coils varies with the type of road gradients on roadways. A long-term scenario based on a stochastic mathematical model approach is proposed for sizing and allocating WPT charging infrastructure by considering EV's power distribution system, losses, location routing, and traffic zones [179]. This long-term model facilitates EV charging systems for all types of EVs by developing WPT charging systems. Also, it overcomes the problems associated with conventional charging systems. A framework is developed by a long-term mathematical model for locating WPT charging infrastructure, and routing of charging infrastructure by considering the battery capacity of the vehicle, charging facilities installation cost, losses, and power distribution system voltage deviation, which belongs to the Multi-Depot Multi-Product delivery supply chain system. Also, comparative case studies have been performed by interconnecting IEEE 13-node test feeders and traffic networks [180]. The charging infrastructure is the significant parameter it impacts battery capacity and the daily load curve of the power system is shown in figure 21.

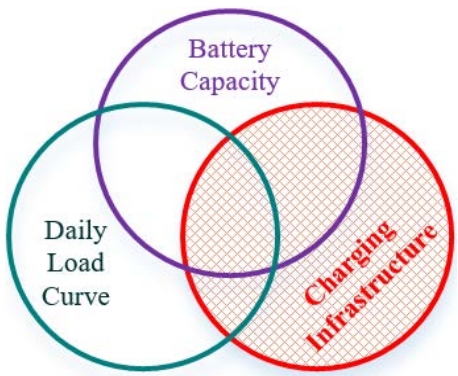


FIGURE 21. Impact of charging infrastructure set diagram.

Charging infrastructure is the most important and challenging parameter in the EV WPT charging domain. It is affected by the significant parameters of the DWPT system are; the daily load curve and battery capacity. Battery needs frequent charging from charging infrastructure which will raise the power demand from the power grid or utility.

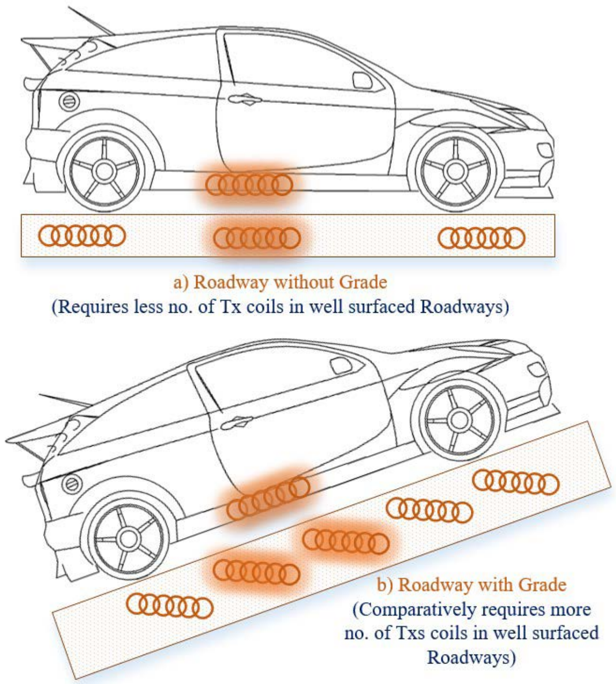


FIGURE 22. Roadways Gradients.

F. ROAD GRADIENT

A road gradient is investigated effectively for inductive power coil placements on roadways, as shown in figure 22. Representing that gradients in roadways require more no. of power Tx coils placed on roadways for EV to pass over in figure 22 b with a charging pad compared to non-gradient well-surfaced roadways figure 22 a.

A smaller time frame gradient of the roadways is compared to determine the charging time based on the pivotal data points, and the distance between the coils and the condition of the roadways is compared. The no. of coils can be increased or decreased for roadways with gradients. The EV will pass through with a minimum fraction of time, also the frequency of the vehicles [181]. The number of coils in a particular slot may be increased or decreased to utilize the energy effectively. Also, the gradients in the roadways will impact the significant parameters of the in-motion WPT system will result in minimum PTE. PTE is affected due to gradients in the roadway affecting the vehicle speed, position of power pad coils and slow zones will all results in a change in the intermediate air gap distance of the EV change in the dynamic moment of the WPT system. The set diagram for the impact of road gradient affecting significant parameters of the DWPT system is shown in figure 23.

Road gradient is an important parameter affecting the DWPT charging system PTE by impacting; changes in speed, positioning, slow-moving zones, and intermediate air gap distance changes between Tx and Rx power pads. This all the factors can be addressed by constructing well-surface-mounted roadways with an effective magnetic coupling charging system on e-roadways.

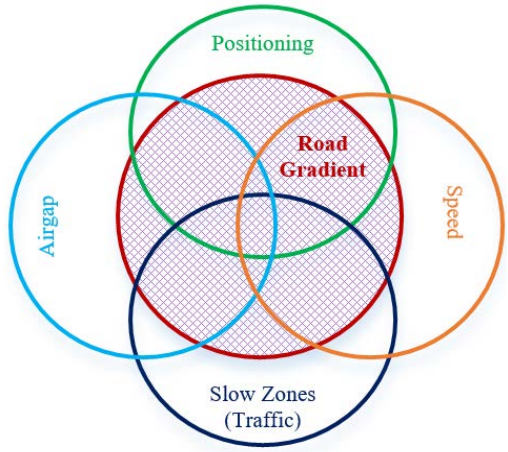


FIGURE 23. Impact of road gradient set diagram.

G. BATTERY CAPACITY

The main challenge faced by EVs is battery capacity; to travel for long range requires a large capacity battery, and proportionally the size and weight of the battery will also increase. Also, charging duration increases, so the battery capacity is considered a significant parameter in EVs. Introducing the DWRIPT EV charging system addresses the battery capacity issue by reducing the need for the battery, size, and cost of energy storage. Battery capacity is affected by the significant parameters shown in figure 24.

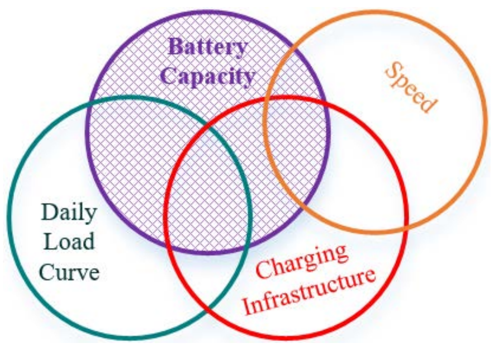


FIGURE 24. Impact of battery capacity set diagram.

The battery is an important parameter in the EV, the capacity of the battery aids the potential to run or operate the EV for a large duration (milage). Battery capacity is the significant parameter affected by a change in speed, battery charging infrastructure, and daily load curve. Battery capacity depends on the EV travel distance, change in speed to cover the distance, location of charging infrastructure, and daily load curve to charge at optimal cost with respect to charging infrastructure facility.

H. DAILY LOAD CURVE

Another essential parameter of in-motion EV charging is the power grid daily load curve its impact is forecasted and pre-planned for load scheduling. Which is directly affected by daily time; this parameter is considered for the research work based on the National Renewable Energy Laboratory (NREL) and Oak Ridge National Laboratory (ORNL) investigations [182]. It is analyzed to plan according to the type of roadways, traffic zones, speed breaks, and time of the day. A load factor of the power supply is planned to produce enough power at different time zones of the day.

Based on the load factor curve of the day, more favorable decisions can be made to schedule the power generation to build efficient energy saving during in-motion EV charging systems. Figure 25 shows the load cure for one whole day impacted by the parameters of In-motion EV charging and Time. The impact of the daily load curve affected due to the significant parameter changes are; battery capacity and charging infrastructure is represented in figure 26.

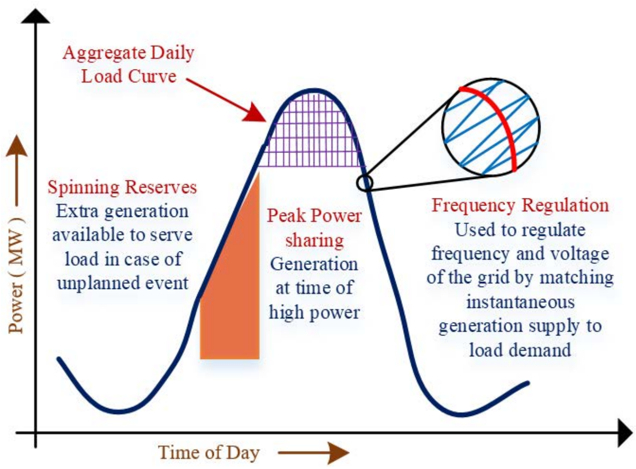


FIGURE 25. Load curve of the day plan.

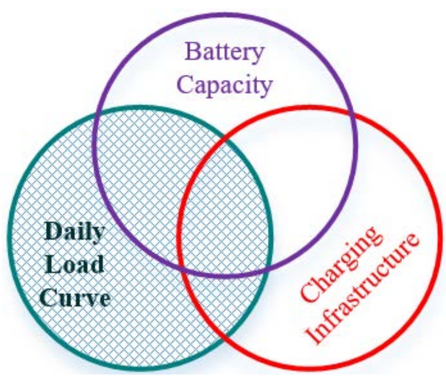


FIGURE 26. Impact on daily load curve set diagram.

The daily load curve of the power grid or utility is affected due to the raise in EV load, which can be addressed by maintaining sustainable energy management systems. The daily load curve is affected due to EV charging infrastructure and the capacity of the EV battery. Charging infrastructure utilizes the power to re-charge the EV energy storage unit, battery capacity low capacity battery needs frequent charging and higher battery capacity consume more energy to be stored in the battery to be utilized in runaways.

I. SUMMARY

By investigating the significant parameters of the DWPT EV charging system, the interlinking or logical dependence between parameters are identified and parameters are represented in the set diagram in figure 15. Followed by parameters are described in brief individually, it defines the reader to understand the impact of each significant parameter on the DWPT EV charging system power transfer efficiency.

VII. CHALLENGES AND OPPORTUNITIES OF THE WRIPT POWER PAD FOR IN-MOTION EV CHARGING SYSTEM

In-motion WRIPT EV charging systems use high-frequency and high-power operational topologies to transmit magnetic power through inductive links into the intermediate wireless region between Tx and Rx coils. Power transfer happens between the Tx & Rx coils that undergo various lateral misalignments during In-motion in the horizontal and vertical axis. To achieve higher PTE between Tx and Rx coils, effective inductive couplings should be ensured. Also, the DWPT EV charging system undergoes various other challenges to be addressed in future opportunities by peer investigation on the DWPT EV charging system.

Challenges in the WPT systems are the research gaps to be investigated in future opportunities of WRIPT system design. Challenges identified through our survey, from our survey, major challenges noted during the review are; effective magnetic coupling, interoperability & integration of the WRIPT system, construction /embedment of e-roadways, compensation network architecture, and health & safety. All these challenges /research gaps are identified to represented in figure 27 and discussed in detail in the following sessions;

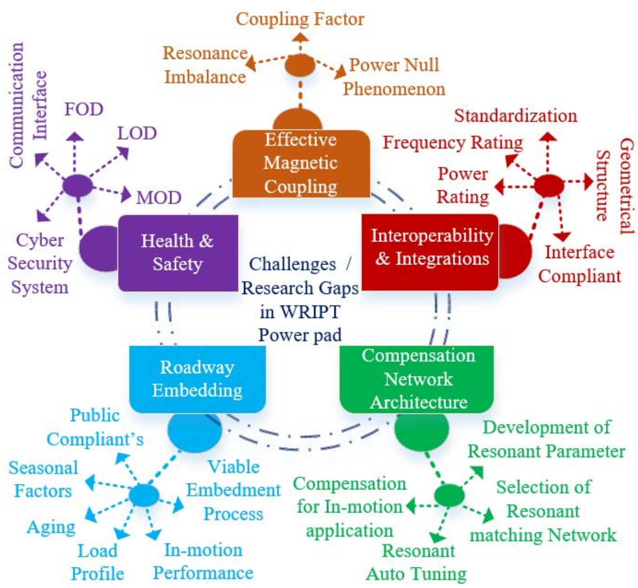


FIGURE 27. Challenges in the WPT Power pad.

A. EFFECTIVE MAGNETIC COUPLING

Magnetic resonance inductive coupler should ensure effective magnetic coupling to enhance power transfer efficiency in

DWPT EV charging system applications. The effectiveness of magnetic resonance inductive coupling is ensured by the proper alignment of the Tx and Rx coil in the magnetic coupling region. Improper alignments undergo misalignments during in-motion moments, resulting in a resonance imbalance that reduced the coupling factor and introduces PNP in WPT. To enhance higher PTE with a reduced coupling factor and to eliminate PNP in power transfer, the coupling quality of Tx and Rx coils is improved to ensure the effectiveness of inductive couplings [183]. Effective inductive coupling is established through mutual inductance or leakage inductive links. These can be addressed by selecting the suitable physical geometry for power pad coils and designing effective magnetic coupling architecture in future research /investigations. Also, a suitable compensator network topology is designed to regulate power transfer magnitude or effectively compensate minor misalignment transients during the inmotion operation of DWRIPT.

B. ROADWAY EMBEDDING

In-motion charging of EVs needs sequencing of transmitter coils in the roadway lane to construct the electric roadways. Electric roadways electrify the moving vehicles through the DWPT charging system. E- roads constructed by embedding or mounting a wireless transmitter coil on the road surface by following EMI safety standards to address public compliant's. EV has many other challenges while operating and re-charging for different geographical locations in various developing countries [184]. The load profile and aging factor maintenance of roadways mounted coils are challenges discussed in the article [185]. These challenges can be solely addressed in future opportunities by finding insights into inmotion operating performance and recharging the EV efficiently during various seasonal factors or environmental conditions. Also, the safety limit of EMI emissions is followed as per standard guidelines, which address the complaints of the MoRTH. The viability of roadway embedding Transmitter coils with huge investment is considered a challenge.

C. INTEROPERABILITY & INTEGRATIONS

The power transfer coil should act interoperable to effectively couple with the receiver pickup coil to transfer maximum power through inductive coupling links. Power transfer coil interoperability depends on selecting a geometrical coil structure; all the geometrical structures are unsuitable for performing an interoperable operation [186]. Some geometrical coils are proposed in the form of unipolar, bipolar, and quadrupole combinations by integrating the compensator network within the pad structure [187]. In order to overcome the interoperability challenges in the WPT system power and frequency rating are calibrated to standardize for simplifying the further development of novel geometrical-shaped coils. Also, the DWPT power pad coil has a grid interface complaint and position-sensing challenges are the research gaps.

D. COMPENSATION NETWORK ARCHITECTURE

DWPT EV charging system has a compensator network for resonance matching and regulating the high-frequency power with Tx and Rx coils to the power modulation unit. The compensator regulates the minor transient introduced during instant variations between Tx and Rx coils during the inmotion moment. Many compensator network architectures are discussed here designed to enhance the power transfer capacity of the DWPT system [32], [189]. Designing and tuning resonance compensator network parameters for particular magnetic coupling networks is a challenging task to maintain resonance. There was a need for novel hybrid compensator network networks to act universally for the DWPT EV charging application need to develop in the future.

E. HEALTH AND SAFETY

Health and Safety operation is the primary constraint for sustainable societies. The in-motion WRIPT system uses the resonant inductive field for transferring inductive power wirelessly, and it's trending in recent DWPT technology. This magnetic field will heat the coil and surround metal objects due to field eddy current conduction. Temperature is harmful to living beings straying near the charging area. These challenges can be addressed by; Live Object Detection (LOD), Foreign Object Detection (FOD), and Metal Object Detection (MOD) are developed for the safer operation of the WRIPT system [139]. These field-based detection algorithms are proposed for medium and high-power applications using various soft computing techniques. In this developing technological world, web technology is also integrating with society's safety & health need. Cyber security is integrated into communication, and Transportation needs to make things simple, secure, and automatic. The security system is implemented to handle risk or thrift [190]. This challenge has huge scope in the research gap that can be addressed using various software-based algorithms in future opportunities.

VIII. INFERENCES

This article presents an empirical survey of the WRIPT power pad for charging EVs during the in-motion moment. The different WRIPT coil geometrical structures available for static and dynamic WRIPT applications in previous research are compared with their operating performance and PTEs are comparatively tabulated. Then discussed the various design parameters considered for the development and optimization of the power pad. Comparatively discussed the optimization parameters with the usefulness of soft computing techniques, and categorize the magnetic flux establishment in WPT inductive coupling links. WPT power pads are classified according to the type of magnetic coupler with respect to the single and multi-coil geometry. Various possible magnetic field coupling topologies proposed in previous research are the most considerable; their operating performances are compared and tabulated. In addition, the performance evaluation of the power pad is presented comparatively, with safety standards followed by global industries and organizations to develop the DWPT system. Also, it includes the test bench developed for in-motion testing of WRIPT technology with industrial standards tabulated as per test bench power capacity. Significant parameters for the DWPT system with challenges and opportunities are discussed in this present literature article.

The survey article helps the reader to understand the important parameters associated WPT system with its impact on the development of wireless EV charging systems. To find insight solutions to address the challenges associated with development parameters and considerations, which enhance PTE. We believe that the article finds it useful for research, academic and industrial communities to find technical insights to address challenges in WRIPT in-motion EV charging application to establish DWPT technology fully fledged.

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