**Wireless Electricity for Electric Vehicle Charging**

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**Rules of Electricity**

**Ohm’s Law and Kirchhoff’s Laws**

No discussion of electricity, including wireless electricity, is complete without an introduction to Ohm’s Law and Kirchhoff’s Laws. Ohm’s Law considers the relationship between voltage, current, and resistance. Current is the amount of charge that flows through a conductor in a given time interval, or the rate at which charge is flowing, and is measured in Amps. Voltage is the potential difference between two points, measured across a wire or component, or the difference in charge between two points, and is measured in Volts. Resistance is the opposition to current in a circuit, or a material's tendency to resist the flow of charge (current), and is measured in Ohms. These values, current, voltage, and resistance, describe the movement of charge, and thus, the behavior of electrons. To study these values, we use circuits, which are closed loops that allow charge to move from one place to another. Components in the circuit allow us to control this charge and use it to do work. Ohm's Law states that the current flowing through a circuit is directly proportional to the voltage applied, and inversely proportional to the resistance of the circuit. This relationship is expressed mathematically as V = I \* R, where V is voltage, I is current, and R is resistance. One method for calculating these electricity values is to use linear algebra to construct a matrix and solve for the unknowns.

Kirchhoff’s Laws describe rules for current and voltage in a circuit. Kirchhoff's current law (1st Law) states that the current flowing into a node (or a junction) must be equal to the current flowing out of it. This is a consequence of charge conservation. Kirchhoff's voltage law (2nd Law) states that in any complete loop within a circuit, the sum of all voltages across components which supply electrical energy (such as cells or generators) must equal the sum of all voltages across the other components in the same loop. This law is a consequence of both charge conservation and the conservation of energy.

**Maxwell’s Equations**

**Faraday’s Law of Induction**

**Ley Lines and Ancient Electricity**

**Ancient Electricity**

Electricity has been harnessed in various forms by ancient cultures on Earth. We all know the story in the U.S. about Benjamin Franklin proving that lightning contained electricity, though older cultures around the world have also experimented with electricity in various forms. Electricity is an aspect of our everyday life that has been around since ancient times. The Baghdad Battery, around 2000 years old, was found in Iraq that contained a cylinder of copper and an iron rod suspended in the center. Replicas of the battery were made that could produce a charge of about one volt when used with vinegar or lemon. The Baghdad Batteries may have been used to electroplate items, such as putting a layer of one metal (gold) onto the surface of another (silver), a method still practiced in Iraq today. Ancient Egyptians recorded electric shocks from fish, and the ancient Greeks recorded experiments in static electricity. Some people have even argued that the Egyptian pyramids were giant power plants designed to harvest electricity from the Nile River.

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While there's no concrete evidence of a widespread electricity grid in the ancient world, some researchers and theorists propose that ancient civilizations may have harnessed energy through methods like piezoelectricity and electromagnetic resonance, potentially using structures like pyramids and obelisks as part of a power system.

Pyramids as Power Plants:

Some theories suggest that the Great Pyramid of Giza, and possibly other pyramids, were not just tombs, but also complex power plants that combined piezoelectric effects (electricity generation from pressure on quartz crystals), hydrogen, and electromagnetic resonance.

Obelisks as Part of a Grid:

Some researchers propose that obelisks, like the Luxor Obelisk, were part of a power grid that transmitted electricity wirelessly from the pyramids to other locations, such as the Temple of Luxor.

Ancient Astronaut Theorists:

Some theories, popularized by shows like "Ancient Aliens," suggest that ancient structures, like pyramids and obelisks, were part of a vast, extraterrestrial-built energy grid.

Ley Lines:

The concept of ley lines, or Earth's hidden energy grid, is another area of exploration, suggesting a connection between ancient sacred sites and a network of energy pathways.

Hydro Power:

While not electricity, ancient civilizations did utilize water power for various tasks, including turning millstones, with the Roman Empire and eastern Mediterranean region extensively using water wheels by at least the first century BCE.

Ley lines are straight alignments drawn between historic structures, prehistoric sites, and prominent landmarks, believed by some to mark "earth energies" or serve as pathways for alien spacecraft, though considered pseudoarchaeology and pseudoscience by archaeologists and scientists.

Origin:

The idea of ley lines emerged in early 20th-century Europe, with Alfred Watkins, a British author, being a key figure in popularizing the concept.

The Theory:

Ley line believers propose that ancient societies deliberately erected structures along these alignments, and that these lines represent "earth energies" or "invisible energy pathways".

Earth Mysteries Movement:

Since the 1960s, the Earth Mysteries movement and other esoteric traditions have embraced the idea of ley lines, often linking them to alien spacecraft or psychic energies.

Archaeologists and Scientists' Perspective:

Archaeologists and scientists view ley lines as an example of pseudoarchaeology and pseudoscience, lacking scientific basis or empirical evidence.

Ancient Monuments: Some believe that ancient monuments and settlements are aligned along ley lines, suggesting a deliberate placement based on these invisible pathways.

Alien Spaceship Pathways: Some believe that ley lines serve as guides for alien spacecraft, linking them to theories of extraterrestrial presence.

Alfred Watkins:

Alfred Watkins (1855-1935) is credited with originating the idea of ley lines and surveying alignments in the prehistoric landscape of Britain, particularly in his native Herefordshire.

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What are ley lines?

Ley lines are energetic alignments of ancient sites, geographic features, or significant landmarks, that are connected by an invisible but highly energised lines charted across the landscape. These alignments hold spiritual significance, as they connect us across time and space with our ancestors and their wisdom. Tracking ley lines, and exploring the energy of the sacred sites upon them, is a powerful and rewarding experience. Whether you visit these sites in person, or via remote viewing, it is always an extraordinary revelation – and a true blessing – to sense into their very special energy.

Where do ley lines come from?

We have British antiquarian and archaeologist Alfred Watkins (1855–1935) to thank for the concept of ley lines. He wrote about these sacred energetic maps in the early 20th century in his book The Old Straight Track (1925). In it, Watkins suggests that ancient structures like stone circles, churches, and burial mounds were purposefully aligned along these ley lines.

St. Michael's Line in England

Many spiritually inclined visitors to England make a beeline for its big hits: Glastonbury Tor and Avebury stone circle. These two special sites lie on the world-renowned St Michael's Line, a famous ley line running from Land's End through St. Michael's Mount in Cornwall to Burrowbridge Mump in Somerset.

There is another big hit not mentioned above, and Stonehenge needs no introduction. Apart from being THE place to be every solstice, it is a fascinating neolithic site that is rich with history, mythology, mystery and spiritual significance. The location of Stonehenge forms a perfect equilateral triangle to St Michael's ley line with Avebury in Wiltshire and the Tor in Glastonbury.

The Apollo–Athena Axis in Europe

The Apollo-Athena Ley Line connects important ancient sites across Europe through places like Mont Saint-Michel (France) and continuing through Delphi (Greece) to the Temple of Apollo in Athens. These are sites historically linked with the gods Apollo and Athena.

The Paris Meridian Ley Line in France

Also known as the Rose Line, this ley line runs along the Paris Meridian, a line similar to the Prime Meridian. It aligns with ancient structures like Chartres Cathedral and is associated with myths of hidden energy beneath Paris, as popularised in novels like The Da Vinci Code.

The Nazca Lines in Peru

The Nazca Lines in Peru are a famous set of large geoglyphs in the desert that have been linked to ley lines by some researchers. These enormous drawings of animals and shapes align with astronomical events and are believed by some to be part of a vast ley line system.

The Rainbow Serpent in Australia

Deeply sacred to Indigenous Australians, Uluru is also a significant point in the global ley line grid. Known by many as the solar plexus of the world, the magnetic point of Uluru connects to Lake Titicaca and Uluwatu along the female great dragon ley line, known as the rainbow serpent in Australia.

The Great Pyramid of Giza in Egypt

Many believe the mysterious Great Pyramid is mapped to the stars, and aligns with powerful ley lines that cross through significant ancient sites, including the Sphinx and the ancient temples of Luxor and Karnak. If you have been lucky enough to visit, you will be familiar with the powerful energy of this incredible site.

Mount Shasta in California, US

A popular spiritual hotspot in the US, Mount Shasta is referred to by many as the root chakra of the world. This immense mountain features in many Native American creation myths as the birthplace of humanity. It is also associated with much mysterious activity, with reports of meetings with ascended masters and even frequent sightings of Big Foot. It is thought to lie on an important ley line as a vital node in the Earth's spiritual energy grid.

Serpent Mound in Ohio, US

Perhaps you've watched Graham Hancock's brilliant but controversial Ancient Apocalypse on Netflix. In this series, he draws attention to the ancient site of the Serpent Mound in Ohio. This prehistoric effigy mound is another site believed to be aligned with Native American ley lines, which also connects with Teotihuacan in Mexico.

as one which efficiently transmits electric power from one point to another through the vacuum of space or the Earth's atmosphere without the use of wires or any other substance. Wireless power transmission is also often referred to as "beamed power transmission". (Brown, 1996).

In most applications the microwave system consists of four major parts: (1) the conversion of d.c. power into microwave power, (2) a transmitting antenna to convert the microwave power into a narrow beam, (3) a segment of space in which the microwave power is transmitted, and (4) the absorption and conversion of microwave power back into d.c. power at the point of reception (Brown, 1996).

**Properties of WPT (Brown, 1996).**

(1) No mass, either in the form of wires or ferrying vehicles, is required between the source of energy and the point of consumption.

(2) Energy can be transferred at the velocity of light.

(3) The direction of energy transfer can be rapidly changed.

(4) No energy is lost in its transfer through the vacuum of space, and little is lost in the Earth's atmosphere at the longer microwave wavelengths.

(5) The mass of the power converters at the system terminals can be low because of

operation at microwave frequencies.

(6) Energy transfer between points is independent of a difference in gravitational potential between those points.

1.4. Choice of frequency and interference problems

Another important and general aspect of wireless power transmission is the frequency or wavelength to be used for it. In general, any frequencies from 1 GHz all the way up to and including optical frequencies could be used. In the vacuum of space there is no transmission loss at any of these frequencies. In the Earth's atmosphere, however, there will be attenuation at the higher frequencies, particularly when there is rain, so that there will be a reliability consideration when the higher frequencies are used. The efficiency of the transmitting and receiving components will always be greater at the lower frequencies. On the other hand, the use of the lower frequencies will necessitate large transmitting and receiving aperture sizes which are not attractive for some applications (Brown, 1996).

**History of WPT**

Nikola Tesla was a pioneer in the field of wireless power, but he never achieved his dream of a fully operational wireless power system. However, many of his concepts have influenced modern wireless technologies, including Wi-Fi, wireless charging, long-distance communication, and cell phones.

**History of WPT**

The first work on electromagnetism was conducted by André-Marie Ampère, who formulated Ampère’s Law in 1820, which describes the force of attraction or repulsion between two current-carrying wires (Pei, 2022).[[1]](#footnote-0) Ampère’s work builds on the fact that the physical origin of the attractive force between two wires is that each wire generates a magnetic field, following the Biot–Savart law, and the other wire experiences a magnetic force as a consequence, following the Lorentz force law. Shortly after Ampère, in the 1830s, Michael Faraday observed the transfer of electrical energy without wires, which culminated in Faraday's Law of Induction, which states that the electromotive force drives a current in a conductor loop when subjected to a time-varying magnetic flux.[[2]](#footnote-1) In 1864, James Clerk Maxwell proposed Maxwell's equations leading to a theory that unified electricity and magnetism in electromagnetism, or electromagnetic energy transmission in a free space.[[3]](#footnote-2) The next discovery in electromagnetism came twenty years later in 1884, when John Henry Poynting defined the Poynting vector and gave Poynting's theorem, which describes the flow of power across an area within electromagnetic radiation and allows for a correct analysis of wireless power transfer systems.[[4]](#footnote-3) Then in 1888 Heinrich Rudolf Hertz verified Maxwell’s equations through experiments and discovered electromagnetic waves and electromagnetic radiation, and demonstrated high-frequency power transfer using a spark gap and parabolic reflectors at both the transmitting and receiving ends of the system (Faccioa et al., 2006). In 1897 Nikola Tesla illuminated phosphorescent lamps using Tesla coils in a wireless power transfer experiment that transmitted power with microwaves between two objects 48 km apart, and between1891 to 1904, Tesla conducted numerous investigations on electromagnetic and electrostatic energy transmission (Tesla, 1914). Tesla created Alternating Current (AC) and poly phase systems, in order to transfer energy to any point on our earth by using our earth and its atmosphere as a conductor. In 1964 W.C. Brown developed the first microwave wireless power transfer system, using a rectenna for remote power transfer that could use magnetrons, which are essential for converting electricity into microwaves, and also convert microwaves back into electricity (Brown, 1996).

Dynamic wireless charging (DWC) for electric vehicles was first introduced in 1976 and researched by the Lawrence Berkeley National Laboratory (LBNL) (Niu et al., 2019; Jang, 2018; Suna et al., 2024)). In 1993 the University of Auckland patented a non-contact power distribution system, including for use in electric vehicle charging (Boys and Covic, 2015). The Massachusetts Institute of Technology (MIT) developed a mid-range WPT technology in 2007 which could light up bulbs over 2m using magnetic resonance (Kurs et al., 2007). In 2009, the Korean Advanced Research Institute (KAIST) developed the first-generation prototype of the On-Line Electric Vehicle (OLEV) project (Suh et al., 2011; Ko and Jang, 2013; Lee et al., 2010).

In 1996 General Motors (GM) produced the first modern EV with the GM EV1, which used an inductive charging system named MagneCharge, and also led to the development of EV critical technologies such as low-rolling-resistance tires, keyless ignition, a heat pump for HVAC, and regenerative braking (Knight-Ridder and Adler, 1996; Witzenburg, 2021). In 2013, Elix Wireless introduced a 10-kW wireless charging system using PMPT technology in conjunction with the University of British Columbia, with a patent on magneto-dynamic coupling (MDC) technology (Green Car Congress - Energy, 2015; Whitehead, 2015; Li, 2009; Thakur and Natale, 2009). In 2014, Vahle and Hella resolved the issue of foreign object heating through use of low field primary coils, which facilitated uninterruptible charging (Turki, 2014). In 2015, Qualcomm Halo and the University of Auckland, developed a 7.2 kW wireless charging system for the BMW i8 safety car (Westlake, 2015; Qualcomm, 2015; Ombach, 2014), whose Double D (DD) coils (pads), which are more efficient and misalignment tolerant than the circular and rectangular pads (Boys and Covic, 2013), have also been integrated and tested on safety cars including Renault Fluence and Honda Accord (Mahesh et al., 2021; Niu et al., 2019; Pei, 2022).

In 2016, Bombardier manufactured a high-power WPT system called PRIMOVE with a power capacity from 200 kW to 400 kW (Woronowicz et al., 2016; Niu et al., 2019; Pei, 2022; KOnrad, 2014; Wirth, 2016). Also in 2016, WPT technology designed for EVs was first commercialized by Tesla and Evantra, with the commercialization of Tesla Model S equipped with Evantan Plugless system, providing wireless inductive charging at a rate of 7.2 kW per hour (Ganz, 2016). In 2017, Nissan and WiTricity announced plans to equip fast wireless charging on the next generation of LEAF (Leading Environmentally-friendly Affordable Family car) (WiTricity, 2017). In 2022, Momentum Dynamics announced a dual-power mode capability in automatic inductive charging (AIC) that provides a wireless system with the ability to charge light-duty EVs at both high (50-75kW) and low (7-22kW) power, with the ability for the vehicles to intelligently recognize and charge a vehicle battery at any power using a common inductive component on the vehicle (Momentum Dynamics, 2022).

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**Wireless Power Transmission, WPT**

Wireless power transfer (WPT), also known as wireless energy transmission (WET) or wireless charging, is a technology that allows electrical energy to be transmitted from a power source to an electrical device without the need for wires or batteries as a physical link. With WPT, the need for traditional power cables is eliminated, and may be used to power electrical devices where interconnecting wires are inconvenient or hazardous. The most common uses of wireless power transfer are for charging mobile devices, such as smartphones and electric toothbrushes, as well as for electric vehicles (EVs) and some medical devices. The next devices to be powered by WPT include IoT devices, industrial machinery, and transferring power over longer distances for space-based solar power systems. Methods for improving the efficiency, range, and standardization of wireless power transfer are continuously being researched, as the efficiency and range of wireless power transfer systems can vary depending on the technology used.

Wireless electricity can be divided into two domains, near field and far field (Kracek and Mazanek, 2011). In near field, or nonradiative technology, which includes inductive coupling (between coils of wire) and capacitive coupling (between metal electrodes), power is transferred over short distances by magnetic fields. When wireless electricity is transmitted using radio waves, microwaves, or laser beams, it is known as far field or radiative technology. Far field technology can be used for solar powered satellites and wireless drones, where energy needs to be transmitted over longer distances, but must be aimed at the receiver. For these long distances, electrical energy is converted into electromagnetic waves, which are then transmitted through the air and received by a compatible device (Bush, 2014).

WPT can be classified in several ways as function of the power, range, frequency, technology, etc. Depending on the transferring frequency f and the associated wavelength λ, WPT technologies can be divided into two big categories characterized by different operation mode:

•Near-field when d << λ;

•Far-field when d >> λ.

(d) being a function related to the physical size of the device (Shinohara, 2014). However, using point source approximation (d) can be assumed to be the distance.

Frequency conversion is used in WPT systems to convert the frequency of the power source to optimize energy transfer, using power electronic converters such as inverters and rectifiers to transform the frequency and voltage of the electrical energy. Matching the impedance of the transmitter and receiver circuits to maximize power transfer efficiency and transfer between the source and the load is achieved using matching networks, which consist of inductors and capacitors. Field shaping can be used to control the shape and distribution of the electromagnetic fields, which involves optimizing the design of coils, antennas, and other components to focus the fields and minimize losses. Modulation techniques can be used to control the power flow and improve the stability of WPT systems, which involves varying the amplitude, frequency, or phase of the electromagnetic fields.

In near-field coupling, the power is transferred over electrically short distances by magnetic fields using inductive coupling also called magnetic coupling, or by electric fields using capacitive coupling also called electric coupling. When these two couplings operate in resonant conditions, the power transfer efficiency is improved and these technologies are respectively known as magnetic resonant coupling (MRC) and capacitive resonant coupling (CRC).

In far-field operation mode, the WPT technology is categorized into radiofrequency (RF), microwave (MW) and optical.

The WPT technology consists in the transmission of electrical energy from a source (transmitter), generally powered by alternating current (AC) at frequency f, to a device (receiver) without using wires, but through a time-varying electromagnetic field according to the diagram shown in Fig. 1.3. The receiver extracts energy from the electromagnetic field and delivers it to a load which is often a battery. The distance d between the transmitter and the receiver is generally called range. In many applications including those in the mobility sector, transmitter and receiver are separated by air and the separation space is more properly called airgap. In other applications the separation media could be biological tissues such as in the case of implanted medical devices (Kim et al., 2017), or ground as in the case of wireless underground devices (Kisseleff et al., 2016), or water as in the case of submarine implants.

An important parameter that determines the type of waves is the frequency, which determines the wavelength.

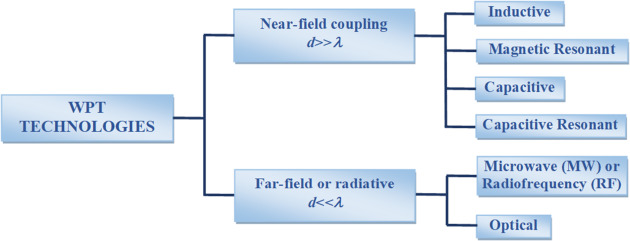
**Near Field**

1. Inductive Coupling
2. Resonant Inductive Coupling, Magnetic Resonant Coupling
3. Capacitive Coupling
4. Capacitive Resonant Coupling
5. Implantable Medical Devices
6. Electric Vehicles
7. Smartphones
8. Electric Toothbrushes

**Far Field**

1. Microwave
2. Radiofrequency
3. Optical
4. Solar Powered Satellites
5. Wireless Drones

**Figure 1. Classification of WPT Technologies**



Feliziani, M., Campi, T., Cruciani, S., and Maradei, F. (2023) Academic Press, Wireless Power Transfer for E-Mobility, Fundamentals and Design Guidelines for Wireless Charging of Electric Vehicles, <https://doi.org/10.1016/C2021-0-01579-0>

**Wireless Power Process and Infrastructure**

In a wireless power transfer (WPT) system, electromagnetic fields are generated and manipulated to transmit energy without the need for physical wires, instead relying on electromagnetic source transformations. These fields can be either magnetic (inductive) or electric (capacitive). Maxwell's equations are the fundamental laws governing these fields, providing the theoretical basis for WPT. A wireless power transmission system consists of a transmitter, oscillating electromagnetic field, and a receiver. The transmitter device is connected to a power source such as a main power line, which converts the power into a time-varying electromagnetic, electric, or magnetic field, and transmits that power across space to a receiver device, which extracts power from the field and converts it back to DC or AC electric current for use by an electrical load.[[5]](#footnote-4) The transmitter converts the input power into an oscillating electromagnetic field via an antenna or coupling device, and the receiver then converts the oscillating fields into electric current. There are several options for what constitutes the antenna, including: a coil of wire which generates a magnetic field, a metal plate which generates an electric field, an antenna which radiates radio waves, or a laser which generates light. The purpose of electromagnetic source transformations within WPT systems are to optimize the electrical energy, so that it can be efficiently transferred through electromagnetic fields.

In a wireless switch, inside the switch there is a magnetic coil, or antenna, and when the switch rocker is pressed it creates enough energy to send a radio signal to the receiver. The built-in receiver is wired to the light and stored in the light fixture. If the receiver is a plug-in module then it is simply plugged into an outlet and the device it controls is plugged into the receiver (McMaster, 2023). Wireless switches, consisting of a transmitter and receiver, can reduce the cost of wiring a house by 50%, by reducing the material and labor cost for wiring houses. However, most wireless switches until recently have required batteries to operate. Moez’s Alberta system utilizes switches that run without batteries, collecting energy from ambient sources such as radio frequency signals, with each floor having one or two RF (radio frequency) power transmitters to power up all switches inside the house. Energy consumption can also be reduced with wireless switches, by accommodating sensors for temperature, humidity, and occupancy, wirelessly controlling vents, and turning lights on and off as occupants move from room to room (McMaster, 2023).

**Characteristics of Wireless Electricity Technology[[6]](#footnote-5)**

1. The distance over which they can transfer power efficiently
2. Whether the transmitter must be aimed (directed) at the receiver
3. The type of electromagnetic energy they use
4. Time varying electric fields
5. Magnetic fields
6. Radio waves
7. Microwaves
8. Infrared or visible light waves

Wireless power uses the same fields and waves as wireless communication devices like radio. Radio transmission is a wireless communication technology which transmits information and a tiny amount of power, and involves electrical energy being transmitted without wires by electromagnetic fields, and is used in cellphones, radio and television broadcasting, and WiFi.[[7]](#footnote-6) [[8]](#footnote-7) Wireless power technologies are more limited by distance than wireless communication technologies, because whereas in wireless communication technology such as radio the sufficiency of information transmitted is more important than the amount of power reaching the receiver, but in wireless power transfer the amount of energy received is what is important, so the efficiency, or fraction of transmitted energy that is received, is the most significant parameter.[[9]](#footnote-8) Wireless powered communication (WPC) is when wireless information transmitters or receivers are powered via wireless power transfer. Simultaneous Wireless Information and Power Transfer (SWIPT) is when the power of wireless information transmitters are supplied via the harvested power.[[10]](#footnote-9) Conversely, Wireless Powered Communication Network (WPCN) is when wireless information receivers are supplied via the harvested power.[[11]](#footnote-10) [[12]](#footnote-11) Regulations and standards ensure that wireless power systems limit human exposure and that of other living beings to potentially dangerous electromagnetic fields.[[13]](#footnote-12) [[14]](#footnote-13) Minimizing energy losses, or maintaining power transfer efficiency, is an important concern in WPT system design, with the coil design, impedance matching, and frequency selection playing a significant role in efficiency. The range, or distance over which power can be transferred, is also a key parameter in WPT systems. Imura et al. (2009) and Lee and Lorenz (2011) demonstrated that optimizing shape, arrangement, and number of the turns in the transmission and receiver coils can increase the WPT efficiency (Fisher et al., 2014).

**Advantages of Wireless Power Transfer**

Convenience: One of the most significant advantages of wireless power transfer is its convenience. Users can charge their devices without the need for physical cords or connectors simply by placing them on a charging pad or within a certain range of the power source.

Reduced Wear and Tear: Since there are no physical connectors, there is less wear and tear on charging ports and cables. This can extend the lifespan of devices, especially those with delicate or frequently used charging ports.

Safety: Wireless power transfer systems are designed with safety in mind. They often include temperature monitoring and foreign object detection to prevent overheating or damage. This can reduce the risk of electrical accidents or fires.

Flexibility in Design: Wireless charging can work through various materials, such as wood, plastic, and glass. This allows for more flexibility in the design and placement of charging pads. It can be integrated into furniture, vehicles, and various consumer electronics without disrupting the visual aesthetics.

Aesthetics: Wireless charging pads can be integrated seamlessly into the design of furniture, vehicles, and consumer electronics, enhancing aesthetics and reducing clutter caused by cords and cables.

Mobility and Portability: Wireless charging is particularly useful for mobile and handheld devices, like smartphones and wearables. It allows for convenient and hassle-free charging on the go.

Healthcare Applications: In healthcare settings, wireless power transfer can be used to charge medical devices like pacemakers, eliminating the need for surgery to replace batteries.

Electric Vehicles (EVs): Wireless charging for electric vehicles offers a more convenient and hands-free way to charge electric cars, especially for autonomous vehicles that can park and charge on their own.

Space Applications: In space, wireless power transfer can be used for transmitting power from solar panels on satellites to the spacecraft's systems, eliminating the need for physical wires that can be damaged or compromised in the harsh space environment.

IoT Devices: Wireless power transfer can be used to power and charge a variety of Internet of Things (IoT) devices, eliminating the need for frequent battery replacements.

Harsh Environments: In applications where wires or connectors are exposed to harsh environments, such as underwater or extreme temperatures, wireless power transfer can be a more reliable and durable solution.

User Experience: The simplicity of wireless charging enhances the overall user experience, making it easier for people to keep their devices charged and ready for use.

While wireless power transfer has many advantages, it's important to consider factors like efficiency, cost, and compatibility with specific devices and applications when determining its suitability for a particular use case.

**Disadvantages of Wireless Power Transfer**

Lower Efficiency: Wireless power transfer is generally less efficient than traditional wired charging. Some energy is lost as heat during the transfer process, which can result in slower charging and wasted energy.

Limited Range: The range of effective wireless power transfer is limited. Most systems require the device to be placed very close to the charging pad or source. This means that devices must be accurately aligned and can't be moved too far from the power source during charging.

Slower Charging: Wireless charging, in most cases, is slower than wired charging. This can be a drawback when you need a quick charge for your device.

Device Specificity: Different devices may require different wireless charging standards or technologies. For example, not all wireless chargers are compatible with all smartphones or devices, which can be confusing for consumers.

Higher Cost: Wireless charging technology often costs more than traditional charging methods. The charging pads and associated components can be more expensive to produce and purchase.

Heat Generation: Wireless charging can generate heat, both in the charging pad and the device being charged. Excessive heat can affect the lifespan and performance of batteries.

Compatibility and Standardization: There are multiple wireless charging standards, like Qi, PMA, and others. This lack of standardization can lead to confusion and incompatibility issues, as not all devices work with all wireless chargers.

Energy Loss: In some wireless power transfer methods, such as resonant inductive coupling, there can be energy loss as radio waves propagate between the transmitter and receiver coils, reducing overall efficiency.

Bulkiness: Some wireless charging solutions, like charging pads or stands, can be bulkier than simple charging cables, making them less portable.

Security and Privacy: In some applications, like wireless charging kiosks in public places, there may be concerns about security and privacy, as there's a potential for data interception or malware injection through the charging process.

Environmental Impact: Wireless charging systems still rely on electricity generated from various sources, including fossil fuels. If the energy source is not clean and sustainable, the environmental benefits of wireless charging can be limited.

Limited Use in High-Power Applications: Wireless power transfer is less efficient and practical for high-power applications, like charging electric vehicles, requiring high energy transfer rates.

It's important to weigh these disadvantages against the advantages and consider the specific needs of the application or device when deciding whether to use wireless power transfer

**WPT Technologies**

WPT methods can be classified into eight categories: IPT (inductive power transfer), RIPT (resonant inductive power transfer), PMPT (permanent magnet coupling power transfer), CWPT (capacitive wireless power transfer), piezoelectric charging, OWPT (optical wireless power transfer), MR-WPT (microwave radiation wireless power transfer) and UTET (ultrasonic transcutaneous energy transmission). Laser power transfer is a form of optical power transfer. IPT and R-IPT are the most used universally. Inductive power transfer (IPT)) is created with the magnetic field of the electromagnetic wave, and can be divided into non-resonant IPT and resonant IPT (RIPT). According to the medium for power transmission, IPT, RIPT and PMPT are categorized as magnetic coupling WPT, and CWPT is classified as electric coupling WPT. IPT, RIPT, PMPT, CWPT, and piezoelectric charging are near field technologies, and thus can only be achieved within limited distance, while OWPT, MR-WPT and UTET are classified as far-field approaches where the wave length is shorter than the transmission distance. Ahmad et al. (2017) describes three common procedures for far field technologies: 1) They convert electrical energy into an ultrasonic wave, microwave or laser; 2) They transmit converted energy to expected objects; 3) They harvest and convert energy back into electricity. Radiative transfer transmits energy using electromagnetic waves, such as microwaves or lasers, and is capable of long-range power transfer. Transferring power over several kilometers, such as with microwaves and lasers, can overcome the problem of limited air-gap distance. The antennas for both laser (optical) and microwave power transfer are too large and unsafe to operate in populated places, even as laser (optical) power transfer requires a smaller transmitter antenna compared to microwave power transfer (AboHarga et al., 2024).

In WPT systems the receiver transfer power to the batteries or drive system through power electronic converters. Another concern with WPT is its leakage EMF radiation at higher frequencies. This radiation is restricted by using proper shielding to make it safer (Mahesh et al., 2021).

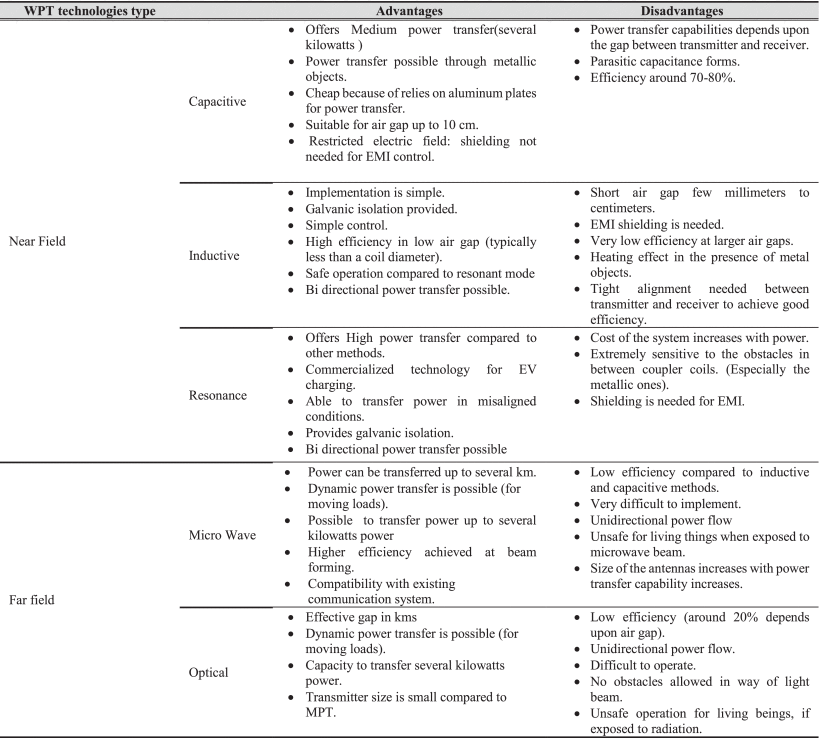
WPT system can be divided in different categories with respect to transmitting power ranges. Low power range WPT system covers: < 1 kW, medium range WPT covers: 1–100 kW and high power range WPT > 100 kW.

In WPT system power can be transferred unidirectional (G2V) and bidirectional (vehicle to grid vice versa). V2G application in conductive charging is more complex than wireless charging. Vehicle to vehicle (V2V charging is possible while stationary or moving)

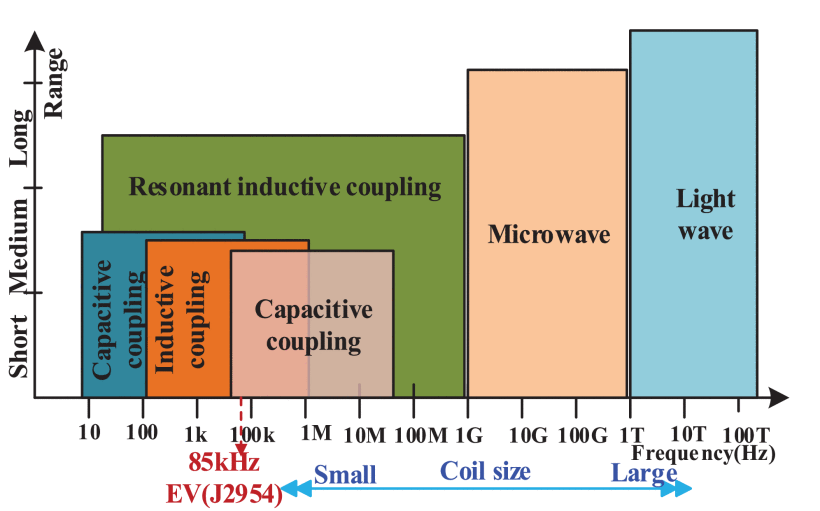
We can transfer power small distances to long distances i.e. several cm to kilometers.

The power transmission medium effects the efficiency of the system. Major losses occurs in this region For instance, In the article [8] author presented that underwater WPT(water as a medium) system provides 5% lower efficiency compared to air-gap system(air as a medium).

1) Coupling (Near field), 2) Radiative (Far field). Coupling system further categorized into magnetic field and electric field radiative type categorized into two types microwave and laser types



(Mahesh et al., 2021)



(Mahesh et al., 2021)

**DWC, Dynamic Wireless Charging**

C. Panchal, S. Stegen, and J. Lu, “Review of static and dynamic wireless electric vehicle charging system”, Engineering Science and Technology, an International Journal, vol. 21, no. 5, pp. 922–937, Oct. 2018, doi: 10.1016/j.jestch.2018.06.015.

Dynamic WC, is a form of stationary source for mobile vehicles, which means charging the vehicle while it is moving. In DWC technology, transmitter coils, charging pads, are embedded in the road or highway, which may be implemented as segmented pads or a long power rail track, with each pad activated for a split second while the vehicle traverses the charging infrastructure, with receiver coils installed on the vehicle. In the segmented method each pad has a separate power supply which is switched on when the EV moves across those pads (Choi et al., 2015; Mi et al., 2016). The long rail track has a simple structure and easily distributes power, though it causes extra power losses if the vehicle connected secondary coil does not cover the entire track. The power rail, both segmented and long track, requires a power range of several watts to kilo watts, and is influenced by the magnetic power transfer capability of magnetic coupler properties. *Table 9 shows the rating and shape of power rails constructed by using magnetic pads.* Research has shown that segmented power rails, which require many cables, can reduce leakage EMF and energy loss (Choi et al., 2015; Mi et al., 2016; Gil and Taber, 2013; Choi et al., 2013; Huh et al., 2011). As the vehicle travels over the coils, energy is transferred wirelessly through electromagnetic fields, providing continuous charging without the need for stops. DWC reduces the need for large batteries and frequent charging stops, increasing the range and efficiency of electric vehicles (Jang, 2018; Suna et al., 2024; Fisher et al., 2014). Vehicle speed is an important consideration for dynamic wireless charging. depends on vehicle speed. In DWC vehicle movement affects the secondary coil which is assembled to the vehicle, and the charging position also changes with respect to the ground assembled primary coil. In addition, flux transfer efficiency depends on proper alignment between transmitter ground coil and vehicle mounted receiver coil. When the EV is moving, maximum power transfer occurs when the secondary pad is perfectly aligned with one of the transmitter pads. As the vehicle moves forward and the secondary pad shifts while moving toward the next ground transmitting pad, there is a reduction of power transfer between the coils because the receiver pad’s alignment with the first transmitter pad reduces while alignment with the next transmitter pad increases (Miller et al., 2015; Mahesh et al., 2021).

This change in power transfer occurs because all the transmitter pads are connected in phase with series connection. Therefore, all the time exited current runs through both the coils and the pool of magnetic field generated by each coil and that field returns over by the air gap between the coils. This effect of a moving EV with a DD coil on a lumped track is derived as,

where is the speed of the EV, is the distance between coils, and and are the mutual inductances. This equation states that the velocity of the EV is inversely proportional to the energy transfer between coils, though EV speed does not affect the total energy transferred in a time particular interval (Mahesh et al., 2021).

Stationary WC, or quasi-dynamic wireless charging (QWC), is static state charging by stationary sources, and occurs when the vehicle is stationary but the engine is still running, and the user parks the vehicle over a charging pad on the floor, and a corresponding charging pad mounted on the underside of the vehicle picks up the signal and charges the vehicle. Stationary charging occurs over a short period of time, and the vehicle does not receive a full charge. Opportunity charging is a term that has been developed to refer to idle electric buses charging at bus stops via pads embedded in the pavement at the stop. Charging at bus stops allows electric city buses to reduce their battery sizes, making the buses more efficient by reducing their weight (Fisher et al., 2014). Private vehicles could also be charged at traffic lights or during normal traffic patterns (Pei, 2022). A quasi-dynamic wireless charging system takes some advantages from DWC, and needs less investment compared to DWC (Mahesh et al., 2021). Static WC, also static state charging by stationary sources, occurs when the charger is placed in a specific position, and the vehicle is turned off while a full charge is performed, such as with home chargers or car parks.

Mobile source charging for stationary vehicles would include for example instances where AAA brings a mobile battery charger to charge a vehicle with a depleted battery. Huang et al. (2014) reports that the optimal battery capacity for a mobile charger is 40 kWh, as if the battery capacity of the mobile charger is too small, the mobile charger is to be returned for recharge too often, though if the capacity is too large, the mobile charger would diverge away from the service central area which would affect other users who are in need of it (AboHarga et al., 2024). Another option for charging electric vehicles, reminiscent of how the military fuels airplanes in flight, is known as V2V charging, or mobile source for mobile vehicles, where energy is transferred between two moving vehicles, enabling the continuous operation of electric vehicles without necessitating a stop for recharging (Nguyen et al., 2020; Zhao et al., 2017; AboHarga et al., 2024).

DWC optimization system is concerned with the power optimization, segment allocation and pad length. From the [equation (1)](https://ieeexplore.ieee.org/abstract/document/#deqn1-deqn2):

,

where is magnetic flux density, is permeability of free space, and is length of conductor, we see that mutual inductance of the system depends on speed. Chen et al. (2015) determined that primary pad mutual inductance is critical to consider in obtaining the appropriate primary pad length. Zhang et al. (2014) found that optimum pad length is not influenced by either the speed of the vehicle when less than 3 km/h, or when the track length is 3 meters, which is the peaking of the averaged coupling coefficient at .

The benefits of using a track length at are as follows:

1. the coupling coefficient stays at its maximum;
2. the coupling coefficient is independent of the vehicle speed;
3. the design of the power converter and its control method is more straightforward.

**Vehicle Speed and Power Utilization**

Zhang et al. (2014) makes the following observations:

1. the power requirement from the track output per sectional-track length decreases with increasing speed of vehicles moving above the track;
2. the number of vehicles powered from a sectional track decreases dramatically with increasing vehicle speed;
3. the sectional-track utilization is lower for higher vehicle speed.

**Track Length and Efficiency**

Typical vehicles have a ground clearance between 150 and 300 mm, depending on their actual sizes. The clearance will set a lower limit on the air gap of the primary track and the secondary pickup. If an EV has an air gap of 150 mm to the road, the track system in the road has to be covered by 50 mm of bitumen, and the practical air gap is around 200 mm. Pickup size of less than 1 m2 has been implemented to provide 2 kW (Budhia et al., 2011) and 26.7 kW (Huh et al., 2011) power transferring through an air-gap separation of 200 mm. A case study using standard test cycles for urban and highway driving conditions has previously revealed that 40 kW per car is needed for all traffic scenarios studied to avoid the use of battery power (Chopra and Bauer, 2013).

**Sectional Edge Correction**

It is evident from Fig. 8 that the coupling coefficient starts to decrease when the sectional length is close to the length of the pickup. In practice, sectional track length longer than the length of the pickup can be easily designed. Therefore, sectional-track length longer than that of the pickup is assumed subsequently. However, the coupling coefficient will decrease when a vehicle is entering or leaving a sectional track. The edge corrected coupling coefficient at a particular track length is calculated using the coupling coefficient averaged over the entire alignment distance of a sectional track. Upon averaging, the coupling coefficient is chosen from the previous track if the alignment distance is smaller than the track switching point, as shown in Fig. 9(c). Otherwise, it will be chosen from the current sectional track. The curve of the average k has the same variation tendency as that of k before correction. However, when the track length is equivalent to the length of the pickup, the existence of edge effect results in a lower average value of k since the edge areas occupy considerable portion of the track length. The average value of k approaches k as the track length increases.

**Multiple PIckups**

In practice, multiple vehicles move along a single sectional track. The study of a pickup with our sectional-track system is therefore extended to a multipickup system, where the number of vehicles n in a sectional track is limited by the vehicle speed and sectional-track length. In our RVIPT system, all pickups are designed identical. The secondary impedances are identical for identical loading conditions, and the total reflected impedance from all pickups is

where and are edge correction factors for both ends of the sectional track, as studied in Section VI. This is equivalent to the reflected impedance of a single identical pickup with an equivalent mutual inductance given by

where . Hence, the improvement of coupling coefficient (Wang et al., 2005) is simply

where is the coupling coefficient of a single pickup and is a real number less than or equal to , taking into consideration the sectional edge correction.

To help understand the system, we define the equivalent length of a vehicle moving at a speed as

where is the length of the vehicle and is the resultant following distance given by the result of Fig. 5. Three possible coupling scenarios can be identified as follows:

(a) ; maximum number of vehicles moving in accordance with the multilane model

(b)

(c)

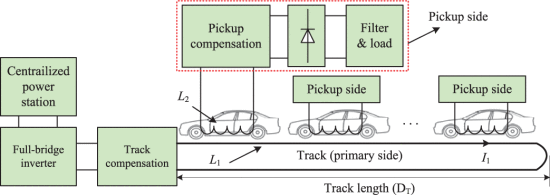
which correspond, respectively, to (a) the track being shared with maximum number of pickups, i.e., ; (b) the track being occupied with exactly one vehicle, i.e., ; and (c) every vehicle being coupled with only one track while other tracks being inactive. In case (c), for each active track, .

1. For a fixed track length, the maximum decreases rapidly with increasing vehicle velocity .
2. The curves of shown are under the assumption of maximum utilization of sectional track, i.e., is at its maximum.
3. The value of decreases with increasing vehicle velocity until , which marks a crossing point on the dotted black curve, satisfying case (b). Any further increase in vehicle velocity decreases the utilization of the sectional track. Then, each sectional track has equal to either one or zero. The coupling coefficient of each active track stays at the dotted black curve of average k .

The relationship among various key parameters, such as vehicle speed, system efficiency, and power utilization of the IPT system, is studied in detail. Specifically, the impact on efficiency due to variation of track length and edge correction is reported.

An IPT roadway vehicle system is a hands-free charging system that offers convenience and reliability unaffected by dirt, chemicals, weather, and so on.

In addition to efficiency enhancement, research has focused on alleviating the positional alignment constraint between the pickup and the track conductors.



A moving vehicle picks up power from track current , and the maximum power picked up is given by (Covic and Boys, 2013A)

where is the operating angular frequency of track current , is the mutual inductance between and of the track and pickup inductances, and is the quality factor of the system. Normally, secondary compensation is necessary to create a resonant tank with the pickup inductor. The secondary compensation guarantees enough power to be received by the pickup. Similarly, a primary compensation is also essential to achieve a lower volt-ampere (VA) rating of the power supply (Wang et al., 2005).

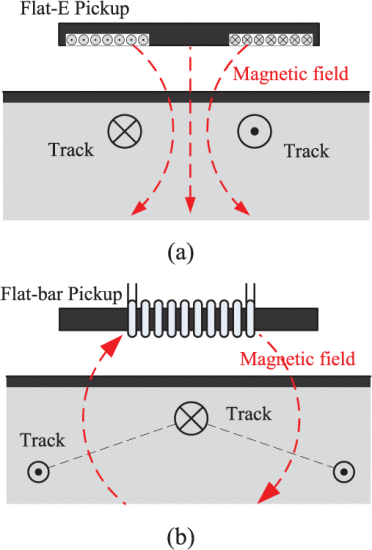
For a secondary series compensated IPT system, the efficiency can be maximized by operating at a constant angular frequency and an optimized system quality factor of , where is the secondary compensated capacitor

where is the coupling coefficient, and are the quality factors of the primary and secondary coils given as

with and being coil resistances. From , high efficiency can be achieved by maximizing . Apparently, the quality factors in and increase with increasing operating frequency . In practice, the quality factors follow the approximate Dowell’s equation, which is valid for frequencies much lower than the self-resonant frequency of the inductor (Zhang et al., 2014). The quality factor peaks at a frequency much lower than the self-resonant frequency of the inductor.

Moreover, the upper bound of the operating frequency is limited by the power being transferred. For a power rating suitable for driving an EV, the operating frequency is usually limited below 140 kHz (Covic and Boys, 2013B). In addition, the pickup VA rating, which can be calculated as (Covic and Boys, 2013C), poses an upper limit on QLs , since the VA rating essentially increases with the operating frequency. At a high power rating and high QLs , arcing between the strands of the litz wire may be induced by the associated high-voltage stress (Garnica et al., 2013). Furthermore, increasing the coil quality factor by increasing copper utilization is not a wise choice from the economic point of view.

The directions of usable flux of a single long track can be horizontal or vertical, as shown in Fig. 4. The structure of the pickup should be designed to save space and allow the freedom of lateral movement. Therefore, the pickup is normally designed to be flat (Covic et al., 2000; Lee et al., 2010). The vertical flux can be captured by the flat-E structure of the pickup, within which the windings are wounded horizontally, while the flat-bar structure is optimized to capture the horizontal flux (Lee et al., 2010). The flat-E structure captures the vertical flux of bipolar tracks. However, the vertical flux is maximized at the center of the two tracks and is minimized above each of the tracks, leaving a tight tolerance in lateral alignment (Covic et al., 2007). In contrast, the flat-bar pickup with a unipolar track has wider range of tolerance in lateral alignment.



***Power Supply Architecture for Dynamic Wireless Charging***

(Mahesh et al., 2021) DWPT is a method to charge the vehicle while moving. DWPT system requires less battery size compared to SWPT, which reduces vehicles cost and weight. In addition vehicles range increases with same size battery (Choi et al., 2015; Mi et al., 2016). Moving of the vehicle makes the short interaction time between transmitters and receiver for that high power conversion system needed. In addition, should have good misalignment tolerance especially horizontal. DWC design architecture needs careful considerations. Power conversion depends on speed of the vehicle and length of primary coil. Considering that it is unfeasible to change drivers mind and habits, when it comes to speed. Another parameter is length of the track. The transmission track along the road, long enough to be successful operation, this track can be divided in to segments in order to optimize the system. But, its optimization depends on operation frequency, speed of the vehicle and traffic on the road. Furthermore each segment in the system consists of one or more coils. As show in Fig. 32, coils can be arranged in series of small segments or long track system. Compared to SWC system, the DWC system behaves as a distributed manner coordination between power electronic converters and coupling pads needs to be increased to improve the system efficiency and charging facility utilization. DWC can be divided into two types considering the architecture of power electronics. The first type uses a single long track (shares single A/C line). The second one uses a segmented track have multiple small coils (Miller et al., 2011; Choi et al., 2015) (shares common DC bus). Coil designing is a very difficult task, while designing the ratio length and span (the pitch) of the coil should be considered (Miller and Onar, 2012).

In one approach, each local coil or ground pad powered with separate H-bridge power converter has highest redundancy, fault in converter least impact on power supply and on other power converters as shown in Fig. 33. Cost of the system decreases when it comes to cables, but when it comes to power converters, it increases the cost of the system and complexity (Miller et al., 2014; Chen et al., 2014). Alternative approach is a centralized single power converter supplies power to the moving pick through extended power track (Nguyen et al., 2015). Number of power electronic components reduces in this method compare to previous method. Maximum power rating of the track and number of EVs on the track influences design of centralized converter. Uncoupled area is more in this system when EVs are not occupied the transmitting pads.

By above considerations one method is as shown in Fig. 34. Single power converter supplies power to the number of inverters by single DC bus. By this method the number of converters is reduced. DC bus designed in order to power more number of inverters to reduce the cost and losses cost instigated by long cables. The modified design of above architecture divided into two categories, one centralized PFC with inverter powers the multiple transmitting pads. Disadvantage of this model is reaction time between transmitting pads to coming vehicle (Jinbo et al., 2016). This problem can be solved by power supply splitting, where transmitting pads powered by single inverter split part to power other converter, which increases reaction time (Jinbo et al., 2016). However, this method increases AC conducting wire results increase cost of the system.

The scheme shown in Fig. 35 the transmitting pads are turned ON and OFF through a switch box. This arrangement reduces the use of power converters and losses. In addition individual control of pads to power particular vehicle (Chen et al., 2014). Drawback of this structure relates to high power loss at connecting the pads. In paper (Ramezani and Narimani, 2020) , in the proposed topology, multiple transmitter coils are series connected. Each transmitter coil is in parallel with a bypass switch. In this structure, multiple transmitters are supplied with only one inverter and one resonant network which reduce the implementation costs and power losses. Moreover, to detect the load on each segment, a new load detection method based on the amplitude of the transmitter coils voltages is proposed.

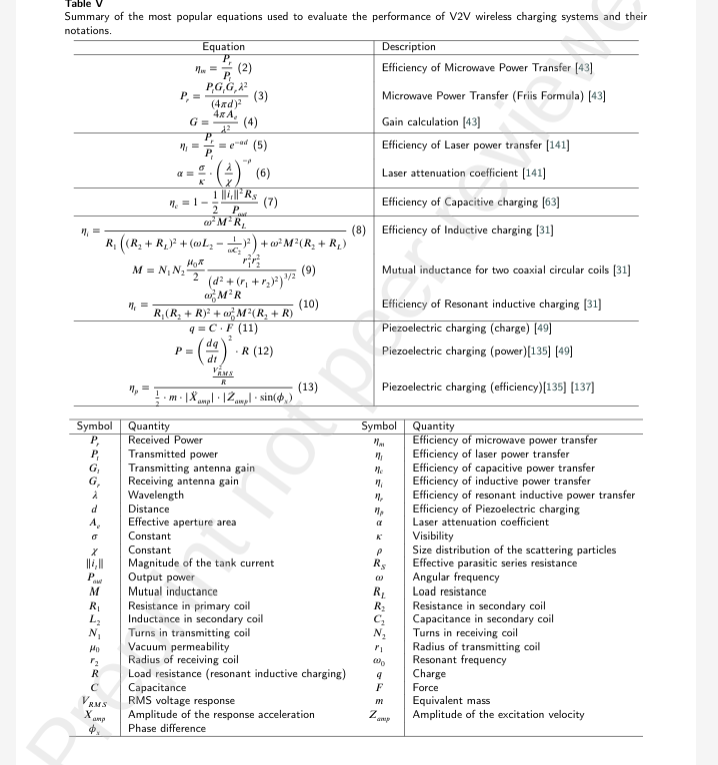
**Flux Pattern on Rail**

)Mahesh et al., 2021) According to the authors in (Bagchi et al., 2021), the couplers forms three types of flux patterns, which are:

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

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

TABLE 16 Comparison Flux Patters in DWC [211]



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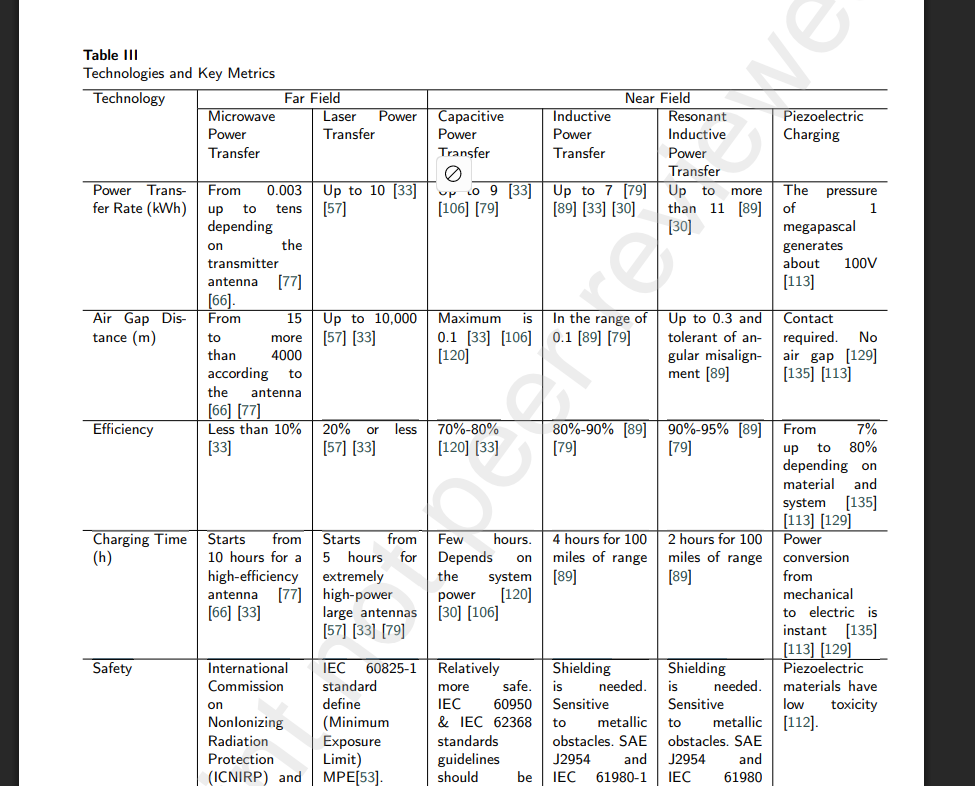
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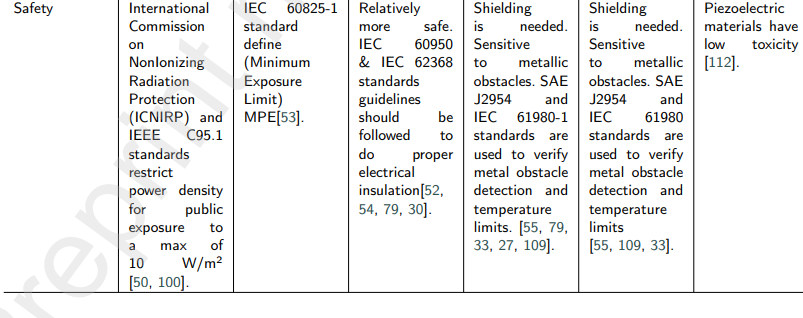
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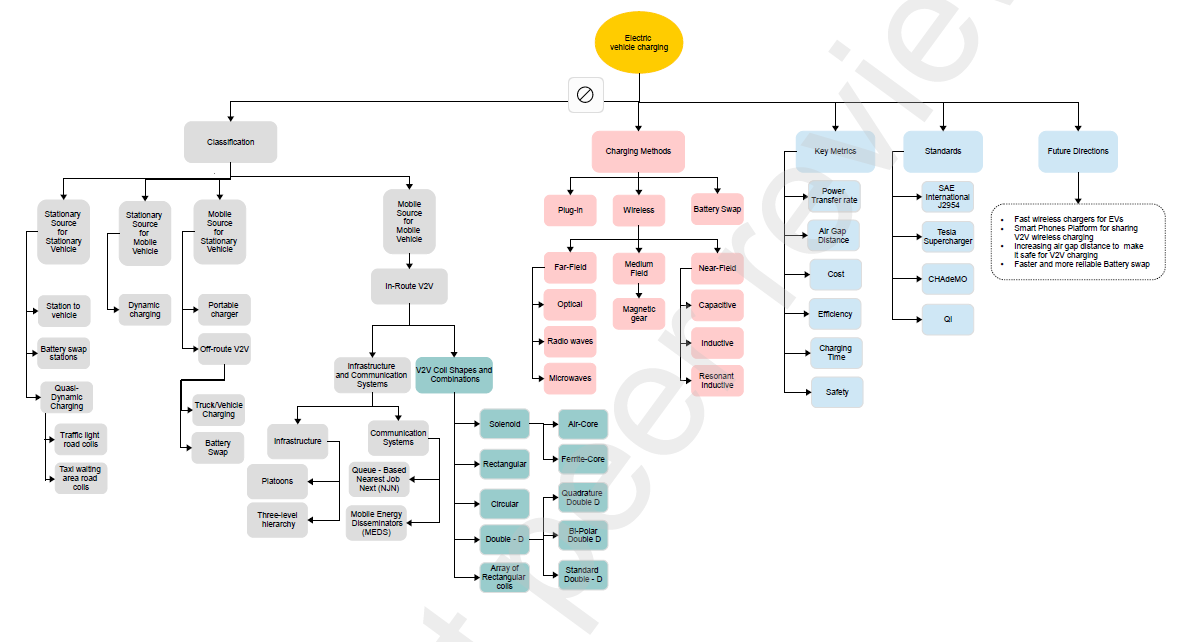
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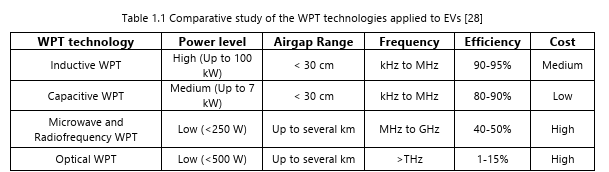




AboHarga, Gehad and Mukhtar, Husameldin and Himeur, Yassine and Gadhafi, Rida and Copiaco, Abigail and Hadi, Sabina Abdul and Gan, Dongming and Taha, Tarek and Ritz, Christian and Atalla, Shadi and Mansoor, Wathiq and Al-Ahmad, Hussain, (2024) A Comprehensive Review of Wireless Charging Technologies with Emphasis on V2V Integration. Available at SSRN: https://ssrn.com/abstract=4682516 or <http://dx.doi.org/10.2139/ssrn.4682516>



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(Pei, 2022)

**Inductive Coupling**

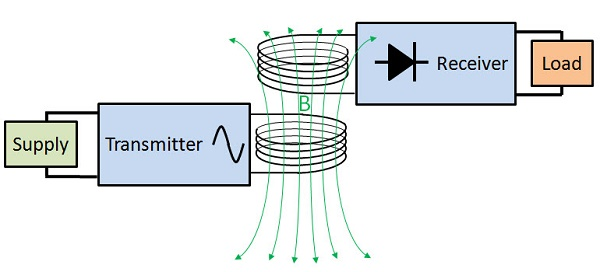
In inductive wireless charging, also known as inductive power transfer (IPT), works off of electromagnetic waves and works similar to the operation of a transformer. In IPT, electromagnetic fields are induced to transfer power by running currents through a coil of wire, and then exposing another coil nearby to that magnetic field to induce an electric current in the nearby coil to form a transformer with an air gap (Fisher et al., 2014; Mahesh et al., 2021). IPT requires two coils of wire: 1) a transmitter coil, powered by a converter, in the charging pad or base station; when electricity flows through the transmitter coil, it generates an electromagnetic field around it, and 2) a receiver coil in the device being charged; picks up the electromagnetic field from the transmitter coil. When the coils are closely aligned, such as the device being placed on the charging pad, the two wire circuits are inductively coupled when the transmitter generates high-frequency currents which creates a time-varying electromagnetic field in the transmitter or conductor (primary side coupler) coil via Ampère’s Law, which induces electrical current flow or voltage 𝐸 in the receiver coil (secondary side) via Faraday’s Law of Induction, with the induced voltage then converted to a DC power signal by a rectifier to charge the battery (Triviño-Cabrera et al., 2020; Pei, 2022),

where 𝐸 represents the induced voltage, is the flux of the magnetic field passing in the area limited by the receiver, and indicates the number of turns in the receiver.

The currents are then transferred to the load directly or through a power system to charge a battery or power the device. The transmitter and receiver coils must be in close proximity to each other and aligned for effective IPT performance due to the weak magnetic coupling occurring in presence of an air gap. The inductive coupling principle works similarly to that for an electrical transformer. However, whereas the primary and secondary coils in electrical transformers are strongly coupled through a ferromagnetic structure that channels the magnetic flux along a specific path, in a WPT system the presence of an air gap leads to a weak magnetic coupling between the primary transmitter coil and the secondary receiving coil.

Non-resonant IPT can transfer power with a magnitude of up to 7 kW and a maximum gap distance of 10 cm (AboHarga et al., 2024). The efficiency of the IPT system can be enhanced by tuning the secondary coil frequency equal to operating frequency (Wei et al., 2014). Sample et al. (2008) reports that the limit of the air gap extends up to 20 cm at a cost of lower efficiency when operating at the range of radio frequency (Sample et al., 2008).

**Figure 3 - Inductive coupling principle**

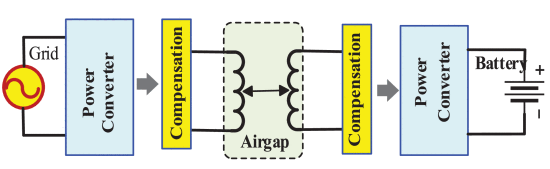


<https://www.edgefxkits.com/blog/wireless-power-transfer/>

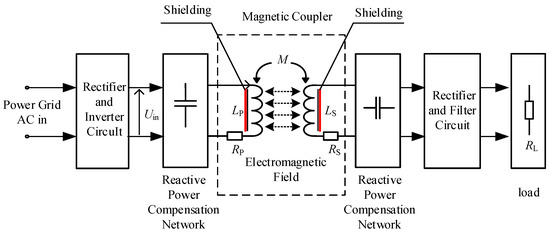
IPT has been used to charge devices in several fields, including electric vehicles (Villa et al., 2007; Sallán et al., 2009; Kim et al., 2013), industrial material handling systems (de Boeij et al., 2008), smartphones, electric toothbrushes, implantable medical devices, and laptops (Liu and Hui, 2007A; Waffenschmidt and Staring, 2009; Liu and Hui, 2007B). IPT technology, when used in wearable and implanted medical devices (WIMD), allows for the monitoring and regulating of vital organs, while pacemakers regulate irregular heartbeats like Arrhythmia with electrical impulses (Chen et al., 2009; Sato et al., 2004).

**Magnetic Resonance, Resonant Inductive Coupling, Magnetic Resonant Coupling, Resonant Inductive Power Transfer**

Resonant inductive coupling, or magnetic resonant coupling, is an improvement of inductive charging in terms of power transferring capability, designing and coupler coils, that uses resonance to improve power transfer efficiency at longer distances between the source and receiver. MRC or RIPT is needed over IPT because unless the coils are very close together and aligned correctly, IPT is inefficient (Mur-Miranda et al., 2010; Fisher et al., 2014). In MRC, the transmitter and receiver coils are tuned to the same resonant frequency, allowing for more efficient power transfer over a greater distance, operating at specific resonant frequencies. Magnetic resonant coupling is often preferred because in inductive coupling, the air gap between the transmitter and the receiver can result in a poor magnetic conductive environment (Niu et al., 2019; Feliziani et al., 2023; Pei, 2022). While an RIPT system transfers higher power than an IPT system, RIPT is also more susceptible to interference from metallic objects positioned between the transmitting and receiving coils (Pei, 2022; Triviño et al., 2021). Resonant inductive charging can reach up to 11 kW of power transfer with larger tolerance to air gap distance (as high as 25 cm) (AboHarga et al., 2024). Resonant inductive wireless charging has high efficiency and easy maintenance. In RIPT, compensation networks (capacitors/inductors or both), structures composed of reactive elements, are added in the series or/and parallel formations to connect both the transmitter and receiver coils to form the resonant condition (Mahesh et al., 2021). In an RIPT system, similar to other WPT technologies, existing grid voltage is transformed to high frequency AC (HFAC) via power electronics converters, and the HFAC signal is then delivered to the coupler coil. The secondary coupler coil, the receiver, generates voltage by the generated magnetic fields, and the generated voltage is converted to DC power to power the battery through power electronics converters (Triviño-Cabrera et al., 2020; Mahesh et al., 2021).

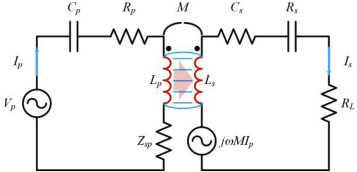


(Mahesh et al., 2021)



Parallel–series topologies are adopted in this circuit—transmitting coil and compensation network are in parallel; and the receiving coil and compensation network are in series. In Figure 1, LP and LS are the inductance of transmitting coil and receiving coil. RP and RS are the internal resistance of transmitting coil and receiving coil. Uin is the output voltage of electric energy after rectification and high-frequency inversion. M is the mutual inductance between transmitting coil and receiving coil. k is the coupling coefficient. RL is the load resistance. IL is the current of RL. IP is the current of the transmitting coil, QP and QS are the quality factor of the primary and secondary circuit. η is the efficiency of the wireless charging system. In the case of full reactive power compensation, the output power PO of the system can be expressed in Equation (1)

According to Equations (1) and (3), it is obvious that the output power increases with the coupling coefficient, and the efficiency of the wireless charging system is also influenced by the coupling coefficient. The mutual inductance and coupling factor between the coils can be changed by changing the design of the magnetic structure of the magnetic coupler.



(Niu et al., 2019)

a RIPT system: two separate series-tuned sides coupled with a mutual inductance. The value of M is closely related to the number of coil turns, coil layouts and relative positions of both sides. In this system, the mutual inductance can be denoted by

where and are the self-inductances of the primary and secondary windings, respectively, and k represents the coupling coefficient.

, , and are four key indexes when evaluating a RIPT system.

directly reflects how well the receivers are coupled to the transmitter, therefore, it is of great significance to have higher k value in a lumped RIPT system (Li and Mi, 2015). However, has its limitation when applied in evaluating a distributed system (Boys et al., 2007). It also should be noted that tighter coupling does not necessarily lead to higher power transfer.

As far as the power capacity of a RIPT system is concerned, the reflected impedance ZSP should be discussed, and it can be determined by

where , are the resistances of secondary coils and the load, ω is the angular frequency of the AC current, and is the compensation capacitance of the secondary side. indicates the influence on the primary side arising from the secondary side. The higher is, the larger power class can be realized. It is implied in (2) that if the capacitive reactance can be adjusted to exactly cancel the inductive reactance, will reach its maximum value,

Theoretically, the maximum uncompensated apparent power can be calculated by

where IP is the current in the primary coil,

Nevertheless, considering the EV battery pack is usually deemed as a pure resistive load, the maximum uncompensated apparent power that can be transmitted to the batteries only reaches half of the value calculated by (4). When ω and IP are both kept as constants, SU\_max can be applied as a benchmark to assess the power capacity of different coupler designs [44].

By defining the secondary circuit quality factor as

it has been verified that the power capacity of a double series-tuned RIPT system can reach QS times of its uncompensated counterpart (Boys et al., 2000). In terms of power transfer, quality factor is defined as the ratio of the energy stored in a resonant tank to the energy dissipated per cycle. Therefore, higher QS implies lower power loss (Li and MI, 2015). However, trade-off has to be made since increasing QS will result in additional system volume and cost, besides, very high QS value makes it hard for the system to get tuned in that little frequency variation brings about great change of the AC impedance.

(Mahesh et al., 2021) The resonance inductive WPT operating principle is based on Amperes Law and Faradays Law as mentioned above, the HFAC signal passing through the primary winding produces a time varying magnetic field (Ampere’s law). The resultant magnetic flux is proportional to Permeability of free space, number of turns and current flowing through it (1). The time varying magnetic flux induces electric current the secondary winding (Faraday’s Law), equation (2).

, Faraday’s Law

where is magnetic flux density, is permeability of free space, is length of conductor, is induced voltage, and is magnetic flux. indicates number of primary turns, and indicates number of secondary turns.

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

A WPT system able to function at resonant or above resonant condition. At low power applications leakage inductance results small voltage drop even with high current. For high power and high frequency applications results higher voltage drop due to large leakage inductance. it is difficult archive high power without increasing current input. In other side increase current causes more conduction losses. In addition, extra reactive power(compensation) needed to increase the VA rating of the inverter (Wang et al., 2005; Miller et al., 2014). Usually, achieving ZVS or ZCS Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS) at higher frequency is very difficult and it is required to achieve high efficiency (Choi et al., 2015).

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

Those are structure, air gap between two coils, compensation scheme, resonant frequency, coil and design, power electronics topology and alignment.

Ignoring the magnetic losses and resistance of the coil, simplified form of apparent power exchanged between to can be calculated.

where the true power transfer can be presented as,

In following analysis, consider that to power transfer happening. when the power flows from to reaches maximum.

The apparent power transferred to two-coil system is,

Hence, the total reactive power flows between two coils is

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

where,

‘k’ indicates coefficient of coupling in between and ’s maximum can be achieved by solving the following equations

,

and obtained the solution as

,

In resonance condition value near to 0, at gets maximized, at same instant the power transferred also maximized. The phase angle among the two currents and is about 90° contrary to 180°. Where i.e. tightly coupled. In this condition to achieve high efficiency value to be increased. In this case, if self-inductance of the coil resonates with capacitor and it makes and lowers value, this method is not suggested.

Instead of self-inductance if capacitor resonates with leakage inductance of the coil. Coupler behaves as a transformer and value increases, however, the whole system doesn’t work under resonant condition.

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

To get more efficient power transfer at a certain coil current. and should be in phase since lags by 90° on the secondary coil. At the receiving side, the pure resistive nature can be observed. In same time, complex power at the primary side must be minimized.

When the complex power given as,

We have,

where indicates resistance of secondary winding and load resistance as

Describing quality factors by, , , the transfer efficiency is defined as

Expression of efficiency can be rewritten as,

Where

The maximum efficiency

**PMPT (Permanent Magnet Coupling Power Transfer)**

Niu et al. (2019) describes PMPT as wireless power transfer technology with a low operating frequency achieved via magnetic field, with the coupling mechanism derived via magnetic interaction between synchronously rotating permanent magnets. In PMPT, either a self-contained motor or static windings that are positioned around its surface are used to drive the transmitter PM (Thakur and Natale, 2009). The PM rotor in the receiver is rotated at the same speed but in the opposite direction as that of the transmitter due to the gear effect. Due to its low operating frequency, problems of magnetic exposure and foreign object heating are mitigated. As PMPT suffers from noise, vibration and harshness issues (Qui et al., 2014; Du et al., 2018; Johnson et al., 2017), the tensile strength of PM material, the maximum rotation speed of PM rotors, and the bearing structure selection should be given more attention in the design process of a PMPT system (Niu et al., 2019).

**Capacitive Coupling, Capacitive WPT (CWPT)**

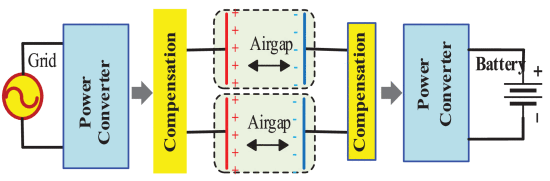
Capacitive coupling is an electrostatic field based system which uses electric fields to transfer energy between conductive plates, and is suitable for compact designs with low-power and small-gap WPT applications due to the constraints on the developed voltage (Niu et al., 2019; Chang et al., 2015; Dai and Ludois, 2015; Sodagar and Amiri, 2009). A capacitive WPT circuit includes two pairs of parallel metallic plates facing each other, acting as a transmitter and receiver to form an equivalent capacitor, which are connected in series and form a pair of coupling capacitors, to transmit power power in the form of electrostatic energy through the metallic medium (Rim and Mi, 2017; Wang et al., 2022; Pei, 2022). CPT is more flexible to angular misalignment in up to 1 mm small gaps (Lu et al., 2015). Whereas IPT and RIPT systems require bulky ferrite as flux path, CWPT is supported by an electric field with an easily controlled direction (Niu et al., 2019). Safety is not a concern with EMF exposure for CWPT because nearly no electric flux can escape outside the dielectric materials (Liu et al., 2009). CWPT systems work well for both low current and high voltage systems, and are lower weight and cost less than IPT systems. Through inductive compensation, where additional inductors are added to capacitor plates on each side to reduce impedance, soft switching operation and increased power transfer efficiency are enabled (Mahesh et al., 2021).

*When an alternating voltage excitation is applied at the transmitter side, the electric flux density 𝐷 between the metallic plates changes to form a displacement current 𝐼 and achieve a wireless power transfer by Maxwell’s full current theorem (Wang et al., 2022). However, the capacitance 𝐶 is small with air alone, so a common capacitor holds a dielectric between the plates to increase 𝐶 (Wang et al., 2022).*

*where 𝜀 is the dielectric constant, is the permittivity in a vacuum, is the relative permittivity, and 𝑆 is the area where displacement current flows. The change in electric flux density field , that is, the change in the electric (time derivative of the electric field) is important, as well as the change in the magnetic field at the time of electromagnetic induction (Wang et al., 2022; Kline et al., 2011; Dai and Ludois, 2025).*

**Electric Resonance, Capacitive Resonant Coupling**

Capacitive WPT is cheaper than IPT and RIPT technologies, though capacitive resonant WPT also has lower transmission efficiency than RIPT systems (Triviño et al., 2021; Pei, 2022).



(Mahesh et al., 2021)

**Piezoelectric Charging**

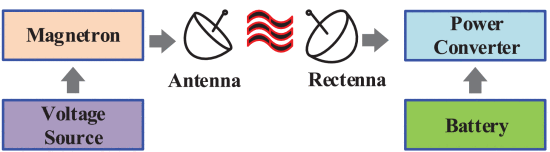
An advantage of piezoelectric charging is immediate power conversion from mechanical pressure to electricity, although direct contact is necessary (AboHarga et al., 2024; Yang et al., 2017).

**UTET (Ultrasonic Transcutaneous Energy Transmission)**

(Niu et al., 2019) For UTET, it is suitable for multi-device charging with the help of nondirective field (Dai and Ludois, 2015; ,UBEAM, 2015; Sanni et al., 2012).

**Microwave Power Transfer**

Microwave power transfer refers to WPT based on the microwave to transfer energy in a far-field context, which can also be extended to Radiofrequency (RF) signals with minor modifications. MR-WPT can transmit both directive or nondirective power, which makes it applicable to monolithic microwave integrated circuits and solar power satellites (Matsumoto, 2002; Hwang et al., 2010; Shinohara et al., 2013; Niu et al., 2019). However, the feasibility of microwave power transfer faces challenges due to high propagation loss and safety concerns related to microwave radiation, in addition to the impracticality of large antenna arrays required for efficient MPT (Huang and Zhou, 2015; AboHarga et al., 2024). From a high-voltage DC generator source, a magnetron (vacuum based oscillator) is fed which creates a microwave signal, and then it is sent through a transmitting antenna. This signal is received by the receiving antenna, also known as a rectenna (antenna + rectifier) to convert the microwave signal to a DC signal, which is received by the power converter and is transferred to the load (Niu et al., 2019; Pei, 2022; Mahesh et al., 2021).



(Mahesh et al., 2021)

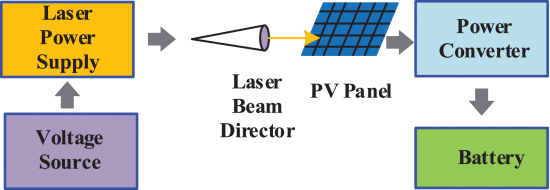
**Optical Power Transfer (OPT)**

Optical power transfer is a general term for transferring power by converting electrical energy into optical energy (light) and then back into electrical energy at a receiver.

In OPT, power is radiated in the form of electromagnetic waves in the THz range, thus it exists as light (Mahesh et al., 2021). This type of wave requires the power transmitter and the receiver to be in the line of sight; that is, without any intermediate obstacles, as the wave cannot traverse them (Fisher et al., 2014; Niu et al., 2019; Pei, 2022). OPT uses a transmitter which consists of a laser diode which generates a light beam with a specific power and wavelength, with a beam director adjusting the direction of the power transfer. In the secondary receiver side, a photovoltaic (PV) cell converts the received light into power with the power converter, while the rectifier converts the power signal to DC signal, which is then fed to charge a battery or load. A High Intensity Laser Power Beam (HILPB) system has the ability to transfer power to any point, but conversion efficiencies, wavelength, and the temperature and materials of the PV cells will limit the performance of the system (Fisher et al., 2014; Pei, 2022; Mahesh et al., 2021; Jin and Zhou, 2019).

**Laser Power Transfer, OPT**

This is a specific type of OPT where the light source is a laser. Lasers offer advantages like high power density and narrow beam focusing, making them suitable for long-distance and high-power applications. Distributed laser charging (DLC) can be used for wireless charging of mobile devices, and offers the benefit of self-aligning for mobile applications (Liu et al., 2016). Self-aligning means that DLC allows charging without precise positioning or tracking, as long as the transmitter and receiver maintain the line of sight (Zhang et al., 2018).



(Mahesh et al., 2021)

Table 1. Comparison among different WPT methods. (Niu et al., 2019)

| **Methods** | **Efficiency** | **Merits** | **Demerits** |
| --- | --- | --- | --- |
| IPT | 99.5%  @6.6 kW, 0.5 mm [[28](https://www.sciencedirect.com/science/article/pii/S1364032119305106#bib28)] | Extremely high efficiency | Limited achievable power transfer distance |
| RIPT | 94%  @11 kW, 10–15 cm [[29](https://www.sciencedirect.com/science/article/pii/S1364032119305106#bib29)] | A good balance of power transfer distance and efficiency | Parameter-sensitive (e.g. mutual inductance, load impedance) |
| PMPT | 81%  @1.6 kW, 15 cm [[7](https://www.sciencedirect.com/science/article/pii/S1364032119305106#bib7)] | Low EMF exposure and temperature rise of foreign object | NVH problem |
| CWPT | 84%  @30 W, 5 mm [[11](https://www.sciencedirect.com/science/article/pii/S1364032119305106#bib11)] | No core losses, simpler and more compact design | Higher exciting voltage for the same power class |
| OWPT | 84%  @30 kW, 1 mile [[30](https://www.sciencedirect.com/science/article/pii/S1364032119305106#bib30)] | Free of flux guidance and no comparable energy density | Hazardous and easily affected by weather conditions |
| MR-WPT | 59.2% @10 kW, 1.2 m  [[27](https://www.sciencedirect.com/science/article/pii/S1364032119305106#bib27)]  5.01% @250 mW, 1 m [[31](https://www.sciencedirect.com/science/article/pii/S1364032119305106#bib31)] | No rigid alignment required, potential in both near-field and far-field applications | Poor efficiency and inevitable field exposure |
| UTET | 39%  @30 mm, 360 mW [[32](https://www.sciencedirect.com/science/article/pii/S1364032119305106#bib32)] | Non-radiative and suitable for multiple pickups | Inefficient and costly |

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**WPT Standards**

These standards are set to protect humans from the adverse health effects caused by electromagnetic radiation from man-made devices. The standards set for these vehicles’ wireless charging not only ensure their functionality and efficiency but also guarantee safety by preventing any hazardous incidents associated with high power transfers and significant air gap distances. Both the IEEE and the ICNIRP have determined that there is no strong evidence that exposure to electromagnetic fields causes cancer. However, other adverse health effects are possible, including tissue heating as well as nerve and muscle stimulation. Retinal phosphene visualization is another possible effect; that is, electromagnetic waves can induce the sensation of light in the retina without light actually being present.

1. In the United States, the Society of Automotive Engineers (SAE) published the fourth version of SAE J2954 in 2020.
2. In Europe, the IEC is the institution responsible for establishing standards through the IEC 61980
3. International Organization for Standardization (ISO) has defined the standards under ISO-19363 in close synchronization with SAE J2954 and IEC 61980
4. “Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz” is made by the Institute of Electrical and Electronic Engineers (IEEE)
5. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz) are made by the International Commission on Non-Ionizing Radiation Protection (ICNIRP)
6. In the USA, safety standards are governed by the Federal Communications Commission (FCC)

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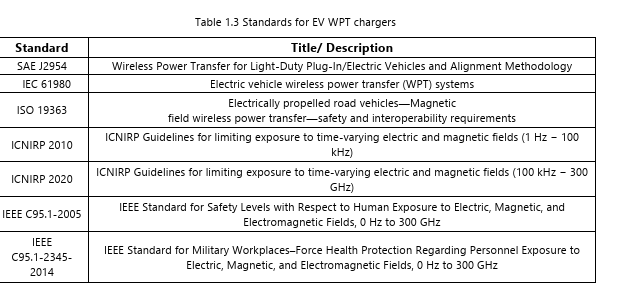
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(Pei, 2022)

**Electromagnetic Modeling**

Conducting electromagnetic modeling, device prototyping, sensing electronic experiments, and measurements of antenna systems within a full anechoic chamber and prototyping facilities involves a complex and highly technical process. Here's a breakdown of the key aspects:

Electromagnetic modeling, or electromagnetic simulation, is used to simulate and predict the behavior of antenna systems for wireless power transmission before physical prototyping. Software like ANSYS HFSS, CST Studio Suite, and FEKO are used to model and analyze electromagnetic fields and antenna performance. These tools employ numerical methods like the Finite Element Method (FEM), Method of Moments (MoM), and Finite-Difference Time-Domain (FDTD) to solve Maxwell's equations.

Some key metrics to consider include charging time (measured in hours), air gap distance (measured in cm or mm), efficiency, maximum power transfer rate (measured in kW per hour), and safety. The charging time measures the duration it takes to fully charge the battery, whereas the air gap distance measures the gap separating the transmitter from the receiver assuming no obstacles are present. Air gap has an inverse relation with efficiency which makes smaller air gaps better for power transfer. The charging efficiency measures the percentage of electrical energy transferred from the transmitter to the receiver. Power transfer rate refers to the rate at which electrical power in kilowatts is wirelessly transmitted to an electric vehicle’s battery in one hour. Lastly, safety is defined here as a descriptive metric for the security of users and vehicles from hazards during the wireless transfer of electrical power. Charging efficiency is the most commonly used metric to measure wireless charging performance as it directly impacts the overall energy consumption and cost. Charging time is also critical as it determines how fast the vehicle can be charged and how convenient the charging process is for the user. Safety is also a critical metric, as it ensures the potential risks and hazards associated with wireless charging, such as the potential for electric shock or fires, are minimized.

Modeling parameters include: frequency range, antenna geometry, material properties, and environmental factors are considered in the simulations. Simulation results provide insights into antenna parameters like radiation patterns, gain, impedance, and return loss.

2. Device Prototyping:

Purpose:

To create physical prototypes of antenna designs for testing and validation.

To refine designs based on experimental results.

Prototyping Facilities:

3D Printing:

Used to create complex antenna structures and housings.

PCB Fabrication:

Essential for manufacturing antenna circuits and matching networks.

Machine Shops:

Used for fabricating metal components and precise mechanical parts.

Assembly and Soldering:

Critical for assembling antenna components and ensuring reliable electrical connections.

3. Sensing Electronic Experiments:

Purpose:

To integrate sensing electronics with antenna systems for applications like wireless sensing and communication.

To evaluate the performance of the integrated system.

Experiments and Measurements:

Network Analysis:

Using vector network analyzers (VNAs) to measure antenna impedance, return loss, and S-parameters.

Spectrum Analysis:

Using spectrum analyzers to measure radiated power and spectral characteristics.

Signal Processing:

Implementing signal processing algorithms to extract information from received signals.

System Integration:

Integrating sensor circuitry with the antenna, and testing the combined systems performance.

4. Measurements in a Full Anechoic Chamber:

Purpose:

To obtain accurate and reliable measurements of antenna performance in a controlled environment.

To minimize the effects of unwanted reflections and interference.

Anechoic Chamber:

A shielded room lined with RF-absorbing materials to eliminate reflections.

Provides a "free-space" environment for antenna measurements.

Measurement Techniques:

Radiation Pattern Measurements:

Rotating the antenna and measuring radiated power at different angles to determine its radiation pattern.

Gain Measurements:

Comparing the received power from the test antenna to a standard gain antenna to determine its gain.

Polarization Measurements:

Measuring the antenna's response to different polarizations of electromagnetic waves.

Key Considerations:

Calibration:

Accurate calibration of measurement equipment is essential for reliable results.

Environmental Control:

Maintaining stable temperature and humidity in the anechoic chamber is important for consistent measurements.

Safety:

Working with high-power RF signals requires strict adherence to safety protocols.

By combining electromagnetic modeling, device prototyping, sensing electronic experiments, and anechoic chamber measurements, engineers can develop and optimize high-performance antenna systems for a wide range of applications.

**Metamodeling analysis of RIPT systems**

(Pei, 2022) During the development of the RIPT system, accurate 3D models are needed, able to correctly describe the geometry, the materials (e.g., coils, ferrites, and vehicle chassis), and the phenomena involved (e.g., the effect of transient electromagnetic phenomena) with the operating frequency between 10 and 100 kHz. However, the computational cost of 3D models based on volumetric meshes (FEM, finite difference method, etc.) is rather high.

Several metamodeling techniques have been developed to describe the relationship between the input variables and the observed output, such as Support Vector Regression (SVR) (Moustapha et al., 2022), Multigene Genetic Programming Algorithm (MGPA) (Searson, 2015), Polynomial Chaos Expansions (PCE) (Blatman and Sudret, 2011), and so on. They have been applied to generate several metamodels that are trained with a limited set of samples. But, how to choose training samples effectively and define internal parameters for the metamodeling techniques depends on the studied system and the range of variability of the input variables.

Reference (Trinchero et al., 2019) applies the SVR, the least-squares support vector machine (LS-SVM) regressions with polynomial and Gaussian radial base function (RBF) kernels, and the PCE method to predict the impact of 30 uncertain parameters on the maximum efficiency of a WPT application in the bandwidth 500 MHz to 1.5 GHz. In (Capua et al., 2021), it derives low-complexity behavioral analytical models of the mutual inductance between the couplers of WPT systems as functions of their reciprocal position by means of the MGPA method. In (Delgado et al., 2022), a MGPA metamodel is investigated to express the self-inductance and the mutual inductance versus geometrical parameters of the ferrite and coils for the WPT system. Reference (Di Capua et al., 2021) uses an analytical, behavioral model that relates mutual inductance between the coil pair to their relative positions along the actual vehicle trajectory for a dynamic WPT system. In (Cirimele et al., 2020), it adopts the parametric model order reduction technique with the Monte Carlo (MC) approach to quantify how and how much the uncertainties on the components and material parameters of a WPT system for the static charge of EVs affect the overall efficiency and functionality of the final produced device. It is based on a standard system among the ones provided by the current SAE J2954 recommended practice.

Although these articles have verified the feasibility of the metamodeling techniques in WPT systems, there is no research to compare which metamodeling technique is the most suitable for the RIPT system among SVR, MGPA, and PCE methods. Moreover, the post-process of the PCE approach-sensitivity analysis (Sudret, 2008) is not taken into account to analyze how the input variables impact the system performances. Besides, metamodeling techniques allow to compare at low cost the performance of different shaped couplers for the RIPT system.

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**Electric Vehicle Wireless Charging**

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B. Esteban, M. Sid-Ahmed, and N. C. Kar (2015) A comparative study of power supply architectures in wireless EV charging systems, IEEE Trans. Power Electron., vol. 30, no. 11, pp. 6408–6422.

Wireless power transfer can be used to charge autonomous driverless electric vehicles without the need for human intervention.

The currently available technology for EV battery charging consists of plug-in charging (conductive charging or wired charging) and Wireless charging (contactless) methods. Plug-in charging system further classified in to Off-Board and On-Board chargers based on charging platforms. One of the main concern with conductive charging is high power cables, to plug EV, those are difficult to handle. Hazards can happen due to damaged cables or mishandling. Furthermore, Conductive charging methods are prone to vandalism and theft. An alternative new technology is WPT, introduced by Nikola Tesla in 19th century, with the time this technology developed and became competitive solution for wired charging systems. This technology has capability to replace the plug-in interface by transmitters and receivers, allowing power flow in a contactless manner in the form of electromagnetic or static waves as shown Fig 2 (Mahesh et al., 2021)

The charging phase begins once the vehicle is stopped in specific areas, such as traffic lights, parking slots, etc., without the need for human intervention. This is known as static (or stationary) WPT. Electrified roads are planned in the near future to allow wireless charging of the batteries while the vehicle is in motion via dynamic wireless power transfer (DWPT) (Mi et al., 2016; Cirimele et al., 2019; Lazzeroni et al., 2021; Miller et al., 2015a). To achieve practical use of WPT technology on commercial products, interoperability between different vehicles and charging systems is a key requirement to ensure (ISO 19363, 2020). To this end, all interested stakeholders are participating in a massive standardization effort. The first important result of this activity is the SAE standard (SAE J2954, 2022) for stationary charging of EVs which will be presented in detail in Chapter 8

Electric vehicle wireless charging (EVWC) technology operates on the principles of magnetic inductance and magnetic resonance.

EV wireless charging strengths include:

•

big increase of the EV range when the electrification of the road infrastructure will be widely deployed;

•

reduction of the on-board battery size and therefore reduction of costs and weight;

•

improvement of electrical safety as there are no electrical contacts and the system is totally waterproof;

•

comfort since human intervention is no longer required;

•

less maintenance as there are no electrical contacts subject to wear.

The WPT technology has several engineering challenges, but the most critical is the possible increase of the electromagnetic pollution. As example the WPT technology based on coupled inductors is characterized by a significant emission of magnetic field in the environment. Therefore, it requires a careful study of electromagnetic field (EMF) safety and electromagnetic compatibility (EMC), i.e., the impact that the magnetic field produced by these systems both on people inside and outside the vehicles, and on other electronic devices, such as in-vehicle control units and off-board systems in road and signal infrastructure. Currently these problems are deeply studied and must be solved soon to facilitate the diffusion of WPT automotive systems on a large scale (Kim et al., 2016; Campi et al., 2019b, 2020; Cruciani et al., 2019, 2020; Ding et al., 2014; Cirimele et al., 2017; Lee et al, 2022).

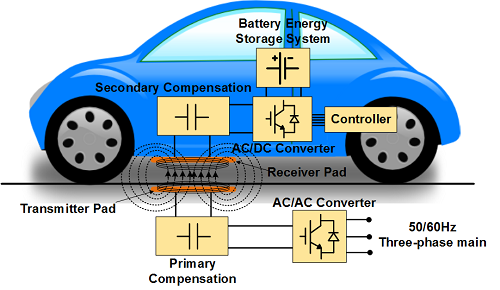
**Inductive Power Transfer Systems for Electric Vehicles**

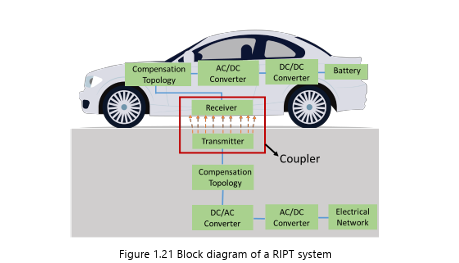
<https://eps.fiu.edu/inductive-power-transfer-systems/>

Inductive power transfer (IPT) is an emerging technology for transferring power without any physical contact based on electromagnetic induction. This technology has recently found many applications in commercial and residential sections such as material handling, biomedical implants, transportation systems and static and dynamic electric vehicle charging. This technology is employed to transfer power from one system to another across a relatively large air gap between two loosely coupled inductors which have a weak magnetic coupling. Since it is unaffected by dust or chemicals and eliminates sparking and the risk of electrical shock, it can be used in hazardous environments. This technology offers high reliability, robustness, high efficiency and provides a clean, safe, and robust way of transferring power. Also, it has rapidly gained an increased interest in the industrial and commercial sectors. In Figure 1, a typical IPT system is shown. This system is composed of power converters, loosely coupled magnetic structures and compensation components.

Contactless electric vehicle (EV) charging based on inductive power transfer (IPT) systems is a new technology that brings more convenience and safety to the use of EVs. It enables automated charging processes without the interaction of the driver by eliminating the charging cables. Contactless EV charging is divided into two main categories: static charging and dynamic (in-motion) contactless charging. In static charging, the goal is to charge the EV using a contactless charger when the EV is parked in a charging station. This is a solution that enables safe, efficient, and convenient overnight recharging of EVs. On the other hand, a dynamic contactless EV charging system enables contactless charging of the EVs while they are moving. This system is comprised of a power supply, primary and secondary converters, primary and secondary magnetic structures, and corresponding compensation circuits. The existing barriers in the deployment of IPT systems are their high cost, lower efficiency compared to conventional charging systems, vehicle misalignment sensitivity, and electromagnetic field (EMF) emissions. The aim of this research is to enhance the efficiency and reduce the cost and contribute to the development of IPT technology for EV charging applications.

Figure 1: A typical inductive power transfer system for contactless electric vehicle charging.

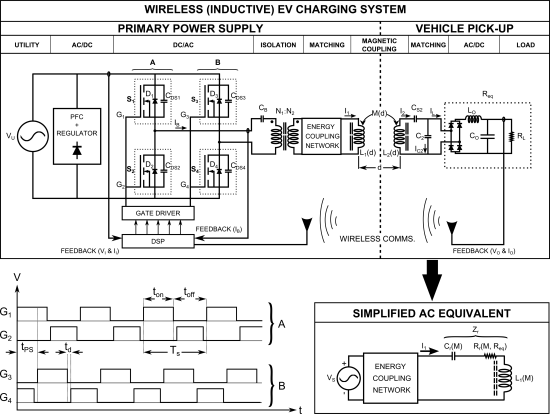


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(Pei, 2022)

The electrical network provides a DC-link voltage for the system through the AC/DC converter with power factor correction. The system consists of a transmitter, a receiver, converters, and resonant compensation networks for the transmitter and the receiver. The magnetic field produced by the transmitter induces an alternating field in the receiver. The AC power is then rectified in order to charge the battery. Compensation topologies are added to the transmitter and the receiver to create the resonant case and reduce additional losses (Mahesh et al., 2021; Niu et al., 2019; Pei, 2022). The magnetic coupler (transmitter and receiver indicated in the red framework), the transmission distance (air gap), the compensation topologies, and the misalignment between the transmitter and the receiver directly influence the performance of the system. The performance includes transmission efficiency, magnetic flux density leakage, and the cost of the system.

1. Magnetic Coupler Design, Transmitting and Receiving Coils with Shielding
2. Compensation Technologies, The Compensation Scheme
3. The Power Electronic Architecture
4. System Optimization



(Esteban et al., 2015)

**IPT Power Supply, Primary Side (Boys et al., 200o; Pantic et al., 2011)**

1. Utility Input: Low-frequency energy source, which could be single phase as in Fig. 1 or three phase.
2. AC/DC: Power conditioner that in addition to converting the utility input to a regulated dc voltage, carries out power factor correction, and serves as one of the control mechanisms for regulating the power flow of the entire system by modulating the dc input voltage (Wu et al., 2012; Chinthavali et al., 2013).
3. DC/AC: Voltage fed full-bridge switching network that efficiently converts the incoming dc energy to high-frequency (HF) energy. It produces a HF square wave with fundamental component equal to the chosen operating frequency. Usually the bridge semiconductors are switched in accord with the phase-shift (PS) scheme illustrated in Fig. 1, allowing for power flow regulation through modulation of the PS delay time tPS between each leg of the inverter. The semiconductors used in the implementation of this paper are MOSFETs, accordingly, the parallel capacitors and diodes across each switch in Fig. 1 are the parasitic elements of each device (Huh et al., 2011; Sallan et al., 2009; Wu et al., 2012; Boys et al., 2008; Miller et al., 2012; Mecke and Rathge, 2004).
4. Isolation: HF transformer required for compliance with regulatory safety standards. This stage could be implemented with a step-up or step-down transformer depending on the energy-coupling network (ECN) topology being used. The capacitor CB is a dc-blocking capacitor that prevents transformer saturation and depending on the power supply topology may also be used to adjust the effective inductance of the transformer to some desired amount which is then used as one of the energy storage elements in the next stage (Chinthavali et al., 2013; Boys et al., 2008; Hao et al., 2011; Wu et al., 2011).
5. Matching: A network of very low-loss (high Q) energy storage elements used to efficiently inject the HF energy to the next stage and by extension lower the volt–ampere (VA) rating of the power supply. This stage is also commonly referred to as an impedance matching network (IMN), a resonant tank, bandpass filter, or a compensation network depending on the feature being highlighted in (Wang et al., 2005; Miller et al., 2014; Wang et al., 2004; Wu et al., 2012).

Across a large and variable air gap, the secondary side can be similarly subdivided into an interconnection of the following subsystems.

1. Matching: Another network of energy storage elements that serves the same purpose as the one on the primary side. A parallel resonant arrangement with partial series compensation was chosen for this study because it is a commonly used topology for EV charging due of its constant current source characteristics (Wang et al., 2005; Onar et al., 2013; Wu et al., 2012; Covic et al., 2008). The addition of a capacitor in series with an inductor and deliberate operation above resonance so as to reduce or trim the overall inductive reactance to some smaller value is called partial series compensation. Partial series compensation is often used in IPT systems with parallel resonant topologies so as to trim the primary and/or secondary coil self-inductance to some lower value that is then resonated with a parallel capacitor (Keeling et al., 2010; Elliott et al., 2010). Capacitor in Fig. 1 is used for partial series compensation of the secondary coil. In a practical design, the use of partial series compensation on the secondary coil may serve one or both of the following purposes: 1) reducing the VA rating of the components connected to the resonant tank, and/or 2) boosting the current out of the secondary coil, thereby enhancing its power delivery capabilities. The later function is often carried out during the physical implementation's fine-tuning stage, where there is often a need to increase I2 to achieve the design's target power level, but the pick-up coil's magnetic characteristics have already been largely fixed by its construction. It is relevant to note that for the parallel secondary topology, the maximum load current that may be delivered without the use of partial series compensation occurs when the pick-up is perfectly tuned and is equal to , where is the short-circuit current that would flow in the secondary coil if it were shorted, while coupled to the primary.
2. AC/DC: A HF rectifier with an output LC filter that provides the dc power to the vehicle battery. While other alternative ac/dc power conversion schemes can be implemented on the secondary side so as to actively shape the power flow, the simple HF rectifier with LC filter was chosen for this study because it results in a reduced cost and complexity on vehicle side system integration (Onar et al., 2013A; Onar et al., 2013B).

Common to both primary and secondary is the magnetic coupling stage. On the primary side, an inductive structure, commonly referred to as a magnetic pad or coupler, generates the ac magnetic flux that couples power to the secondary. Conversely, on the secondary side, another inductive structure, commonly referred to as a pick-up, captures a fraction of the primary flux. The size and geometry of the two coils may be identical or completely different. Like the primary- and secondary-side IMNs, this stage is also designed so as to have the highest possible unloaded quality factor, which generally means the use of a stranded Litz conductor, with the total number of strands and gauge of each strand sized so as to minimize the ac loss at the operating frequency (Covic and Boys, 2013A; Bosshard et al., 2015).

As highlighted in the magnetic coupling stage of Fig. 1, the mutual inductance and the primary and secondary coil self-inductances vary as a function of position, this fact plays an important role in the design of the power supply (Covic and Boys, 2013B; Wu et al., 2012; Budhia et al., 2011). Fig. 1 also shows the wireless communication feedback mechanism used to close the control loop in order to actively regulate the power flow due to positional changes between the source and sink coils and/or changes in loading Miller et al., 2014; Wu et al., 2012).

With respect to Fig. 1 provided that the output inductor Lo is large enough to ensure continuous conduction of the rectifier diodes over the system's full range of operation, then the following relation holds true

As illustrated by the ac equivalent circuit in Fig. 1, at steady state, the entire system may be greatly simplified for analysis and design by replacing the primary-side power electronics with a sinusoidal voltage source and reflecting the secondary side to the primary, which results in a reflected impedance in series with the primary coil.

The simplified input voltage may be expressed as

The RMS amplitude of is related to the FB's dC-bus input voltage , the operating frequency , and the PS control delay , as follows:

The reduction of the primary-side power electronics to a sinusoidal voltage source is commonly referred to as fundamental-mode analysis (FMA). The application of FMA to power electronic converters, and in particular to IPT systems, is a very well-established practice in the literature and is possible because the resonant networks that are connected to the output of the FB have significant filtering capability, which effectively reject all harmonics with the exception of the fundamental component of the HF square-wave inverter output (Huh et al., 2011; Wu et al., 2012; Pantic et al., 2011; Steigerwald, 1988; Ma and Zhou, 2004).

The second simplification may be achieved by the application of standard circuit analysis techniques at the secondary followed by the application of the mutual inductance circuit model to reflect the secondary to the primary (Wang et al., 2005; Wang et al., 2004; Wang et al., 2000).

When a parallel secondary is reflected to the primary, it presents an impedance Zr to the primary power supply. For a given frequency, the real and imaginary parts of Zr are both functions of the variable mutual inductance M and the load Req. The variability in M results from changes in alignment between the coils, while the variability of the load is due to changes in the battery's voltage and current profiles as it charges. Moreover, the imaginary part of Zr is capacitive in nature (Covic and Boys, 2013; Wang et al., 2001).

The reflected impedance seen at the primary can be shown as

where is the equivalent secondary coil's inductance after application of partial series compensation

The power that is, thus, delivered by the RMS primary current to the reflected load is given by

If the system is operated at or close to the secondary's resonant frequency

the term will be equal or very close to one. When this happens (4) and (8) become

where is known as the voltage boost quality factor, and is defined as

as is depicted in the simplified ac equivalent circuit of Fig. 1, when the system is operated at resonance, the dependence of the reflected capacative reactance on the load is eliminated. Equation (11) is conventionally known as the IPT power equation, and it is deemed by many authors as the starting point for the design of a resonant IPT system (Covic and Boys, 2013B; Stielau and Covic, 2000; Wu et al., 2012). In theory, the minimum RMS primary current required to transfer a desired maximum amount of power , when the system is operated at resonance is equal to

The application of partial series compensation to the secondary coil results in three different quality factors (Wu et al., 2012; Keeling et al., 2010; Ellitott et al., 2010). The first one is the conventional loaded quality factor of the standard parallel RLC network. The second quality factor that may be defined is known as the current boost quality factor:

is used to quantify the increase in I2 from its uncompensated value Isc to its compensated value, . The amount of partial series compensation that may be carried out as quantified by has been reported as being limited to less than 3 because of the added sensitivity to the overall resonance tuning of the secondary (i.e., due to component aging), as well as because of saturation of the pick-up coil ferrite that results from the increased flux density (Keeling et al., 2010; Elliott et al., 2010).

The third quality factor that may be defined is the secondary's overall quality factor, which takes into account the effect of both and ; this later quality factor is defined as

For practical designs, is limited to being less than 10 (Stielau and Covic, 2000; Boys et al., 2000), and for most high-power EV charging systems it is less than 6. This limitation in the overall secondary is due to the challenges that arise in controlling the system because of the narrower bandwidth at higher values of . Another factor that dictates the limit imposed on is the need to maintain the secondary's VA ratings within the limits prescribed by governing safety standards such as UL (Covic and Boys, 2013B; Wu et al., 2012; Budhia et al., 2011).

With the aforesaid definitions in mind, may also be expressed in terms of the three quality factors that result from the application of partial series compensation as

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Once the coils were built their magnetic attributes were experimentally measured and used to carry out the design of the primary- and secondary-side power electronics. For precise measurement of the pads’ coupled self- and mutual-inductances, as well as coupling coefficient over their range of positional operation, the test bench shown in Fig. 4(c) was built. To measure and , the coupled pad's were energized with a known primary current by means of an inverter with a series resonant capacitor. The required measurements were taken, while the pads were misaligned in the vertical and/or horizontal directions in small steps.

The coupled-coil self-inductances were measured at each point along the horizontal offset trajectory with an meter. The mutual inductance was obtained by measuring the secondary's open-circuit voltage and the primary's current . The coupling coefficient was obtained by two separate methods. The first method applied was the measurement of the primary-coil voltage and so as to use the voltage transfer ratio as a measure of (Miller et al., 2012). The second method used was the use of the conventional ac circuit definition of given as the ratio of and the square root of the product of the coupled self-inductances. Both methods produced very similar results. Fig. 2 shows the pads measured magnetic attributes over a range of axial misalignment spanning 64 cm for a coil-to-coil separation distance of 16 cm. Fig. 2(b) shows all pad attributes together, while Fig. 2(c) shows an expanded view of the mutual and self-inductances only. As can be seen, the coupled self-inductances were measured for two different conditions: 1) a shorted secondary pad , and 2) an open secondary pad . The measurements are taken with the meter on one pad, while the other one coupled to it has its terminals either shorted or opened. Consideration of these two cases is necessary because depending on the resonant topology chosen for the primary and secondary matching networks, the self-inductance may behave differently. For example, for the parallel resonant topology, the pad's self-inductance varies according to the short-circuit measurement profile, while for the series resonant topology, the inductance varies according to the open-circuit measurement profile (Wu et al., 2011). The plots of mutual inductance and coupling verify the existence of a fixed characteristic null in the magnetic profile of circular coils (Budhia et al., 2011). Another noteworthy observation is that Lsc and Loc both converge to a common value as the pads are decoupled, with the convergence starting around the characteristic null point. As already noted, the operating range of coupling is a crucial design variable that must be known in order to properly design the power supply, this in fact is one of they key items that will be standardized by the J2954 task force for interoperability (Sae, 2013). Fig. 2 shows the operating range of coupling being considered for this comparative study, namely the region to the left of the vertical dashed line inclusive. This range corresponds to a maximum axial misalignment distance of 12 cm, which translates to a coupling coefficient in the neighborhood of 0.18–0.25.

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**Magnetic Coupler Design, Coupled Structure**

**Magnetic Pad Design and Characterization**

(Esteban et al., 2015) The first step in the design of an IPT system is the selection of a suitable inductive structure geometry from a number of available choices (Stielau and Covic, 2000; Wang et al., 2005; Huang et al., 2009). Once a geometry that best suits the target application has been selected, a thorough FEA-based EM optimization of the design is undertaken prior to fabricating it. The goals of the FEA optimization are (Budhia et al., 2011; Elliott et al., 2010; Budhia et al., 2013; Zaheer et al., 2012; Kissin et al., 2009; Budhia et al., 2010):

1. achieving the highest possible values of mutual inductance and magnetic coupling over the system's target range of positional operation;
2. reducing the design's physical size and material cost as much as possible without compromising its power transfer capabilities;
3. achieving self-inductance values that will ensure coil voltage levels that are within established UL safety regulations;
4. ensuring regulatory compliance with established field emission standards (ICNIRP);
5. having a complete understanding of how all key magnetic attributes vary over the system's range of positional operation so as to properly design the primary and secondary power electronics in terms of component ratings and closed-loop control.

The design of the primary power supply requires that the following parameters be known:

1. maximum power transfer level ;
2. nominal operating frequency ;
3. magnetic pad characteristics: , , , and ;
4. secondary-side ECN topology and energy storage element values;
5. nominal load value ;
6. nominal value of the three secondary quality factors: , , and ;
7. the nominal dc-bus input voltage of the inverter .

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(Pei, 2022) The magnetic coupler is the most important part of the RIPT system, which normally includes a pair of coils, the magnetic cores, and the shielding. Air-core coupler has a serious drawback in that its electrical parameters are very sensitive, especially when there are ferromagnetic objects in proximity (Mahesh et al., 2022; Niu et al., 2019; Jayalath and Khan, 2021; Mohamed et al., 2020). To address this problem, the magnetic cores work as a magnetic flux guide, and they are made of ferrite (Jayalath and Khan, 2021; Mohamed et al., 2020). The shielding is used to prevent magnetic flux density leakage. (Niu et al., 2015) Transferring power through the air gap between the ground and chassis, coupled structure is the fundamental component of a WEVC system. Air-core coupler has a serious drawback that its coil parameters are very sensitive especially when there are ferromagnetic objects in proximity. To address this problem, the ferrite as a magnetic flux guide and the aluminum plate as a shield are usually used in RIPT systems operating below 100 kHz (Li and Mi, 2015).

In RIPT system, magnetic coupler is the basic and important part. Magnetic coupler made up of transmitter coil, receiver coil and shielding. Transmitter and receiver coils exchange power through an air as a medium and shielding controls flux distribution (Mahesh et al., 2021).

Several coil shapes of the magnetic coupler have been proposed and evaluated in the literature so far because the geometry and configuration of the coils are crucial for determining the transmission efficiency of the RIPT system and its magnetic flux density leakage.

1. Circular coils- (Biswas, 2018)- CP is the most widely used design. A very simple structure that round coils sit above a circular ferrite pad has been reported to charge small electronic devices (Hui et al., 2014). The field generated by CP is non-polarized and loose, resulting in poor coupling. Despite having lower coupling than other similarly sized coil geometries over identical air gaps and misalignment, for static EV charging applications, the circular geometry is still the most widely used (Covic and Boys, 2013B).

The AC power loss of the pad as a result of skin effect is defined by (17), where and are the nominal operating primary and secondary pad voltage and current at rated power, and is the coil's unloaded quality factor defined with respect to its AC resistance at the target operating frequency

1. Square coils- (McDonough and Fahimi, 2014)
2. Rectangular coils- (Duan et al., 2012)
3. DD coils- (Budhia et al., 2013)- DD coils can be reasonably considered as a combination of CP and solenoid, as shown in the lower portion of Fig. 9 (e). DD coils and solenoid are both polarized pads. Therefore, the concentration of magnetic field along a single path improves the coupling and the tolerance to misalignment. When mounted on the ground side, the similarity between DD coils and CP is that they are all wound in a single-sided way so that the undesired rear flux is decreased, and thereby the eddy-current loss is almost negligible. According to the phase relationship of the primary currents, these two DD coils could be excited in various modes including the case where one of them is shutdown. Among them, the reverse series driving mode (common mode) is often the best from the perspective of offset tolerance and maximum power transfer. Nevertheless, DD structure can only provide parallel field under this mode. Similarly, CP can only generate perpendicular field. This makes them fail to interoperate with certain receivers. When mounted on the vehicle side, DD coils can only couple horizontal flux components. If not totally aligned, a net vertical flux that DD coil fails to capture is produced. Therefore, a quadrature receiver coil is added to make full use of the vertical component (Kim et al., 2017).
4. DDQ coils- (Budhia et al., 2013)- multi-coil solution called DDQP tends to improve the interoperability, though two independently tuned and rectified coils lead to extra circuit cost.
5. BP coils- (Zaheer et al., 2014)- BP is another decoupled receiver, consisting of two largely coplanar, partially overlapping coils (Covic et al., 2011). It artfully creates an internal quadrature coil without adding extra coils. Compared with DDQP, it significantly reduces the usage of copper at little cost of horizontal tolerance (Zaheer et al., 2012), but it is rather sensitive to angular offset (Nguyen et al., 2014; Ni et al., 2015). Both BP and DDQP are initially designed for receivers, but they can then be used as transmitters because their independently controlled coils can be energized in different modes, generating parallel, vertical and compound flux pattern, and thereby allowing them to energize different types of on-board coils (Covic et al., 2011).
6. DDC pad- (Chowdhury and Liang, 2020) better performance than DD pad.
7. Tri-polar coils- (Matsumoto et al., 2014; Kim et al., 2017)
8. Multi-transmitters-one receiver- (Li et al., 2016)
9. Dual transmitters-dual receivers- (Li et al., 2018)

Planar pad structures were proposed in (Budhia et al., 2011; Biswas, 2018; Ahmad and Alam, 2019; Luo and Wei, 2018; Zaheer et al., 2015). In these structures, the core, coil and shield are designed and arranged in a way to minimize volume and weight of the pad, and misalignment tolerant in all directions, which are very important features of a WPT system. Planner pads are classified into two types based on the coupled flux component: Non-Polarized Pads (NPPs) and Polarized Pads. (PPs). Non-polarized (NPPs) is defined as a single coil with vertical flux components to be coupled with the receiver coil and transfers the power. Example: circular pad (CP) and rectangular pad (RP). Polarized (PPs) pads: generate vertical and horizontal flux components and both are coupled with the receiver coil and responsible for power transfer. As an example: double-D (DD), double-D quadrature (DDQ) and bipolar (BP) pad. Introducing intermediate coils enhance the power transfer between the source and load (Moon et al., 2014; Kim et al., 2011; Zhang et al., 2011; Kiani et al., 2011; Ahn and Hong, 2013).

structures of coils on several factors (including coil shape, misalignment, system complexity, interoperability, and flux leakage) (Pei, 2022).

The performance of the coupling pads is depending upon the coupling factor (k) , quality factor (Q ) and misalignment tolerance. For that different type of coil designs/shapes proposed by researchers. Magnetic couplers usually made up of Litz wires to reduce losses due to skin effect. Ferrite cores used for proper flux guidance, which increases the mutual inductance, minimizes leakage inductance and also provides shielding. The kQ factor depends upon the geometry of coil, core material, and the distance between two coils (Mahesh et al., 2021)

After, ferrites are added to the coils, which aims for proper flux guidance to increase the mutual inductance, minimizes leakage inductance, and also work as the magnetic shielding to decrease the magnetic flux density leakage

**Shapes of Ferrite**

1. E-type, E-core, transformer structure- (Kim et al., 2001)
2. W-type
3. U-type, U-core, transformer structure- (Kim et al., 2001)
4. Plate-type
5. Disc-type
6. Pot-type

**Coupler Designs (Niu et al., 2019)**

1. GU60 pot core- predecessor of circular pad, (Hu et al., 2013)
2. Disc core- (Sakamoto et al., 1999; Matsuo et al., 2000)
3. U–U pair (divided coils)
4. U–U pair (centralized coils)
5. Track pad using elongated E core- satisfactory track pad in a DWC system.
6. Flat-E core

different core weights and air gaps. Coils’ shape and position also affect the coupler performance.

The above four coupler types are regarded inappropriate for EV charging mainly because they go against the concept of flat and lightweight design.

Coupling pads are mostly used in SWPT system (Covic and Boys, 2013). Because of their high cost, fragile, heavy weight and sensitivity to misalignment of transformer structures such as E and U cores, pad shaped structures have been proposed, which are less weight and size compared to traditional transformer cores (Mahesh et al., 2021).

By using three phase system in pads increases power transfer density. Provides uniform flux and improves transmitting distance. Three phase system advantageous over single phase system. In three phase system to increase power transfer density and to achieve balanced inductance and electrical balance a trifoliate coil introduced in (Matsumoto et al., 2014). This structure powered by single three phase inverter.

Three-phase for DWC system introduced in (Li et al., 2019), which gives power to a 1.2-meters long test track made up of six square coils. That gives Longer charging zone for dynamic charging system. In article (Kim et al., 2017), a tripolar pad with decoupled coil structure introduced, each of the coil in it exited separate inverter. This structure gives better performance in terms of cross-coupling and flux density compared to trifoliate coil and drawback is, it needs more power electronic infrastructure. In the article (Pries et al., 2020), three phase bipolar coil introduced. This structure has capable of transferring high power with high density and usable in heavy duty applications. Disadvantage of this coil structure is heavy, costly and high translational crosscoupling inductance. Single and three phase system compared in (Matsumoto et al., 2012), Proposed three phase system has more efficient and uniform power, and it requires small DC link compared single phase system (Su et al., 2019). While using three phase magnetic couplers in VSI is best option (Matsumoto et al., 2014; Kim et al., 2017). In Fig. 20 Pad structures classified in to two types based on flux path and further classified on the basis of number of coils. In many literatures used coupling factor k as the main factor to assess the different designs (Ongayo and Hanif, 2015; Liu and Habetler, 2015; Bosshard et al., 2013). Some of them used kQ as the criteria (Bosshard et al., 2016). Ahmed et al compared most of the structures based on his knowledge. The comparison was achieved, considering several factors, such as shape, coupling performance, misalignment tolerance, shielding, polarization, interoperability, magnetic flux, and charging zone (Mohamed et al., 2020). Table 5 and Table 6 compares single sided coils Table 7 and Table 8 compares double sided coils. The dual coupled transmitters with multiple inverters proposed in (Li et al., 2016) to achieve high power transmission. In this method transmitting side two decoupled transmitters overlapped with each other and receiver side only one receiver is used. It hardly meets the demand due to design constraints. To resolve this issue dual coupled transmitters and receivers proposed in (Li et al., 2018).

**Advanced coupler designs for EV Charging (Niu et al., 2019)**

1. Hierarchical structure of a circular pad
2. Solenoid- To fabricate a more compact coupler, the concept of solenoid is introduced (Chen et al., 2016). A hybrid solenoid coupler introduced in (Tejada et al., 2019), for reduce leakage losses and increase tolerance toward lateral misalignment.
3. Flux pipe Solenoid- Additional wings expand its coupling surface, making it better resistant to the offset. Compared with the basic solenoid, its core is not fully wrapped, instead, two sets of coils connected electrically in parallel while magnetically in series are separated by the side of midsection. This layout achieves a trade-off between flux density and copper loss (Budhia et al., 2010).
4. H-shaped solenoid- aimed at reducing flux leakage (Talbot and Anthony, 2016). As a transmitter, it strengthens the magnetic field close to the secondary side while weakens the counterpart at its back.
5. DD-DDQ pair, DDQP-
6. BP-TP pair
7. Hc transmitter (parallel-connected)- (Shimizu et al., 2013) can produce compatible field pattern using either parallel or serial coils.
8. Hc transmitter (series-connected)
9. Unsymmetrical coupling structure, (Yao et al., 2019)

**RIPT System Characteristics**

1. Firstly, the power class is supposed to be large enough, making it comparable to conductive charging.
2. Secondly, the magnetic flux lines are expected to be so concentrated that a high k value can be obtained.
3. Thirdly, the temperature rise and radiation leakage of a RIPT system should be strictly limited in safety range. Unfortunately, these goals are usually not achievable at the same time.

Furthermore, the design of a RIPT system must be compliant with international standards to reduce the EMF leakage to allowable levels as defined in SAE International J2954. Shielding is usually placed above the receiver to minimize the leakage flux around the system, thus improving the coupling performance and leading to better efficiency and quality factor (Patil et al., 2018; Hiles et al., 1998; Zhou et al., 2017).

**Magnetic Shielding**

Figure 1.25 Types of shielding in the RIPT system, (a) passive magnetic, (b) passive conductive, (c) passive conductive and magnetic, (d) active, and (e) reactive resonant

Passive shield method is effective in low- and medium- power IPT systems (< 100 kW) and they are able to suppress EMFs levels to be below the safety limits. In addition, they are cheaper, simpler in implementation and more robust (Campi et al., 2014). For high-power IPT systems, active and reactive shielding are more promising for the system to comply with standards. Adding ferrite cores (Passive Shielding) will improve the system efficiency by reduce leakage inductance at some extent but it alters the value of inductances system performance. It means that the inductance value must be readjusted. Aluminum shielding or metallic shielding decreases system performance but it also significantly reduces EMF level. Reactive shielding improves EMF leakage suppression compared to metallic shielding. However, the position shielding loop and shielding impedance need to be carefully considered (Mahesh et al., 2021).

1. **Passive Shielding, Magnetic or Conductive**

(Pei, 2022) It is effective with magnetic materials (Campi et al., 2014; Mohammad et al.m 2019; Kadem et al., 2021) or conductive materials (Zhou et al., 17), or combining them together. Some of the IPT systems take the vehicle chassis as conductive material for shielding (Ibrahim, 2014). This method improves the system efficiency and significantly reduces EMF level to some extent, but it alters the receiver inductance and the mutual inductance. It also causes a heat problem on the metallic sheet due to the eddy-current losses (Patil et al., 2018; Mohamed et al., 2020). Passive shielding relies on the use of conductive material, ferromagnetic material, reactive shield coils and zero-permeability metamaterial (Niu et al., 2019).

1. **Passive Shielding, Magnetic**

(Mahesh et al., 2021) To reduce or block the leakage flux by adding passive components (conductor or magnetic) to the system. Magnetic passive shielding are done from materials which are non-conductive and high permeability, to direct flux in particular path to enhance self and mutual inductance by increasing the system performance and reducing the leakage flux (Campi et al., 2014; Mohammad et al., 2019). The magnetic shield is achieved by magnetic core (ferrites) installed in the pad. Although using ferrites system the performance increases but it also increases weight and cost. Magnetic loop around the coil is minimizing the leakage flux, as was proposed in (Mohammad et al., 2019). This method can reduce the emission by 60%, by considering matched DD. There is another method for minimizing the magnetic materials in the system for flux controlling. This is done by combining conductive and passive shielding, which is the trend in IWPT systems.

1. **Passive Shielding, Conductive**

(Mahesh et al., 2021) This method depends on Faraday and Lenz’s law. When we place conductive material (aluminum plate) in the presence of alternating magnetic field induces currents (eddy currents) on it (faradays law). Due to the inductive nature of the material, a new magnetic field is generated by the Eddy currents. Which is in the opposite direction of original magnetic field. It tries cancel original flux in opposite direction (Lenz’s law). This helps to the lower the net field around the system (conductive shielding). Drawbacks of this method is large magnetic field loss on metallic plate and eddy currents can’t be controlled., it adversely effects on system performance by reducing efficiency 1% - 2% and temperature generated by eddy currents on the plate. For that suitable material should be chosen for coil design to resist these temperatures. Many researchers have proposed different methods with changing conducting plate, shape and position (Bosshard et al., 2016; Zhang et al., 2017; Bandyopadhyay et al., 2016; Ke et al., 2016; Budhia et al., 2009; Moon et al., 2015). some of the applications vehicle chassis taken as conductive material for shielding (Ibrahim, 2014). Normally conductive shielding applied with ferrites to improve the magnetic field around the coils so it is called conductive passive shielding. As per SAE J2954 recommended dimensions for aluminum back plate is 800 mm ×800 mm ×0.7 mm, applicable for the power ranges WPT1 to WPT3.

1. **Active Shielding**

(Pei, 2022) It involves extra coil turns (shielding turns) wounded in the reverse direction to create a magnetic field in a reverse direction to the original magnetic field created by the coupler to minimize the EMF leakage (Mohammad et al., 2019; Campi et al., 2019). The main challenges in this method are positioning and sizing of shielding coils, the control system needed for the controlling current flowing through the shielding coils, and the increasing cost and weight of the system (Campi et al., 2019; Campi et al., 2020; Choi et al., 2014). In high-power WEVC applications, the losses in passive shielding structures can reach kilowatt level (Tang et al., 2002). In this context, active shielding has attracted increasing attention as an effective and suitable shielding solution. Active shielding also keeps the current in canceling coil 180° offset with the current in main coil; however, the counter current sources is provided by itself rather than original WEVC system. (Mahesh et al., 2021) It is difficult to manage leakage EMF in the high power applications by using conventional passive shielding (Campi et al., 2019). In this case extra turns(shielding turns) wounded in reverse direction to create a magnetic field in a reverse direction to the original magnetic field created by coupler to minimize the leakage field (Campi et al., 2019; Choi et al., 2014). This method requires extra power source for the shielding turns. Main challenges in this method is positioning and sizing of shielding coils, control system needed for the controlling current flowing through the shielding coils. This method shows effectiveness compared by passive shielding method. However, because of the impact on original field system performance is affected. In addition, adding extra turns and power source makes power loss in the system. Furthermore, cost and weight of the system increases (Kim et al., 2014). compared to above methods field opposite field can be controlled properly. In (Campi et al., 2020), shielding with multiple coils and design procedure of their independent feeding is proposed to limit the EMF in critical areas and hence compliance with ICNIRP guidelines. In this method four independent active coils placed at the sides of the transmitter and receiver coils.

1. **Reactive Resonant Shielding**

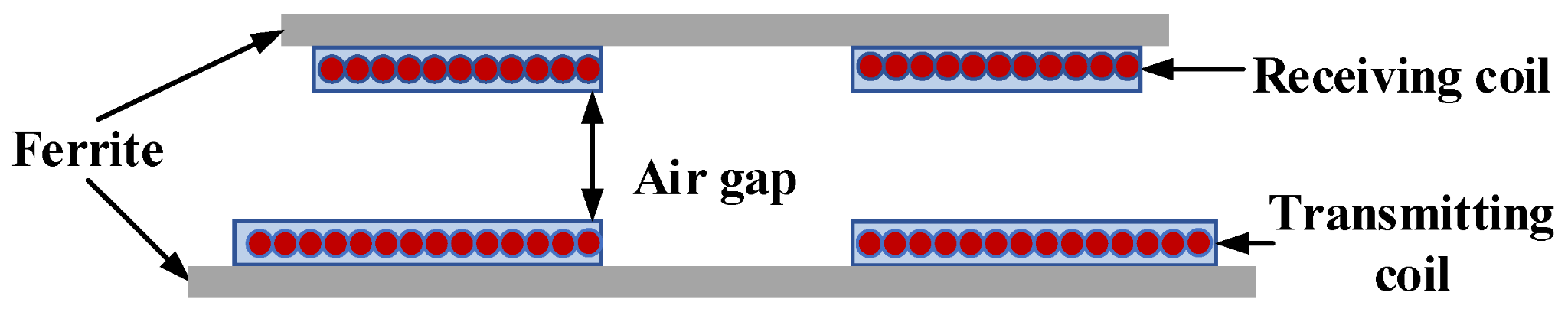
(Pei, 2022) It can be considered as a particular feature of the active shield to avoid the extra source for inducing field in the shielding turns. It incorporates additional reactive components (e.g., capacitor), and the coil turns close to the transmitter coils, but their current excitation comes from the magnetic field naturally generated by the transmitter coil (Park et al., 2019; Kim et al., 2014; Moon et al., 2015). Current flowing in shielding coil turns opposite magnetic field to oppose leakage flux. The magnetic field depends on the resonant capacitor and the number of turns added. The opposite field can't be controlled as an active shielding method and needs more current in the shielding coil turns (Asa et al., 2020). (Mahesh et al., 2021) In this method extra reactive elements (capacitor) and turns are added into the system No need of extra source to induce field in the shielding turns. By using original magnetic field to current induced in a shielding turns. Current flowing in shielding turns creates opposite magnetic field to oppose leakage flux. Magnetic field depends on the resonant capacitor and number of turns added. Opposite field can’t be controlled as active shielding method and needs more current in shield coil (Mohammad et al., 2020).

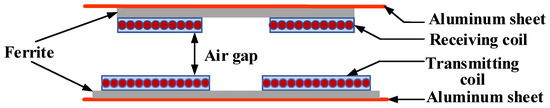
The magnetic leakage flux of a loosely-coupled WEVC system poses an EMF problem to humans and EMC problem to the electronic equipment. Another safety hazard relative to it is that the induced eddy current of metal debris near the GA could cause overtemperature problem and even ignition. For dynamic WEVC system, the portion of leakage flux will be higher than a comparable stationary system due to the k variation arising from the motion of the receiver (Patil et al., 2018; Kim et al., 2013). To address the problem, some shielding measures have been proposed in recent years and they are divided into passive and active types in general.

The most significant problem of RIPT system is leakage EMF, which can affect the surrounding material and living things. The design of EV charging structure must compliant with international standards to reduce leakage EMF to allowable levels as mentioned in the Table 4. Shielding is method refers to placing some metals under the coils to restrain the leakage EMF (Mahesh et al., 2021).

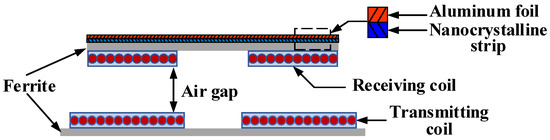
Xu, H., Wang, C., Xia, D., & Liu, Y. (2019). Design of Magnetic Coupler for Wireless Power Transfer. Energies, 12(15), 3000. <https://doi.org/10.3390/en12153000>

Taking the flat disk magnetic coupler as an example, the flat disk magnetic coupler can generate a uniform magnetic field in the energy transfer area. In order to reduce the magnetic field distribution in the nonworking area and enhance the magnetic field concentration in the working area, the magnetic coupler is usually designed. For magnetic couplers with shielding, the traditional ICPT shielding structure is divided into single shield and double shielding, that is, single shield composed of ferrite or double shield composed of a ferrite and an aluminum plate. The schematic diagram is shown in Figure 2 and Figure 3.





When the ferromagnetic material exists, the self-inductance L of the resonator coil increases, the resonance frequency f decreases, and the maximum transmission efficiency point of the system shifts to the left (the frequency decreases). At the same time, due to the increase of M, the maximum efficiency of the system also increases to a certain extent. At this time, if the switching frequency of the power supply at the transmitter is unchanged, the transmission efficiency will be reduced. In light-load systems, if the resonators are over-coupled, frequency splitting will occur, which will reduce the overall output power of the system. When the non-ferromagnetic aluminum plate exists, the eddy current generated in the aluminum plate produces a reverse magnetic field, which counteracts with the magnetic field of the emission source and plays a shielding role. At this time, the self-inductance L of the resonator coil decreases, the mutual inductance M of the system weakens, the resonance frequency f of the system increases, and the maximum transmission efficiency point of the system shifts to the right. For this reason, the combination of shielding materials should be considered in combination with the resonant frequency of the magnetic coupler, the switching frequency of the transmitting circuit, the transmitting frequency of the harmonic wave and the coupling coefficient. Therefore, a new type of magnetic coupler with multilayered shielding structure is proposed, as shown in Figure 4.



The first layer of the shield layer on the receiving coil side of the magnetic coupler shown in Figure 4 is a ferrite sheet, the second layer is a nanocrystalline strip, and the third layer is an aluminum foil. Ferrite is used to shield electromagnetic waves of the kHz level. The thickness of the iron-based nanocrystalline strip is only 26 μm, the resistivity is only 137 μΩ∙cm, and the saturation magnetic induction is as high as 1.6 T (Muhlethaler et al., 2012). The aluminum foil is used for high-frequency magnetic field components that are not shielded from the first and second low-reluctance circuits. In real life, the transmitting coil is generally buried deep under the bottom or fixed, so the shielding requirement of the transmitting coil side is low, while the receiving side is usually moved. In order to save space and reduce the volume of the equipment, the receiving circuit board will be placed above the receiving coil, so the shielding requirement on the receiving side is higher.

(Niu et al., 2019) a typical WEVC system. On the primary side, there are mainly three parts in the power cupboard: AC-DC rectifier, DC-AC inverter and the compensation unit. The controllable rectifier can correct the power factor, as well as provide auxiliary control by modulating its DC output voltage (Tang et al., 2014; Wu et al., 2012). The inverter produces HFAC high frequency alternating current to energize the primary coils, and its switching state should be adjusted online according to the load status. The compensation unit is essentially an IMN impedance matching network, which is used to neutralize the leakage inductance/capacitance for magnetic/electric coupled power transfer, so as to obtain higher efficiency. In addition, it lowers the VA voltage ampere ratings of power electronics significantly with apparent power decreasing. On the secondary side, to prolong the battery life and gain the optimal output characteristics, several measures could be adopted: once secondary coils are excited, secondary compensation unit is engaged to feed constant current, constant voltage or step power to the batteries (Abdullah et al., 2015). If necessary, an extra voltage regulation circuit could be added between the rectifier and battery pack (Boys et al., 2000).

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**Compensation Technologies**

(Pei, 2022) Except for the design of the magnetic coupler, the compensation topology plays a major role in the RIPT system. Due to the dimensions of the coils, the parasitic capacitance is not sufficient to ensure resonance in the operational frequency range (Rim and Mi, 2017; Fisher et al., 2014; Mahesh et al., 2021; Panchai et al., 2018). Consequently, additional reactive structures, known as the compensation topologies, are incorporated into the transmitter and the receiver coils to adjust the operating frequency (Fisher et al., 2014; Mahesh et al., 2021; Jayalath and Khan, 2021; Mohamed et al., 2020; Patil et al., 2018). So this minimizes the reactive power supply and improves both the transmission efficiency and the power transfer capability.

(Mahesh et al., 2021) The compensation is playing a major role in the resonant inductive power transfer system. To reduce VA rating of the system when coupling co efficient decreases less than 0.3. compensation at both sides needed to have flexible and good working characteristics. Due to the network design, parasitic capacitance will not resonate enough or compensate the system. Therefore, additional reactive elements (capacitors or inductors), to adjust the operational resonant frequency. Basic compensation can be achieved adding one capacitor in series/parallel this compensation can be called as mono-resonant topology. There are other compensation techniques works on more than one reactive element referred to as multi-resonant compensation. However improper compensation causes higher reactive current. Higher reactive currents cause more semiconductors loses and conduction losses, particularly on inverter side.

Other main objectives of the compensation are:

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

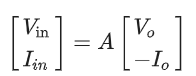
(Mahesh et al., 2021) Voltage source inverter can directly connect to a series compensated transmitter coil. For parallel compensated coil an inductor introduced to change inverter into current source inverter. The secondary compensation done to minimize the VA rating of the coil. Constant current output from a transmitter coil can be modified as voltage source, by making secondary as a series compensation. Similarly parallel compensation at secondary makes current source (Wang et al., 2005). To reduce VA rating of the system achieving Zero Phase Angle (ZPA) condition is necessary. For that current and voltage should be in phase. This can be achieved by tuning the primary capacitor at particular load and coupling condition. Similar, primary side compensation tuned to achieve Zero Current Switching (ZCS) or Zero Voltage Switching (ZVS) by keeping small amount of reactive power (Hu et al., 2000; Tang et al., 2009; Pantic et al., 2011). For compensation topologies, tuned to resonant frequency which is also the ZPA frequency, it is very common that this resonant frequency to be divided into multiple resonant frequencies due to sudden changes in some parameters. This phenomenon known as bifurcation in the RIPT system and the parameter which causes this phenomenon to occur is known as the critical parameter. Bifurcation causes changes in electrical parameters. It may cause damage to the electronic components.

(Pei, 2022) But, some factors (like misalignment, frequency deviation, etc.) make RIPT systems never function under ideal conditions. Using multiple elements in a series-parallel combination makes an effective compensation method to overcome the challenges of the basic compensation topologies mentioned above.

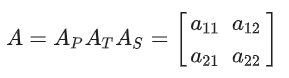
(Niu et al., 2019) Non-negligible leakage inductance derived from the air gap restricts RIPT systems from reaching their maximum performance. In order to achieve efficient and stable WEVC, it is necessary to add a compensation network, also known as IMN impedance matching network or resonant tank (Beh et al., 2013; Miller et al., 2014; Beh et al., 2010; Wang et al., 2005). Typical compensation unit is composed of several passive elements, ensuring all parts of a RIPT system function well. On the primary side, properly tuned compensation can approximately meet ZPA zero phase angle conditions. Therefore, for the power electronic components, it helps minimize the VA voltage ampere rating, and thus improving the economic efficiency. Moreover, rated power transfer can be maintained in a larger charging zone. For the inverter, it remarkably reduces the switching loss by means of fulfilling soft-switching conditions. On the secondary side, the required output characteristics, according to the use case, can be achieved via corresponding compensation schemes. Static LC network is the most common and one of the simplest compensation methods. Dynamic compensation is more complex, such as the switching of resonant elements, adjustable controlled reactor making for ZPA zero phase angle and optimum load based on the maximum achievable efficiency condition, etc. (Yang and Wang, 2009; Qiang et al., 2012; Zargham and Gulak, 2012; Auvigne et al., 2012). Other optional compensation methods include multi-resonator structure and frequency control.

(Niu et al., 2019) In a typical charging process, the CC constant current mode and CV constant voltage mode are dominant in its respective time period. Therefore, a WEVC system is required to be capable of working in both these two modes. However, this may be hardly achieved if only a single type of basic compensation topology is involved. Due to that, a dual-topology which includes two sets of basic compensation circuits is shown in Fig. 11 (Auvigne et al., 2012). Fig. 11 (a) and Fig. 11 (b) illuminate how SS and PS compensation are implemented using switches according to charging requirements. This structure is feasible on the premise that the selected two basic compensation topologies have similar resonant conditions. It also takes the disadvantage of less reliability arising from capacitor switching with very limited degree of freedom in design.

(Niu et al., 2019) Fig. 12 shows a simplified model of an RIPT system as a two-port network, based on which a systematical design of hybrid compensation topologies can be realized (Qu et al., 2017). This equivalent network is driven by an AC voltage source , and the generated electricity is finally fed into to an equivalent load resistance , satisfying

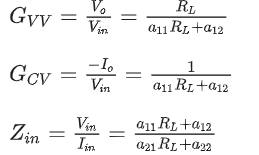


where and are the input voltage and input current on the primary side, and are the output voltage and output current on the secondary side. A represents the transfer matrix of the RIPT system and it can be decomposed as that of primary compensation , coupled structure and secondary compensation , satisfying



where a11, a12, a21 and a22 are the elements of this 2\*2 matrix.

To achieve a goal-oriented design (e.g. CC or CV), the transfer function of voltage ratio , transconductance , and input impedance of the equivalent network should be obtained first.



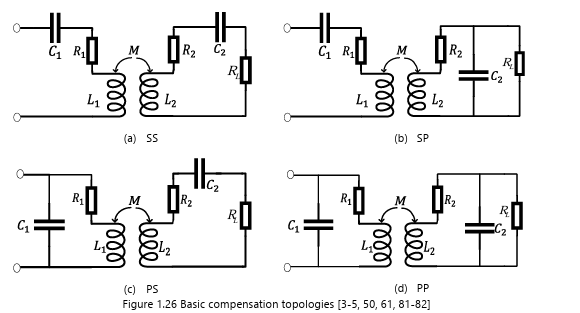
(Niu et al., 2019) For the RIPT systems operated in CV/CC mode, a12/a11 should be zero, respectively. Besides, ZPA conditions could be fulfilled by ensuring the imaginary part of is zero.

**Mono-Resonant Compensation Networks**

(Mahesh et al., 2021) As per connection of capacitor we get four compensation topologies. They can be addressed with two letters as per the series/parallel connection. First letter indicates primary side connection and second letter indicates secondary side connection. as shown in the Fig. 23. Those are Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS) or Parallel-Parallel (PP).

However, the SS topology is often implemented in the RIPT system. The advantage is that resonant capacitors don’t depend on load variation and coupling coefficient, and it makes them less sensitive to the misalignment between the transmitter and the receiver compared to the other topologies (Rim and Mi, 2017; Fisher et al., 2014; Mahesh et al., 2021; Corti et al., 2020). This condition is very useful in the static or dynamic RIPT system (Pei, 2022).

(Pei, 2022) According to (Rim and Mi, 2017; Fisher et al., 2014; Mahesh et al., 2021; Niu et al., 2019; Mohamed et al., 2020; Patil et al., 2018; Shevchenko et al., 2019), there are four basic compensation topologies, which can be achieved by adding one capacitor in series/parallel to the transmitter and the receiver coils. Resonant capacitors 𝐶1 and 𝐶2 are connected to the transmitter or the receiver (𝐿1, 𝐿2 represents the self-inductance of the transmitter and the receiver coils; 𝑅1, 𝑅2 represents the resistance of the transmitter and the receiver coils; 𝑀 is the mutual inductance between the transmitter and the receiver), either in parallel or in series. So, it exists four principle topologies of the resonant circuit in the RIPT system: series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP), shown in Figure 1.26.



(Pei, 2022)

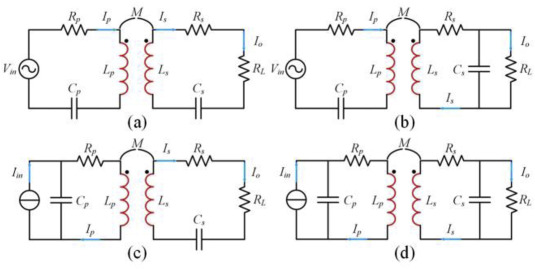
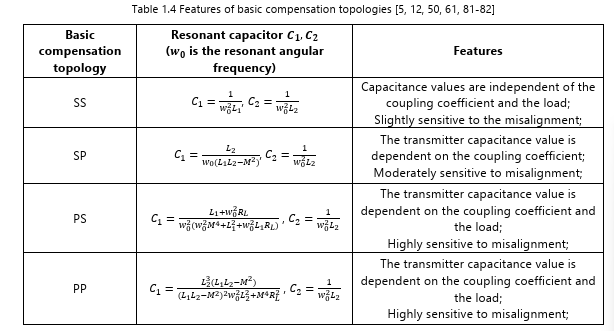


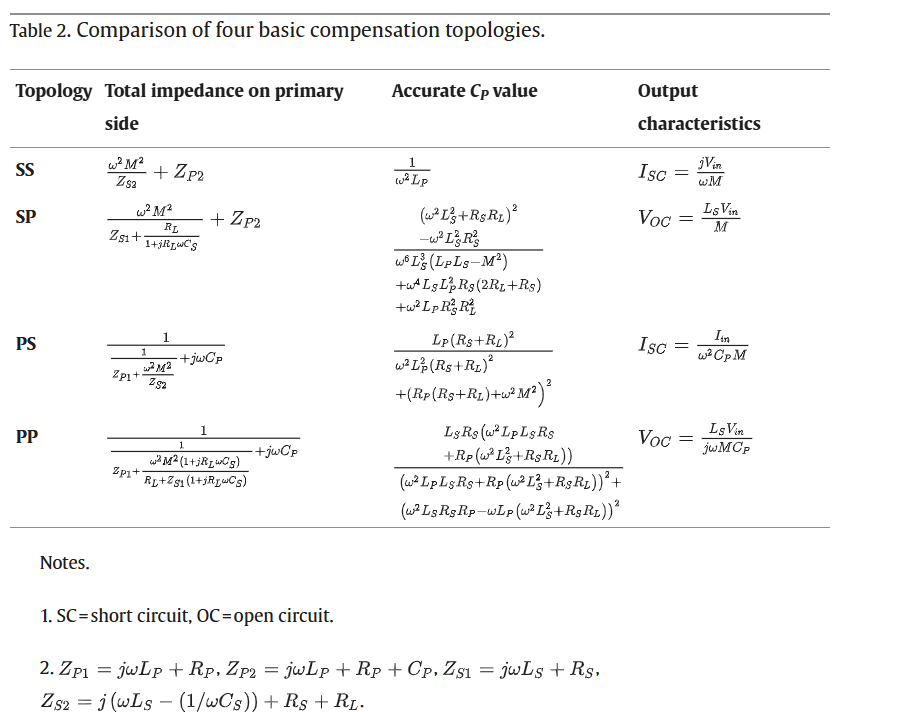
Fig. 10. Scheme of four basic compensation topologies: (a) SS, (b) SP, (c) PS, (d) PP.

(Niu et al., 2019)



(Pei, 2022)

(Niu et al., 2019) Fig. 10 depicts four basic static compensation topologies: SS, SP, PS and PP. The concept of the reflected impedance has been introduced in section 3.2. Herein plus the self-impedance, the primary total impedance of four compensation methods is summarized in Table 2, which is the basis of ZPA analysis (Villa et al., 2012). Obviously, the primary total impedance decreases with the M value becoming smaller, so RIPT systems using SS or SP compensation can transfer more than the rated power since its power supply is equivalent to a voltage source. Therefore, SS and SP configuration are widely considered to be suitable for high-power wireless charging (Villa et al., 2012; Bi et al., 2016). On the other hand, this also leads to the necessity to introduce additional current control. In contrast, PS and PP topology enhances current capacity, and thereby avoiding the unsafe behavior of overcurrent. On condition that the secondary side is in a state of resonance , Refs. (James et al., 2014; Raabe et al., 2007) give the recommended value of when ignoring the internal resistance of coils. Herein for accuracy, the value of is recalculated by taking the coil internal resistance into account, and corresponding results combining with the output characteristics are presented in Table 2. It can be seen that will contain the term if parallel compensation is employed on the ground side, this is to say, its value is related to the load condition, as opposed to the case of series resonance. This concludes with that primary parallel compensation may be not applicable when the load impedance is variable.



(Niu et al., 2019)

A secondary side quality factor needed to calculate to get primary compensation. For series compensation , for parallel compensation where indicates resonant frequency. Quality factor is ratio between the reactive and active power.

*Table 12 shows the primary capacitances of basic compensation techniques*.

(Mahesh et al., 2021) In common applications, SS and SP compensations implemented, because they provide good efficiency. The advantage of SS and SP compensation is capacitance value doesn’t depend on load variation. In addition, SS compensation is primary capacitance doesn’t depend upon coupling coefficient. This condition is very useful in DWPT, because Independent nature on the coupling coefficient, makes less sensitive to the misalignment. On the other hand, SP compensation depends on coefficient of coupling and primary capacitance value needs to be larger for a strong magnetic coupling (Wang et al., 2005; Moradewicz and Kazmierkowski, 2010). In SP topology, the primary side transferred impedance is square of mutual inductance. Due this condition implementing DWC is very difficult.

Two other topologies PP and PS are capacitance values, depends on the coupling coefficient and load resistance. These systems driven by current source converters. PP topology needs higher primary capacitance value compared PS topology (Wang et al., 2005).

The PF for the SS compensation is unity and high efficiency for the low coupling coefficient. The main setback of the SS topology happens at light loads, in the absence of receiver and equivalent impedance becomes zero at the resonance frequency, in this condition current is limited by parasitic impedance (Patil et al., 2018), which leads to unsafe operation. On the other hand, SP compensation depends on coefficient of coupling and primary capacitance value needs to be larger for a strong magnetic coupling (Wang et al., 2005; Moradewicz and Kazmierkowski, 2010).

Two other topologies PP and PS are capacitance values, depends on the coupling co efficient and load resistance. These systems driven by current source converters. Due to their symmetry, SS compensation secondary side’s eases the development of similar control topology is a common option bidirectional wireless chargers. The Table 14 presents the total impedance of four topologies. From the paper (Moradewicz and Kazmierkowski, 2010), mutual inductance between two coils can be expressed as,

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

Transferred power to the load given by,

Misalignment reduces the mutual inductance, results change in total impedance of the system. From [equation (19)](https://ieeexplore.ieee.org/abstract/document/#deqn19) and [(20)](https://ieeexplore.ieee.org/abstract/document/#deqn20),

power transfer directly proportional to transferred power and as per basic efficiency formula output power increases efficiency increases. Basic compensations and there relation with misalignment to the mutual inductance and total impedance, mutual inductance to transferred efficiency and transferred power shown in Fig. 24. In the SS and SP compensation, as current increases to the load, the total impedance decreases. In the PS and PP compensations, as misalignment increases the total impedance also increases, instigating a rapid fall of both currents (Villa et al., 2012). The PS and PP compensations at low mutual inductances offers relatively high PF and High efficiency and a relatively large range of the mutual inductance and load variation (Zhang et al., 2014; Hong et al., 2017). The PP topology suffers from low PF, parallel secondary need high voltage loads and parallel primary needs high current source (Zhang and Mi, 2016). Series compensation at secondary side (SS or PS), achieves smaller average primary input impedance compared to parallel compensation at secondary side(SP or PP) (Fu et al., 2019).

*Basic topologies: behavior mutual inductance to a) transferred power; b) efficiency, misalignment to c) mutual inductance; d) of total impedance (Hong et al., 2017; Villa et al., 2012).*

According to (Sallan et al., 2009), the copper utilization of basic compensation techniques for 200kW are in the order of SS < SP < PP < PS. The SS compensation needs least amount of copper and SP slightly more than that. PP and PS compensation requires more copper compared to SS compensation. Although PS compensation needs less operating frequency because of the higher required current and lesser operating frequency. Hence, SS and SP topologies are appropriate for high power application in view of cost.

**Multi-Resonant Compensation Networks**

(Mahesh et al., 2021) Basic compensation techniques are suitable for the ideal conditions. Due to the factor like misalignment, frequency deviation etc. makes WCS application never function at ideal conditions. Using multiple elements in series-parallel combination makes effective compensation method to overcome challenges of basic compensations.

(Pei, 2022) Compensating with elements LCL and LCC makes the magnetic coil efficient and compact (Li et al., 2015; Kan et al., 2017; Rasekh et al., 2018; Lu et al., 2018; Kan et al., 2018; Deng et al., 2015). The multi resonant compensations like LCC-LCC, LCL-LCL, etc., over their full range of loading and coupling, offer high efficiency (Liu et al., 2016; Zaheer et al., 2017; Zhang et al., 2021; Zhou and Mi, 2016). However, additional elements may cause additional losses compared to mono resonant compensation, particularly for high power applications (Corti et al., 2020; Shinohara, 2021).

(Niu et al., 2019) According to aforementioned principles, 52 compensation configurations for RIPT systems have been derived and summarized in (Qu et al., 2017). Exemplified hybrid compensation topologies are depicted in Fig. 13. SP-S compensation, a simple combination of SS and PS topology is shown in Fig. 13 (a). Compared with SS compensation, the added parallel-connected capacitor in the primary side enhances the safe operation of the power source while easily reach its rated power (Villa et al., 2012; Sallán et al., 2009).

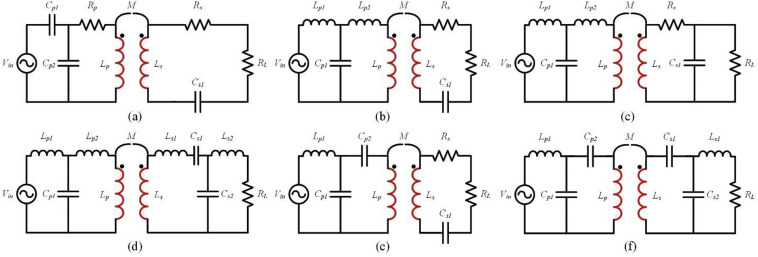


Fig. 13. Hybrid compensation topologies of RIPT systems: (a) SP-S, (b) LCL-S, (c) LCL-P, (d) LCL-LCL, (e) LCC-S, (f) LCC-LCC.

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

The multi resonant compensations like LCC-LCC, LCL-LCL etc., over their full range of loading and coupling offers high efficiency (Esteban et al., 2015). However, additional elements may cause more losses to compare to mono resonant compensation, particularly for high power applications. The advantages of LCL compensation is works as a current source, provides harmonic filtering capabilities, and offers high efficiency (Esteban et al., 2015).

(Mahesh et al., 2021) In literature (Liu et al., 2016), authors compared hybrid LCL compensations: LCL-S, LCL-P and double LCL, particularly their load characteristics, observed presented similar characteristics as LCC. The short circuit is undesired for the LCL-S topology at the risk of large secondary side current. In literature (Zaheer et al., 2017), a boost converter cascaded with LCL-P compensation, In this application, Primary compensation reflected as current source to connect a boost inductor. LCL-S and LCL-LCL topologies provide constant voltage and current output respectively, ZPA is achievable. In (Zhang et al., 2021), LCL-S applied to modified coil design to achieve load independent operation and field enhancement. When it compared with LCL-LCL topology delivered same power with less number of inductors (Zhang et al., 2021).

LCC compensation with four current mode operations proposed in (Li et al., 2015), which is having same features of LCL topology and offers high efficiency, less weight and low cost. Zhou and Mi (2016) applied LCC compensation topology for DWC, to reduce the EMI and decrease the power loss on the system. In article (Kan et al., 2017), double-side LCC(LCC-LCC) compensation topology presented with ZCS application and provides constant current when input voltage becomes constant. In addition, the LCC forms a UPF pick up by compensating reactive power. This method is independent on the co-efficient of coupling coefficient and load conditions (Li et al., 2015A; Li et al., 2015B). This topology is popular because of the characteristics like high misalignment tolerance, high efficiency and load independence characteristics (Li et al, 2015; Kan et al., 2017; Li et al., 2015B; Shi et al., 2018; Li et al., 2018).

In (Corti et al., 2020), the comparison between S-LCC, LCC-S and LCC- LCC is done. The LCC-S shown good performances in terms of efficiency, over a wide load variation. For the S-LLC and LCC topologies, optimal operation, in terms of efficiency, can be achieved over a shorter load span compare to other two. Nevertheless, the voltage stress across the compensation network components is generally lower. In article (Pantic et al., 2011), mathematical analysis for LCC compensation was done to get ZCS operation and compared with ZPA operation. ZCS operation have less switching loses than the ZPA operation. Drawback is it needs higher currents.

In articles (Ong et al., 2014; Byeon et al., 2016), authors proposed a new compensation topology LCCL compensation. Compared to SS compensation, maximum power transferred by the LCCL topology. Furthermore, this scheme produces high power transfer levels at high efficiency and coupling co efficient. In literature (Yang et al., 2018), double sided LCCL was presented. In this method, at calculated frequency, constant current from primary coil achieved. The SP/S compensation proposed in (Villa et al., 2012), which offers combine characteristics of SS and SP compensation. Allows higher position tolerance. The disadvantage is declining coupling conditions causes increase in the reactive power. In article (Hou et al., 2013), novel S/SP type compensation was proposed. ZPA of input impedance achieved, which is independent on load change and coupling factor K. This method can achieve both high efficiency and a constant gain at the full resonant frequency, with this method High power applications with wide range operations achievable (Hou et al., 2015).

*The advantageous and disadvantages of modified compensation topologies is summarized as shown in Table 15.*

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

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

A WPT system with three coil S/S/S compensated proposed to achieve the CV characteristic (Diekhans and Doncker, 2015), three coil S/S/LCC for CC characteristics. Both of these systems can Zero Phase Angle (ZPA). MISO systems mostly used DWC applications (Rim and Mi, 2017; Bosshard and Kolar, 2016). SIMO systems is used to charge multiple coils at a specific time (Hui and Ho, 2005). This scheme applied in maglev train (Song et al., 2002); for the V2G applications cascade IWPT converters with 3 coils LCL compensation presented in (Madawala and Thrimawithana, 2011) and 3-coil SSS compensation with load isolation presented in (Kuang et al., 2018). In MIMO is multiple coils used in the transmitter and receiver is known as MIMO system and it is used for increasing the magnetic communication range (Han et al., 2019). The cross inductance coupler coils is low. In article (Hao et al., 2014) LCL-T topology to achieve maximum power transfer efficiency a parallel inverter. In MIMO system the transmission and receiving frequency should be maintained very precisely. The point-to-point efficiency in the MIMO system is obtaining very difficult due to the inter coupling between receivers and transmitters. According to the article (Shinohara, 2021), the MIMO technology used in communication technology and mobile charging applications, MIMO in EV still need to be explored. Establishing coupling in MISO or SIMO easier compared to MIMO system.

In some of the applications like dynamic charging relative position between coil changes because of misalignment or working method of the system, causes changes in the coupling factor. Since coupling factor effects the both leakage and magnetizing inductances. In this condition achieving compensation is very difficult. Hence the researchers came up with position tolerant compensation methods. To get more stable output, LSS and SS combined to get power stability, compared to single compensation technique (Zhao et al., 2017; Zhao et al., 2016). Mostly position tolerant systems used in DWPT systems.

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**Power Supply Architectures**

the series LC (SLC) resonant and the hybrid series–parallel resonant ( LCL) topologies

**SLC Resonant Power Supply**

Fig. 3(a) shows the simplified equivalent circuit of the SLC power supply with all energy storage elements assumed to be lossless (Wu et al., 2011). As can be seen, the ECN of the SLC architecture is made up of a single capacitor in series with the primary coil

The value of the tuning capacitor is sized according to so that when the system is operated at its target frequency, the resulting equivalent primary inductance seen by the FB (full-bridge converter) is about 10% of (Huh et al., 2011). This partial series compensation scheme is equivalent to choosing so as to fully resonate with at , and then, operating the system at a frequency (Park et al., 2015).

The reason why the SLC power supply is operated slightly (5%) above perfect resonance is that this allows for the reduction of switching power losses in the FB semiconductors by means of the circulating inductive energy associated with the residual inductance positioning zero voltage across the semiconductors in each leg of the FB just before turn-on. This placement of zero voltage across the switches reduces the instantaneous turn-on loss that is normally associated with the finite period of time during which the drain-to-source voltage of the nonideal switch is decreasing, while its drain current is rising. This mode of operation is commonly known as zero voltage switching (ZVS), and the specific mechanism used to reduce to zero is the complete discharge of the parasitic drain-to-source capacitance of the switch by means of current flowing through and the free-wheeling body diode of the MOSFET during the dead-time, , that occurs between the turn-off and turn-on of series switches.

The sizing of , also takes into account the nominal value of at the system's target operating frequency and coupling point; accordingly, is chosen so that the equivalent capacitance resulting from the combination of and will yield the desired ZVS mode of operation previously described. If the system deviates significantly away from its nominal operating range of coupling, then the resulting variation in the equivalent series tuning capacitance and the nonlinear change in described in Section III will take the FB out of the desired ZVS mode and the power losses will increase significantly (Mecke and Rathge, 2004). To prevent the foregoing situation and a potential failure of the semiconductors, the system's switching frequency must be adjusted so as to always maintain ZVS operation. As discussed in (Tang et al., 2011), the frequency control scheme cannot rely on an autonomous phase-locked loop-based approach due to bifurcations that are inherent in the system because of its high order. Instead, a few discrete points in the frequency spectrum around the nominal operating frequency are selected and used to ensure the desired ZVS operating mode. The SLC architecture is attractive primarily because of its very simple matching network, consisting of only a single capacitor, which tends to result in a reduced physical implementation cost and complexity. Despite its reduced component count, the need to dynamically vary the switching frequency of the SLC topology adds to the complexity of the closed-loop controller design. In addition, the effective impedance seen by the FB is very sensitive to changes in both coupling and loading, which further increases the complexity of the controller. The foregoing sensitivity can also result in a very large current stress on the bridge semiconductors when the coupling of the magnetic pads decreases significantly beyond its intended operating range (Miller et al., 2012; Huang, 2006).

When is chosen according to the previously described procedure, the value of the primary current is given as follows:

**Series–Parallel Resonant (LCL) Power Supply**

Fig. 3(b) shows the simplified equivalent circuit of the LCL power supply neglecting all parasitic resistances. As can be seen, the ECN of the LCL architecture has two more discrete energy storage elements than the SLC topology, namely the series bridge inductance and the series capacitance . Moreover, the primary resonant capacitance is now in parallel with the primary coil and . This topology is sometimes also referred to as an LCL-T topology because of the characteristic T-shape of the ECN. The series capacitance is used for partial series compensation of so as to reduce it to a smaller equivalent value . The parallel capacitance is chosen so as to fully resonate with at the system's operating frequency. The bridge inductance is used to convert the HF voltage source characteristic of the FB to an equivalent current source, and for this reason, this ECN is sometimes spoken of as being an impedance conversion network (ICN) (Wang et al., 2004; Hao et al., 2011).

A very desirable characteristic of the LCL power supply is that when operated at or very close to resonance, it behaves as a constant current source over a very large range of coupling and loading making its control loop design easier (Borage et al., 2005). This is in contrast with the SLC topology, which is quite sensitive to changes in coupling and loading and requires a combination of dc-bus voltage and frequency adjustments to maintain its constant current source operation (Covic and Boys, 2013B).

The primary current of the LCL topology is fixed by the effective reactance of the primary coil along with its partial series tuning capacitor and is given as

Another feature of the LCL architecture that is often praised in the literature is that it reduces the current stress of the bridge semiconductors by constraining the large reactive resonant currents to flow only in the resonant tank (Wu et al., 2012). The FB only sources the current associated with the active power flow and the resonant tank losses. The decrease of the bridge current results in a reduced on-time conduction loss for the semiconductors.

The strategy in designing the LCL network is to size the energy storage elements so that the magnitude of all the resulting reactances are equal. Accordingly, the design equations that govern the sizing of the LCL network are as follows:

where is once again given by

and is once again the equivalent inductance of the partially tuned primary coil

The parallel resonant tuning capacitance is obtained from

Finally, the bridge inductance is in practice set to be 10% larger than the value of , so as to ensure that the inverter will always see a lagging/inductive load (Hao et al., 2011)

A lagging load is desirable because if the bridge were to ever become capacitively loaded, then the semiconductor losses would increase significantly due to large reverse recovery currents in the semiconductor's intrinsic body diode (Elliott et al., 2010). Moreover, as noted in (Borage et al., 2005), the power stage can be operated in a ZVS mode provided that the chosen switching control scheme ensures conduction in the intrinsic body diodes prior to switch turn-on. This operating mode coupled with the previously noted reduced current stress during conduction can result in very high converter efficiency.

As was the case with the SLC design strategy, the selection of the capacitance takes into account the reflected virtual capacitance (Wu et al., 2012). The bridge inductance could be implemented with an actual inductor, but by designing the HF transformer so as to have a precise value of an overall equivalent leakage inductance, it can be constructively used as a part of the matching network, resulting in a reduced number of components.

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**Power Conversion and its Control Strategies**

(Niu et al., 2019) The input power from the grid is transformed several times within a RIPT system, and primary DC-AC conversion is the most important step. HFAC high frequency alternating current produced by the primary inverter is applied on the ground coils, creating a strong magnetic field, which inductively generates an AC voltage of the same frequency in the vehicle coils (Li et al., 2015). Among various DC-AC modules categorized as fly back, half bridge, push-pull and others, full bridge inverters are especially preferred for EV charging for their high-power capacity and the ability to cover a frequency range specified in WEVC standards (81.38 kHz–90 kHz).

Control modules enlighten hardware designs. Taking load variation, overvoltage and overcurrent events into account, a smart WEVC system is required to adjust charging current depending on the feedback of the battery, and stop charging if necessary. Hence, a WEVC system can maintain an efficient and safe operation (Huang et al., 2016; Miller et al., 2015). Since the two sides of a system are contactless, it is necessary to introduce a pathway for data exchange and three exemplifications are shown in Fig. 15. It is expected that different charger manufactures can support all these three methods for better compatibility. RF device is small in size, light in weight and convenient in installation. Compared with IR circuitry, its dissipation power is very low (Liu et al., 2009). DSRC could achieve an in-motion target recognition in tens of meters.

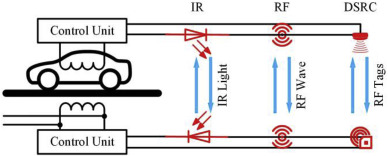


Fig. 15. Three common information transmission pathways.

Proper control strategies could unlock the potential of hardware systems. In general, there are two main control objectives in a WEVC system: constant DC output voltage and maximum efficiency tracking. For the former, the output voltage can be easily regulated by introducing a DC-DC conversion module or using controllable rectifier, adjusting the pulse width or phase angle of the inverter and so on. Therefore, the real difficulty with control is to obtain maximum system efficiency under the condition of constant output voltage. However, there are some causes that the maximum efficiency point cannot be maintained, such as aging inductor, component tolerance, mistuning and load variation considering a one-to-many relationship is formed between the public charger and EVs (Tan et al., 2011; Wang et al., 2013; Dai et al., 2011; Fu et al., 2009). To address the problem, reported MEPT maximum efficiency point tracking methods can be generally divided into three categories: frequency tracking, impedance matching and DC/DC conversion in either the primary side or secondary side. In some cases, two or more control variables are utilized.

**Power Electronic Converters for WPT**

(Mahesh et al., 2021) In WPT system power electronics plays a vital role. Furthermore, in order to improve the power transfer capacity, generating a high frequency is required. These operations carried out by the power electronic converters. Basic power electronic architecture presented in Fig. 27. WPT system reliability, control and efficiency depends upon the performance of converters. In general WPT system consists of two parts, first one to create high frequency and second one converting high frequency to usable frequency or DC. In first part grid voltage(50/60Hz) is converted to DC using PFC or rectifier and the DC signal inverted HFAC by using HFI. Second part consists of rectifier to HFAC to DC. Additional DC-DC converter may require for addition voltage control. The power transfer level and operational methods decides power electronic architecture and topologies. Other factors like cost, weight, flux leakage and switching losses also effects the Outcome. The power converters is classified in the WPT system based on number input phases to coupler and unidirectional or bidirectional power flow.

**Single Phase System**

Single phase WPT system is the most common type of converter used in wireless charging system. It could be made up of controlled or uncontrolled converters with a Voltage/current source. Secondary side different type of bridges used depends upon the application, power capacity and direction (Colak et al., 2015A; Diekhans et al., 2014; Colak et al., 2015B). For high power applications three phase rectifier used in grid side. Although, single-phase wireless charging system covers all power ranges mentioned by J2954. Single phase system has simple construction and control.

**Poly Phase Systems**

To overcome the single phase system draw backs, poly phase systems are developed. Especially three phase system provides higher power transfer capability, and power density compared to the single phase system. Three phase couplers provide more uniform flux distribution, by that allocated space can be utilized properly and can achieve higher power transfer capabilities. Different flux combination can be generated by using tree phase couplers, which are helpful for achieve different design concepts. Other features associated with three phase rotating magnetic field based WPT system is reduced filters and ferrites mass (Pries et al., 2020). Poly-phase topology have the ability to combine multiple coils to increase the power density. Inter phase mutual inductances (cross coupling between phases) is a major concern, which eventually results failure of ZVS operation. Hence, most of the works aimed to reduce the impact of the IPMI (Kim et al., 2017; Matsumoto et al., 2011; Matsumoto et al., 2015; Kim et al., 2018). However, poly phase windings have electrical and spatial phase shift. By using them, it takes the advantage of inter-phase mutual-inductance (IPMI), if the winding are designed in the way to aid the flux of other winding instead of cancellation. In three–phase track systems, resonant tuning done to balance the IPMI (Covic et al., 2007). In article (KIssin et al., 2009), addition ferrites cores added in between phases to achieve proper current balance. In other methods equations derived for the capacitor tuning, by considering IPMI (Safaee et al., 2015; Safaee et al., 2018). Therefore, to achieve best operation in three phase system, great understanding modulation index and flux path of power converters required. Compensation needed to design in way that handles cross coupling.

**Multi-Cell Modular System**

To alleviate voltage/current stresses on semiconductor switches, multiple converters with low voltage rating connected in series/parallel. This method reduces harmonic density and increases power transmission capacity (Li et al., 2015). Another benefit of this technique is related to the use of conventional power converters, such as full bridge and half bridge converters are readily usable. In addition, by employing this topology of converters, reliability improves due to modular redundancy. Multiple converters(low-current rating) arranged in parallel are improve the transmitting current of WPT system in (Hao et al., 2014). A parallel topology constructed by connecting identical LCL-T is demonstrated to reduce the irregular Power-sharing through parameter tolerance. The robustness and reliability is also improved owing to modular redundancy. In literature (Li et al., 2017), the authors have investigated a method based on multi inverter modules connected to single coil realize constant control of the track current and minimization of circulating current for RIPT high power systems. In addition, a protection scheme is designed to disconnect the fault inverter unit, which can ensure the whole system to work continuously and so as to improve the reliability as well as availability dramatically. In (Liu et al., 2015), an Input-Parallel/Output-Series (IP/OS) system is constructed with two transmission side coils with paralleled inverter connection and secondary-side coils connected to load with series connection. To regulate input impedance of resonant circuit, cross coupling should be considered. Fig. 28 depicts block diagram of the multiple converters cascaded in primary and multiple converters cascaded in secondary connected in parallel/series connections.

**Bidirectional Inductive Charger (V2G & G2V)**

In literatures (Onar et al., 2020; Jia et al., 2021) bi-directional WPT systems for grid and mobile ESS connectivity are discussed. The proposed method interfaces the EV batteries to the AC grid and also can redirect the power from the stationary ESS to grid, to EV batteries, or both simultaneously; In (Colak et al., 2015), a multi-level inverter is studied for bidirectional IPT systems. A phase shifted modulation technique is used between primary and secondary inverter ports in order to obtain maximum efficiency points. The topology is explored with different load conditions at the constant frequency and constant output voltage. In (Nguyen et al., 2014), a phase shift modulation strategy to drive the proposed primary side is presented. A cascaded multilevel converter with minimized switching loss in the switching devices in employed on primary side. In secondary side a single coil receiver is used. Multiple sources can be used for single system. Down side of this technique load on the secondary side increases. In literature (Nguyen et al., 2015), multilevel converter used offers simple control, having the advantages like lower switching losses and power scalable operation. The disadvantage this method is, it needs more number of switches and multiple isolated dc voltage sources.

**Single Stage Systems (AC/AC Converters)**

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

**Semiconductor Devices for Power Converters**

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

Introduction of wide band gap devices (WBG) like Gallium Nitride (GaN) and Silicon Carbide (SiC) in wireless charging applications witnessed good result. WBGs offers reduced switching losses, thermal stress and operates at high power levels (She et al., 2017). The SiC devices have four superior material properties because of wider bandgap (McBryde et al., 2010) those are higher breakdown voltage, lower leakage currents, higher thermal conductivity and lower on-state resistance. These qualities avails the devices to operate at much higher frequencies, temperatures, and voltages. Designing power converters with WBG devices will add more energy efficient and powerful than the conventional switches. In the Fig. 36 shown the power levels and frequency levels of switches. These materials have been applied on most of the semiconductor devices. In those SiC MOSFET is the most developed one.

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

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**Control of WPT Systems**

**Power Control Techniques**

(Mahesh et al., 2021) The control of the WPT done by three methods: primary-side control, secondary-side control, and dual-sided control (Patil et al., 2018). In primary side control most of the control concentrated around the primary side. In this method primary full bridge controlled to regulated transmitter current. Some of the cases PFC also regulated. To regulate primary pad according to the load, the secondary side information required in primary side control such as the SOC information, battery voltage, SOC and SOH information. Under this approach minimum interaction with secondary side needed. Hence, On-board electronics minimized, which reduces cost and weight of the Vehicle (Miller et al., 2014). In Secondary-side control:active rectifier with dc/dc converter are regulated to charge battery, due to increase secondary electronics, weight and cost of the vehicle increases.

Dual-sided control, in this technique both sides of WPT system need to be controlled. In This method communication link between two sides required. Both sides controlled independently or jointly depends on operation. In article (Gilchrist et al., 2012), dual side control is applied SWC method, when it comes to dynamic charging facing difficulties in application (Patil et al., 2018). Preferably independent control of both sides most suitable in DWC applications. Nevertheless, while using two independent controllers stability issues should be considered carefully (Patil et al., 2018).

Some of the basic control strategies are:

***1) Frequency Control***

In this method, switching frequencies regulated to control the input power. Drawback this method is, rated power deviation causes increase in reactive power of the system. It results drop in efficiency and may system go out of control (Huang et al., 2013; Wang et al., 2004). This method does not need any mechanical movement or extra components, which means smaller size, less complexity and higher reliability.

***2) Phase-Shifting Control Technology***

In this method, varying the turn-on angle of the switches by regulating the turn-on time of converter switches, to regulate the voltage fed to the magnetic coil by keeping constant frequency. In this method no need to concern over frequency of control operation and it also helps to eliminate selected harmonic frequencies. However, selection of switching frequency plays main role due to pole splitting (Li et al., 2015; Huang et al., 2013; Wang et al., 2004).

***3) Changing Circuit Parameters***

This method is mostly suitable for the low level applications. As mention in the name of the system this method depends on controlling parameters of the system such as resonant frequency, input voltage, input current. The change resonant frequency achieved by the tuning the resonant capacitance (Hsu et al., 2009). In another approach input voltage of this system regulated to control the transmission power. This scheme suitable for high power applications. However, extra DC-DC converters needed for the voltage control operation (Chen et al., 2012), which increases the system size and cost.

***4) Phase-Locked Loop Control (PLL)***

In this method power transmission controlled by adjusting PWM pulses and utilizes PLL to get the soft switching. After analyzing difference between zero crossing point of current and voltage signal, it adjusts the switching frequency of the converter to achieve soft switching operation (Chen et al., 2009). Implementing this scheme is very complex. In article (Samanta and A. K. Rathore, 2018), to regulate the bi directional power flow, resonant circuit’s real and reactive power measured. It is positioned at the receiver side, reduces the resonant circuit reactive power.

In the paper (Ann et al., 2020), author proposed to reduce the volume and cost for a semi bridgeless active rectifier (SBAR) with a variable frequency impedance tuning control. Just applying the fixed frequency control in EV application is not enough, because of the large aluminum shield and the wide range of the misalignment cause a large impedance mismatch. Although, the value of the fixed-frequency control must be designed with a sufficient margin to ensure ZVS) even if the large mismatch occurs. However, this application is not useful for high power applications due to load on the switches. DC-DC buck-boost converter of the DWPT controlled by PI and Fuzzy controllers, and their performances compared in (Smagulova et al., 2020). PI controller has longer settling time, even though, it produces ripple-free output voltage, current, and power signals. On the other hand, the Fuzzy controller quickly settles to the reference parameters. Proportional-integral (PI) based controller is most commonly used in the control system. Sliding mode control and Perturbation and Observation (P&O) method used some of the WPT applications (Yang et al., 2018; Huang et al., 2017). In literature (Huang et al., 2017), decoupled controlling system is proposed, In this method only receiver side DC to DC converter regulates the output voltage, while the secondary side rectifier takes care of impedance matching (Huang et al., 2017).

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**Foreign Object Detection and Vehicle Detection**

(Niu et al., 2019) For a fully-function WEVC system, FOD foreign object detection is indispensable before the charging process is complete. Foreign objects can be roughly divided into metal and non-metal types. For the metal debris in proximity to GA ground assembly, an eddy current is induced inside it due to high-frequency AC field, resulting in temperature rise and efficiency deterioration. Considering the specific heat of metals are generally low and therefore easy to heat up, the high temperature rise could eventually lead to combustion. Non-metal objects that are combustible and possibly appear on the GA ground assembly surface are also fire hazards. What is more, importance should be attached to the living object protection.

MOD metal object detection are given considerable attention in recent years. MOD metal object detection can be achieved by directly using system parameters, which is simple and cost effective without additional sensors. For example, the variation of the quality factor of secondary coils and the impedance of the primary coils have been employed to confirm the existence of metal debris (Fukuda et al., 2012; Riehl, 2016). Noticeably, these two methods are only applicable to perfectly aligned WEVC systems because parameter variation can also result from misalignment. Efficiency comparison, viz., the variation of power losses, is adopted by Qi standard as a MOD metal object detection method though its feasibility for high-power systems remains to be proved (Kuyvenhoven et al., 2011).

A WEVC system should not expose a living object to an unsafe magnetic field. Living object detection is essentially the recognition of the movement under the chassis. It can be enabled using off the shelf technologies, for example, GHz radar sensors (Ombach, 2014).

(Mahesh et al., 2021) Most of the people having dilemma about radiation coming from the WPT system. Another method to remove this dilemma is FOD (Standard SAEJ2954, 2016; Bi et al., 2016; Sonapreetha et al., 2015). If not present on charging zone or misalignment is more than expected primary pad should turned off automatically to prevent the exposure of radiation, leakage flux. Any conductive material (foreign object) present in the vicinity of flux transmission causes heating due to eddy current losses; its temperature also increases rapidly during the charging process, making it a critical heat source Since it has been proven to cause burns to living bodies, such as kids, incautious operators and small animals. To prevent this kind of incidents, several FOD methods have been reported in (Kesler, 2013).

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

***1) Metal Object Detection Methods***

Based on the detection method MOD methods categorized into 2 types: Mechanical/Thermal detection method and selector magnetic detection methods. Mechanical/Thermal Detection(MTD) methods are consisting of the radar or sonar sensors (Jeong et al., 2015; Widmer et al., 2017), temperature sensors (Roy, 2016), image processing (Hoffman et al., 2016; Sonnenberg et al., 2019) and light sensors (Jeong et al., 2015) which detects the mechanical/thermal signs of metallic body like size, shape, temperature, and distance (Jeong et al., 2015; Moghaddami and Sarwat, 2018). Electromagnetic detection(ED) method concentrates on the electromagnetic reaction of a metal object such magnetic field redistribution, power loss and variations operating performance of wireless charging system. These changes can be used as detection parameters. Giving to whether an auxiliary detection circuit is employed or not, these detection techniques classified as two approaches with auxiliary circuit and without an auxiliary circuit.

**A) Without an Auxiliary Circuit**

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

**B) With an Auxiliary Circuit**

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

***4) Living Object Detection Methods***

Based on the detection methods LOD methods categorized into two types: MTD method and ED method. Similar to the MOD method LOD method mechanical/thermal utilizes detectors like radar or sonic sensors (Jeong et al., 2015; Widmer et al., 2017; Poguntke et al., 2017; Strandberg and Tageman, 2017), temperature sensors (Jeong et al., 2015), imaging processing (Hoffman et al., 2016; Sonnenberg et al., 2019) and light sensors (Jeong et al., 2015) to confirm the presence of a living object. Parameters used for detection are shape, distance, temperature and size. Electromagnetic detection methods concentrates on the coupling effect of the living object,

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

**A) Without an Auxiliary Circuit**

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

**B) With Auxiliary Circuit**

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

In the article (Thai et al., 2020), a symmetric detecting coil is utilized to remove blind zones in applications. In DWC system, generally, while EV approaching, an only transmitting pad energized. This method eliminates unnecessary power losses EMF leakage. To achieve this scheme, various authors proposed, various vehicle detection methods. In article (Nagendra et al., 2014), a three-coil sensing system is proposed, to let the supplied power to detect an upcoming EV. In literature (Kamineni et al., 2017), resonant currents in transmitting pad utilized to detect the approaching EV. As discussed above the MTD methods concentrates on the mechanical/thermal signatures of FOD sensors and requirements. These approaches won’t depend on the type of the object and WPT system. Drawbacks of this method is the detection expensive detection sensor, needs extra working space and influenced by environment conditions. Detection method concentrated on change in parameters caused by foreign object. These method most suitable for MOD and applied during charging. Advantages these methods are low cost and simple implementation. Disadvantages are weakly sensitive to small objects, load condition and misalignment effects the detection. Detection methods based on the coupling effect with auxiliary circuit have effective detection sensitivity compared to other detection methods. The Table 17 shows sensors and related detection parameters being used in the FOD (Xia et al, 2020). Among them the active detection methods are implemented before or during charging being suitable for both MOD and LOD. The passive detection techniques are appropriate for MOD and can only be executed while charging. Moreover, these techniques requires signal-processing circuit. The active detection methods usually need an additional driving circuit, which makes system complex. However, sensitivity effective than the other methods. The advantages and disadvantages of the detection methods are categorized in Table 18 (Xia et al., 2020).

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**Position Alignment Method, Misalignment**

(Niu et al., 2019) Position alignment is an important procedure for WEVC. As stated in SAE J2954, only the pass criteria of alignment tolerance are fulfilled in both longitudinal and lateral direction, the subsystem of the ground side and vehicle side will shake hands and the charging process starts. For stationary WEVC, failure to aligned parking will weaken the magnetic coupling of both sides, resulting in efficiency drop and high electric stress. In recently years, various methods have been proposed to combat the adverse effects of the misalignment, such as the optimization of coil design (Chen et al., 2016; Lempidis et al., 2014; Kim et al., 2017), the guidance of magnetic flux by ferromagnetic core (Sakamoto et al., 1999; Matsuo et al., 2000; Hu et al., 2013), adaptive frequency control (Patil et al., 2018) and the utilization of resonant tank (Bi et al., 2016; Kissin et al., 2009). These methods improve the misalignment tolerance to some degree, but fail to tackle the problem fundamentally. Therefore, an auxiliary positioning system is in great need to make the vehicle perfectly aligned to the charging center. In addition, automatic alignment can give strong support for autonomous charging operation (Kim et al., 2013). Position alignment is considered to be a two-step process: Firstly, obtain the direction and magnitude of the misalignment. Secondly, self-correct the vehicle's position via close-loop control. In general, the methods of achieving the first step can be further divided into two categories depending on whether the signal received by the vehicle side is generated from additional device (such as GPS, RFID, optical alignment, or mechanical stop) or the magnetic field of primary coils. For DWC systems, position alignment can also be very beneficial. The load battery can be charged more quickly if precise alignment is ensured between the power lines on the ground and the secondary coil, and thus reducing range anxiety.

(Mahesh et al., 2021) In WPT systems, depending on the regulations and guidelines maintaining alignment is a key issue. Due to misalignment between transmitting and receiver coil cause various problems like increase in flux leakage and reduction in mutual inductance results reduce the transfer efficiency, where in high power system The small misalignment can cause high power losses. Therefore, it is necessary to compensate for misalignment and maintain high efficiency (Zhang et al., 2018). In stationary/dynamic charging of EV, it is challenging to align secondary coil with primary coil, it depends on the driver, the vehicle, and the environment. The variation may be lateral, vertical displacement, rotation and angular tilt. As per the SAE J2954 regulations, wireless charging systems should have misalignment tolerance in any direction (Huang et al., 2017) to some extent. The misalignment positional length is shown in Table. 3. The results from the Table. 19 are taken from the ORNL 6.6 kw wireless power transfer system with 85.5% efficiency (Chinthavali and Onar, 2016). The Table shows the results of the misalignment effect on efficiency. Also, the drop in efficiency. The Table displays the effects of misalignment on efficiency, the drop in efficiency due to misalignment clearly seen.

Researchers proposed different kind of method to reduce the effects of misalignment. The majority of research is focused on advance coil and core structures, like DD, DDC, DDQ, and BP have been analyzed and different coil combination of coils are used, which are shown to be some extent resistant to misalignment coils used, which are shown to be some extent resistant to misalignment (Ahmed et al., 2015; Bandyopadhyay et al., 2017; Mohammad et al., 2016; Kalwar et al., 2016). Researchers also proposed misalignment tolerant methods based on frequency tuning technologies and compensation circuits for power electronics (Zhang et al., 2020; Fotopoulou and Flynn, 2011; Lee et al., 2012).

Misalignment and operating inverter frequency affects the mutual inductance that further influences the resonance frequency (Kamineni et al., 2015; Babic and Akyel, 2006; Khan et al., 2018; Gao et al., 2015). In literature (Varikkottil and L, 2019), the ideal operating frequency for maximum power transfer has been estimated under contingency of misalignment. Detection of misalignment is the important part of the WPT system. In many studies various types of misalignment techniques proposed acoustical positioning (Langer and Thorpe, 1992), optical positioning (Shieh et al., 2018; Liu et al., 2017) and RFID positioning (Shuwei et al., 2014; Tiemann et al., 2016; Ni et al., 2003). optical positioning methods are vulnerable to obstacles and effected by the surrounding environment. Acoustical positioning and RFID positioning effected by signal lack of multipath detection and non-line-of-sight. These methods difficult to incorporate and costly.

In some of the WPT systems, electromagnetic positioning detection methods are implemented (Moghaddami et al., 2017; Gao et al., 2017; Jeong et al., 2018), these methods uses additional coils to measure changes magnetic field produced by primary couplers. This method wont influenced by environment, easy to incorporate, offers good accuracy and low cost. Primary pad needs to produce weak magnetic field by utilizing low voltage source for positioning of vehicle. To produce low voltage, high power inverter in primary side has to work at low DC voltage (Moghaddami et al., 2017; Gao et al., 2017), or have to work at small duty cycle (Jeong et al., 2018). Furthermore, In this method positioning and power transmission doesn’t work at a time.

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**Communication**

In contactless charging system communication plays vital role to guarantee timely information exchange between primary and secondary sides, to ensure reliable and efficient operation. The main factors influences selection of optimum communications method are: 1) low latency; 2)communication with multiple vehicles; and 3) medium range coverage (Patil et al., 2018).

Communication setup also depends upon the power control methods such as: primary-side (transmission-side), secondary-side (receiver or vehicle-side), or dual-side control. (Echols et al., 2017): Primary and dual side control often involves data sharing of the battery’s SOC parameters, like voltage and current levels, as well as coupling and efficiency parameters between the vehicle and ground pad module. Furthermore, communication required for initiation and termination of charging process and positioning of the vehicle, FOD and misalignment.

Most of the communication standards set by SAE, ISO and IEEE. SAE setup generalized communication standards for PHEV/BEV. SAE J2847-6 deals with communication between EVs and there wireless chargers. Also states the requirement and specifications. SAE J2836-6 provides guidelines for on-board chargers and there supply equipment support system. 2391–6 deals with conditions for physical and data link layer communications most of them taken from IEEE 802.11n. Other communication options include Bluetooth (IEEE 802.15.1), ZigBee (EEE 802.15.4 and Wi-Fi (IEEE 802.11). etc. ISO 15118–8 sets standards for high level communications between EVs and supply equipment.

In (El-Shair et al., 2020), the researchers have studied different standards for communication, recommended suggestions through conducting several experiments antenna on position, channel state estimation, effect of shielding on signal quality and SAE J2954 Message set implementation on Prototype testbed.

In literature (Gil et al., 2014), author careful factor such as latency, transmission range, speed of data transmitting and mobile connectivity for different DWC applications. A Dedicated Short-Range Communication (DSRC) for applied in article (Echols et al., 2017). Other communication methods such as Wi-Fi (IEEE 802.11), Bluetooth (IEEE 802.15.1and ZigBee (EEE 802.15.4) need to researched for more options.

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**Economic Analysis of WPT**

The WPT technology economic competition with other technology is influenced by different factors such as in current infrastructure, battery technology and electricity per unit cost. Compared to plug-in charging methods, the major difference SWC system consists of magnetic coupler, which brings an additional cost of US$ 400/8 kW charger (Li and Mi, 2015). Cost of contactless charging is quite acceptable considering the features provided (Brecher and Arthur, 2014).

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**Optimization of RIPT systems**

When the magnetic coupler design and compensation topology are selected, how to optimize the design for IPT systems is under current research. There are three engineering design methodologies to select the optimal design for the system:

Parameter optimization: It allows for doing a parametric sweep on geometry dimensions or material properties, such as the ferrite length and width, coil wire position, number of coil turns, a separation between turns, size and position of ferrites, etc. (Budhia et al., 2011; Budhia et al., 2013; Shinohara et al., 2021; Tavakoli et al., 2022).

Shape optimization: It allows to deform the boundaries of the geometry, such as the coil shape, the ferrite shape, or the shielding shape;

Topology optimization (TO): It allows to determine whether a certain point of the geometry is void or solid, for example, how to arrange the ferrite structure under the transmitter or above the receiver (Otomo and Igarashi, 2019; Gong et al., 2020; Otomo and Igarashi, 2021; HU et al., 2021). The main methods used are the solid isotropic material with penalization (SIMP) method (Bendsøe and Sigmund, 1999), the on-off method (Sato et al., 2015).

To compare the performances of different possible designs, many researchers have considered the uncompensated power rating 𝑃𝑠𝑢, the coupling coefficient 𝑘 (Hariri et al., 2017; Yilmaz et al., 2017; Mohamed et al., 2018; Otomo and Igarashi, 2019; Yao et al., 2021; Yakala et al., 2021), the 𝑘𝑄 factor (Q is the coil’s quality factor) (Yilmaz et al., 2017), power density 𝛼 (Bosshard et al., 2015; Bandyopadhyay et al., 2019; Zhang et al., 2020), gravimetric power density 𝛾 (Bandyopadhyay et al., 2019), transmission efficiency 𝜂 (Bosshard et al., 2015; Bandyopadhyay et al., 2019; Chen et al., 2021; Zhang et al., 2020; Tavakoli et al., 2022), mutual inductance 𝑀 (Zhao et al., 2022), cost (Mohamed et al., 2018; Zhang et al., 2020; Tavakoli et al., 2022), core losses (Mohammed et al., 2019; Chen et al., 2021; Zhao et al., 2022), magnetic field leakage (Yilmaz et al., 2017; Otomo and Igarashi, 2019; Pearce et al., 2019), output power (Tavakoli et al., 2022), weight (Yakala et al., 2021; Chen et al., 2021) and so on as objective functions for optimization. Most of them uses parametric sweep (Budhia et al., 2011; Budhia et al., 2013; Bosshard et al., 2015; Mohammed et al., 2018; Lu and Ngo, 2018; Bandyopadhyay et al., 2019; Yao et al., 2021; Yakala et al., 2021; Chen et al., 2021; Li et al., 2019; Zhang et al., 2020), while some literatures considered optimization algorithms such as Genetic Algorithm (GA) (Hariri et al., 2017; Otomo and Igarashi, 2019; Pearce et al., 2019; Bertoluzzo et al., 2020; Zhao et al., 2022), Particle Swarm Optimization (PSO) (Yilmaz et al., 2017; Tavakoli et al., 2022), Tabu Search (Mohamed et al., 2018).

Up to now, the methods to express objective functions in optimization algorithms are: 1) To deduce the mathematical expressions describing the relationships between the design variables and the objectives (such as self-inductances, mutual inductances, magnetic flux density leakage, and so on); 2) To simulate every design configuration based on 3D numerical methods, e.g., the Finite Element Method (FEM). But when a complex coupler configuration with a large number of variables is involved in the design process, the first method will become very difficult to deduce the analytical expressions, and the second method will take a really long time to simulate all possible design configurations Chapter 1 State of art by 3D FEM. How to speed up the optimization process with a large number of variables in an efficient method is worth studying.



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**Electromagnetic Simulation for Wireless Power Transfer**

Optimizing Wireless Power Transfer with EMWorks Electromagnetic Simulation

<https://www.emworks.com/application/overcoming-design-challenges-in-wireless-power-transfer-systems>

<https://www.cadence.com/en_US/home/explore/electromagnetic-simulation.html>

**What is Electromagnetic Simulation?**

Electromagnetic simulation is a modern method for analyzing the performance of electronic devices and systems using simulation and analysis software, which replaces costly and time-consuming legacy manual prototyping.

To accelerate the design process and meet aggressive delivery schedules, engineers need to be able to perform cross-fabric and multiphysics analysis to model, simulate, and analyze these effects on system-level designs.

There are two divisions or groups into which EM simulation software packages are divided: circuit simulators and field simulators. The software for EM field simulation is categorized according to frequency criteria, either low-frequency, which uses static electric and magnetic field simulation software, or high-frequency, which uses electromagnetic software. The more popular methods for field simulations now include the finite element method (FEM), boundary elements, or finite differences.

EM simulators first take in a physical description of the device, then process the layout into a form that can be used in the analysis phase. This typically involves “meshing” the conductors using the finite element method (FEM). The analysis is performed based on Maxwell’s equations for electromagnetism, and the solutions are combined to give a final result. The analysis result is provided as a model (such as S-parameters) that can be used in circuit simulation to verify performance.

**Why is EM Simulation Important?**

Today’s high-performance electronic systems are being driven by ever-increasing complexity and density, requiring designers to consider issues of electromagnetic interference (EMI) and electromagnetic compatibility (EMC), as well as power integrity (PI) and signal integrity (SI).

To accelerate the design process and meet aggressive delivery schedules, engineers need to be able to perform cross-fabric and multiphysics analysis to model, simulate, and analyze these effects on system-level designs.

The two main reasons for performing an EM simulation are to uncover any unintended EM interactions in the circuit/system and ensure the design meets performance specifications. In addition, there are different occasions on which a designer would want to perform EM simulation, such as when designing a chip, package, board, or system, to optimize the current design by looking at the results of the simulation and then tweaking it to improve it further. Alternatively, EM simulation is useful during the signoff phase, when the design is complete, and it is important to confirm that it is fully optimized and meets specifications.

**How Does EM Simulation Work?**

**In-Design EM Simulation and Analysis**

Electronic product development projects have traditionally embraced a workflow in which the detailed multiphysics EM simulation, analysis, and optimization takes place at a very late stage in the design process, often as the final step of verification and signoff. However, this delay inevitably leads to costly issues that derail budgets and delay time to market as defects in requirements and performance are uncovered that require additional cycles to address these issues. These problems should have been discovered and mitigated earlier in the design phase.

To succeed in today’s highly competitive electronics markets, multiphysics EM simulation and analysis are now being integrated from the earliest stages of the design process in a methodology called “in-design analysis (IDA),” which is moving from an afterthought in the workflow to becoming an integral part of each phase of the design process at the chip, package, board, and complete system level.

**1. In-Design Analysis for RF/Microwave**

An in-design workflow for RF/microwave devices provides EM optimization, parameterization, 3D EM libraries, circuit co-design, full-wave EM extraction, and multi-fabric EM hierarchy support. RF EM in-design technology allows design teams to transition from the ideal circuit design to physical designs with EM-level accuracy, building more complex circuits in a very logical and disciplined approach that helps the design team achieve their goals in the fastest time possible.

A 3D FEM solver can be used during the early stages of RF design, component EM modeling, circuit extraction, and optimization to uncover issues before they surface in the prototyping stage. These capabilities include 3D EM parameterized components and model libraries, support for hierarchical EM analysis of heterogenous designs, and EM extraction-on-demand features.

**2. In-Design Analysis for Automotive Electronics**

Every industry is expanding to embrace electrification, including mobile communications, aerospace/defense, industrial, biomedical, and consumer. Notably, modern automotive development is expanding to include more and more sophisticated electronics, and manufacturers are equipping their new models with advanced driver-assistance system (ADAS) applications to reduce injuries and fatalities by alerting drivers to and assisting them with a variety of issues, including collision avoidance and low tire pressure, as well as self-parking and driving. As demand for features increases, these systems become increasingly complex, making in-design EM simulation and analysis critical for delivering reliable and excellent performance within shrinking market windows.

**3. In-Design Analysis for High-Speed Devices**

In key electronics applications such as high-performance computing (HPC), automotive, machine learning, and 5G, data speeds and volume are increasing exponentially. Crosstalk analysis and simulation in high-speed design is difficult without the right field solver tools or analytical models. Designers of modern high-speed PCBs need to consider single-ended and differential crosstalk and power integrity problems that can be mistaken for crosstalk.

Designers need in-situ EM analysis to understand the relationship between physical design and overall system performance. In tandem with EM simulation and multiphysics analysis integrated within the design process, engineers also need solutions that enable complete and comprehensive high-speed and high-frequency design and analysis workflows within a single platform that goes beyond the chip and extends out through the entire system.

To address these requirements, EMI/EMC and SI/PI technologies can be used throughout the design process to quickly and accurately tackle the largest and most complex structures, identify sections of an interconnect that are susceptible to crosstalk, and take steps to prevent noise coupling between interconnects.

**EM Simulation with Cadence**

**1. Clarity 3D Solver – Best-in-Class EM Simulation**

The Cadence Clarity™ 3D Solver provides optimum EM simulation and analysis for obtaining the high-speed/high-frequency electrical behavior of PCB, package, and IC structures using geometry and material information already defined within the Cadence Allegro® PCB or IC design and Virtuoso system design platforms. By offering EM analyses with virtually unlimited capacity that can cover the broad range of manufacturing technologies found in today’s heterogenous systems, designers can solve bigger problems without the added time, cost, and potential errors associated with design exporting, partitioning, simplification, and reassembly of analysis results. The Clarity true 3D EM field solver enables designers to avoid the error-prone divide-and-conquer methodology and simulate 10X faster while maintaining gold-standard accuracy.

**2. Sigrity Signal and Power Integrity**

Cadence Sigrity™ SI/PI technology delivers powerful, accurate planar 3D EM simulation of signal integrity (SI) and power integrity (PI) that addresses the size and scalability challenges of today’s leading-edge 5G communications, automotive, hyperscale computing, and aerospace and defense industries. The software works with all major PCB and IC package design platforms, including Cadence’s Allegro PCB, Allegro Package, and Integrity 3D-IC design platforms. It provides high-speed system designers with comprehensive, end-to-end SI/PI analysis, in-design interconnect modeling, and power delivery network (PDN) analysis for PCB and IC package designs. Working within a unified, integrated, and collaborative design environment, design engineers are more productive and able to meet compressed schedules and bring products to market on time and within budget.

**3. EMX 3D Planar Simulator**

The EMX Planar 3D Solver is an EM simulator for the design of high-frequency and high-speed ICs. It allows designers to accurately model complex layouts while reducing design cycle time. The solver is optimized for analyzing passives on silicon, primarily planar conductors and small vias like on-chip interconnect. It also has a broad library of process design kits (PDKs) from all the major foundries. This combination delivers quick and accurate processes. The EMX solver is seamlessly integrated with the Virtuoso platform and Virtuoso Studio.

**Analysis of a WPT for Pacemaker Battery Charging**

Pacemakers regulate irregular heartbeats like Arrhythmia with electrical impulses. Rechargeable and battery-less models, powered wirelessly or via RF systems, offer increased longevity and flexibility while reducing the need for surgeries.

The proposed model [6] demonstrates inductive coupling for pacemaker battery recharging. Figure 5 illustrates the composed elements, including transmitter and receiver coils, aluminum plates, and ferrite cores. Operating at a low frequency (20kHz) ensures EMF standards compliance, although it reduces wireless power transfer efficiency. To mitigate this, aluminum plates and ferrite cores are incorporated to enhance system efficiency.

Figure 7 - 3D CAD model of the simulated WPT system

This article will analyze and compute the parameters of the wireless power transfer (WPT) system using EMS's AC Magnetic module coupled with an external circuit. Table 1 outlines the key simulation properties for reference.

Table 1: Main analysis properties

|  | Aluminum plates | Iron cores | Copper | Transmitter and Receiver Coil |
| --- | --- | --- | --- | --- |
| Electrical conductivity (S/m) | 3.86e+7 | 0 | 5.8e+7 | - |
| Relative permeability | 1 | 2400 | 0.99998 | - |
| Number of turns | - | - | - | 10 |

**Pacemaker for WPT and Shielding effects**

Figures 7-10 illustrate the magnetic flux density under various scenarios. Without shielding components, the flux density is symmetrical around the primary coil (Figure 7), with significant leakage into the air. Introducing aluminum plates reduces the field conducted to the receiver (Figure 8), while adding iron cores intensifies the field (Figure 9). In the full model, the magnetic flux is higher, following a direct path from transmitter to receiver (Figure 10). Shielding with iron cores and aluminum plates reduces losses and protects against leakage fields. Inductive coupling is approximately 0.1 without shielding and about 0.13 in the full model.

Figure 8 - Magnetic flux density distribution-without iron cores and aluminum plates

Figure 9 - Magnetic flux density distribution- without iron cores

Figure 10 - Magnetic flux density distribution-without aluminum plates

Figure 11 - Magnetic flux density distribution- with aluminum plates and iron cores

The WPT model's circuit parameters at a frequency of 20kHz are calculated using EMS. Table 2 provides a summary of these results.

|  | Inductance  LTx  (uH) | Inductance  LRx  (uH) | Resistance  RTx  (  mΩ  ) | Resistance  RRx  (  mΩ  ) | Mutual Inductance  MTxRx  (uH) | Coupling Coefficient |
| --- | --- | --- | --- | --- | --- | --- |
| EMS | 4.278 | 3.787 | 16.05 | 19.23 | 51.80 | 0.128 |
| Ref [3] | 4.1685 | 3.7002 | 18.78 | 21.89 | 52.26 | 0.133 |

**Influence of the air gap distance on the coupling coefficient**

The coupling coefficient formula for the WPT system is:

.. The efficiency of WPT increases with the coupling coefficient. Perfect coupling (k = 1) occurs when all flux lines of one coil cut all turns of the second coil, resulting in mutual inductance equal to the geometric mean of the two individual inductances. This leads to induced voltages satisfying the relation

Figure 11 presents an animated visualization showcasing the magnetic flux density's response to changes in the air gap distance between the transmitter and receiver coils. A parametric AC Magnetic study vividly demonstrates the inverse relationship: as the air gap distance increases, the magnetic flux density reaching the secondary coil diminishes, and vice versa.

Figure 12 - Animation of the magnetic flux density versus air gap distance

Figures 12 and 13 display the curves depicting the mutual inductance and coupling coefficient concerning the air gap between the primary and secondary coils. In both cases, as the air gap distance increases, both parameters exhibit a decrease, indicating a weakening coupling between the coils.

Figure 13 - Mutual inductance versus air gap distance

Figure 14 - Coupling coefficient versus air gap distance

Figure 14 illustrates the induced voltage in the secondary coil, mirroring the behavior of the coupling coefficient. Meanwhile, Figure 15 depicts the ratio of

. , which decreases as the air gap widens. This decrease signifies a reduction in transferred energy due to increased distance between primary and secondary windings, aligning with previous observations.

Figure 15 - Induced voltage versus air gap distance

Figure 16 - Ratio of the voltages

**WPT operating at the resonance**

The WPT system achieves its peak efficiency when operating at resonance, facilitated by the addition of resonant capacitances on both primary and secondary sides. The external circuit, integrated within EMS, is depicted below. In this circuit representation, the source is ideal (R=0), while the DC resistance of the windings is internally accounted for within EMS and not explicitly modeled.

The resonant capacitance values are computed using the following formula :

Figure 17 - Resonant circuit modeled inside EMS for the pacemaker WPT system

Figure 17 illustrates the variation of both transmitter and receiver currents across different operating frequencies. It's evident that the maximum current is achieved at the resonant frequency of 20kHz.

Figure 18 - Currents in the transmitter and receiver coils versus frequency

**WPT system inside human body**

In this section, we explore the scenario where a receiver is implanted within a human body, while the transmitter remains external, positioned just a few millimeters beneath the skin. Due to the body's low electrical conductivity, which increases with frequency, induced eddy currents are minimal at the system's low operating frequency. Figures 18a) and 18b) illustrate the front and right views of the meshed model, with a finer mesh applied to the aluminum components to capture any eddy currents within the skin depth. The EMS mesher adeptly follows component curvature, resulting in finer meshing in specific areas.

Figure 19 - Meshed model: a) Front view, b) Right view

Figures 19a) and 19b) display cross-sectional views of the magnetic flux distribution within the human body. The flux is predominantly concentrated around the receiver due to the shielding components. The maximum magnetic field strength is a few microtesla, well below the standard limit of 27 microtesla published in [11].

Figure 20 - cross-section view of the magnetic flux density distribution; a) Front view, b) Isometric view

**Conclusion**

This application note explores the innovative realm of Wireless Power Transfer (WPT), showcasing its transformative impact on technology and everyday life. It delves into the principles of Inductive Power Transfer (IPT), a key method of WPT, which utilizes a transmitter and receiver winding to form a transformer with an air gap, facilitating the wireless transmission of power across various applications, notably in electric vehicles and wearable or implanted medical devices (WIMD).

The focus on electric vehicle charging and medical devices like pacemakers illustrates IPT's versatility and its potential to revolutionize energy consumption and healthcare. The study presents a detailed analysis of a WPT system designed for pacemaker battery charging, operating at a low frequency to comply with EMF standards while optimizing system efficiency through the use of aluminum plates and ferrite cores.

Through EMS's AC Magnetic module coupled with an external circuit, the study analyzes the system's electromagnetic parameters, demonstrating how shielding components can significantly enhance efficiency and safety. The findings highlight the coupling coefficient's role in determining WPT efficiency, emphasizing the system's peak performance at resonance and its adaptability to human body constraints.

In Conclusion, the application note underscores the significance of WPT in pushing the boundaries of energy transmission and medical technology, pointing towards a future where power delivery is more seamless and integrated into our daily lives, thereby supporting the ongoing shift towards renewable energy and advanced medical care.

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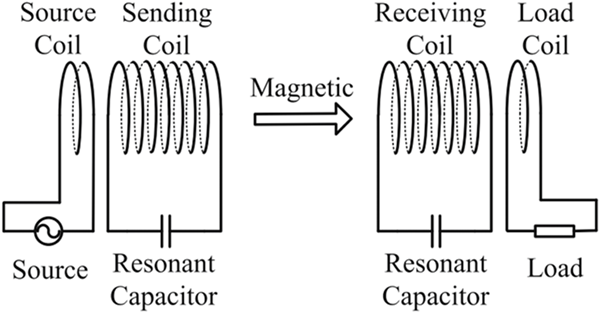
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**What is Resonant Wireless Power Transfer?**

In this application note, we began by evaluating a Wireless Power Transfer (WPT) system, finding its efficiency lacking even at close coil distances. Introducing two resonant capacitors transformed the WPT into a Resonant Wireless Power Transfer (RWPT) system, showcasing its superiority. However, efficient operation requires careful selection of the load. In the final analysis, we compared EMWorks simulation results for the RWPT system with those obtained using commercial power software Powersim, achieving a perfect match in efficiency.

Resonant Wireless Power Transfer (RWPT), developed by MIT in 2008, enhances Wireless Power Transfer (WPT) by utilizing compensation capacitors in both transmitter and receiver. This technology nullifies impedance imaginary parts, enabling higher output power and efficiency compared to traditional WPT. RWPT is widely applied in appliances, wearable gadgets, mobile phones, and electric vehicle chargers, offering superior performance even at mid-range distances relative to coil size.

Fig. 1. Equivalent Circuit of a typical RWPT System [1]



**CAD Model**

In this application note, a WPT system [2] is studied using EMWorks. The system is made of two copper-printed coils. Figure 2 shows the simulated wireless system while Table 1 contains the main dimensions of the model. Later, we will add resonant capacitors to change the system from a WPT to RWPT and study the data resulting from such a change.

Add resonant capacitors to change the system from a WPT to RWPT. However, efficient operation requires careful selection of the load.

Table 1. Main Dimensions of the RWPT System

|  | **Exterior Coil** | Interior Coil |
| --- | --- | --- |
| **Inner Diameter** | 27.7 mm | 11.64 mm |
| **Outer Diameter** | 41.3 mm | 16.14 mm |
| **Inter-Traces Distance** | 1.4 mm | 0.3 mm |
| **Length of the Trace** | 1.6 mm | 0.5 mm |
| **Thickness of the Traces** | 40 um | 40 um |

Using the EMS [3] module of EMWorks, we investigated the following RWPT issues:

Circuit parameters of the simulated RWPT including R and L matrices,

Coupling coefficient versus air gap and alignment,

Efficiency versus frequency and geometry configurations,

Comparison of EMS results against Powersim results.

**Parametric Analysis**

Using the AC Magnetic module of EMS, the coil parameters including self and mutual inductances, AC resistances, and coupling coefficient are computed versus different air gap distances and alignments. These parameters are then used to compute the resonant capacitance and efficiency of the system. To evaluate the effect of air gap distance and the misalignment on the magnetic field distribution, a parametric AC Magnetic analysis is used.

Table 2. Circuit Parameters Computed by EMS

|  | **Exterior Coil** | Interior Coil |
| --- | --- | --- |
| **Self Inductance M (H)** | 1.774798e-006 | 1.281031e-006 |
| **Mutual Inductance L1(H)** | 1.207742e-007 | 1.207742e-007 |
| **Self Resistance R (Ohm)** | 3.410545e-001 | 6.161653e-001 |
| **Mutual Resistance Rm(Ohm)** | 1.920747e-003 | 1.920747e-003 |

From the above circuit parameters, the coupling coefficient

between primary and secondary coils is computed. The greater is k the higher is the transmitted magnetic flux from the emitter to the receiver winding; hence, the efficiency is directly proportional to the coupling coefficient [4].

In addition to the above circuit parameters, the magnetic field and flux are computed. Figures 3a) and 3b) show the cross-section plots of the magnetic flux density results at 2 mm and 40 mm of air gap size, respectively. Clearly, the magnetic flux around the interior coil, i.e. receiver, is higher with an air gap of 2 mm compared to 40mm. Namely, 40 to 80 micro-Tesla versus 18 micro-Tesla for 2 and 40 mm, respectively.

Fig. 3. Magnetic Flux Results, a) Air Gap 2 mm, b) Air Gap 40 mm

The plots of the mutual inductance M and the coupling coefficient k versus the distance between the coils are shown in Figure 4. Clearly, M and k are inversely proportional to the distance separating the coils. Furthermore, with the help of the popular closed-form solution of the mutual inductance M, the inverse proportionality is cubic in nature since

Consequently, to achieve a good coupling coefficient, the coils must be as close as possible. How close? Well, it depends on the level of the coupling desired.

Fig. 4. Mutual Inductance M and Coupling Coefficient k Results vs Air Gap Distance

The above conclusion is also applicable to the induced voltage, under open circuit operation, in the receiver coil, as shown in Figure 5.

Fig. 5. Induced Voltage in the Receiver Coil vs Air Gap Distance

The results of both mutual inductance M and coupling coefficient k, shown in Figure 6, are inspected versus axial alignment using another parametric study in EMS. The coupling between the coils drops only when the misalignment becomes larger than 15 mm. Hence, the studied system can operate at the same efficiency in a short range of misalignments up to 15 mm. This behavior can be attributed to the small size of the receiver.

Fig. 6. Mutual Inductance M and Coupling Coefficient k Results vs Misalignment

Similarly, the induced voltage in the receiver coil is almost constant when for a misalignment less than 15mm and sharply decreases thereafter, as shown in Figure 7.

Fig. 7. Induced Voltage in the Receiver Coil vs Misalignment

Figure 8 illustrates an animation of the magnetic flux density versus different misalignments. The magnetic flux density that reaches the receiver coil is almost constant up to a certain level of misalignment.

Fig. 8. Animation of the Magnetic Flux vs Different Misalignment

**EMS Circuit-Coupling Analysis**

In the above investigated WPT system, the coupling coefficient is relatively low even at small air gap and aligned conditions. To illustrate the limitation of the WPT, we compute its efficiency as per the equation:

, where V1 is the input voltage, I1 is the current in the primary side, is the phase between current and voltage,Iload is the current in the load, Rloadand is the resistance of the load.

EMS circuit simulator is used to model the equivalent circuit of the simulated system as illustrated in Figure 9. Windings 1 and 2 are the coils of the WPT system. The input voltage is 2.5 V / 13.58MHz (phase shift is 0deg) and the load is a 10 Ohm resistance.

AC Magnetic module of EMS coupled to the circuit simulator are used to solve the WPT system. The transmitter and receiver are maintained at an aligned position and an air gap of 15 mm. The coupling coefficient is 0.08 at these conditions, as shown in Figure 4.

Fig. 9. The Simulated Circuit of the Studied WPT System

Table 3 contains the current results in the windings computed by EMS. Using the formula (3), the efficiency of the studied system is 0.17%, which is indeed low.

Table 3. Current Results Computed by EMS

|  | **Current Computed by EMS** |
| --- | --- |
| **Winding 1** | 4.891836e-003 - j 1.479600e-002 |
| **Winding 2** | -5.844385e-004 + j 1.333585e-003 |

To improve its efficiency, resonant capacitors are added to the WPT system making it into a RWPT. In the following paragraphs, we shall compute the efficiency of the RWPT and compare it to that of a WPT system.

Figure 10 shows the new simulated circuit modeled using EMS circuit simulator. The resonant frequency is 13.58MHz while the resonant capacitors are respectively 77.26 pF and 114.42 pF computed based on the famous formula:

Fig. 10. Resonant Circuit of Simulated RWPT System Created Using EMS Simulator

The input and output power of the studied RWPT system are computed versus frequency. Both input and output power show peak values at the resonant frequency, as illustrated in Figure 11.

Fig. 11. Input and Output Power Results vs Frequency

Figure 12 shows the efficiency of the RWPT system versus different frequencies. The efficiency is maximum at the resonant frequency. Without resonant capacitors, the efficiency is around 0.17% while it is close to 11% when the resonant capacitors are used. This proves that the resonant circuit helps in improving efficiency, especially for applications with low coupling coefficients.

Fig. 12. Efficiency vs Frequency

The impact of the load and the air gap distance on the efficiency of the RWPT system is investigated in the following section.

Figure 13 contains the efficiency results versus the air gap distance. The efficiency has a maximum value of around 19% in the range of 2 to 7 mm of air gap distance. It drops as the distance between the coils becomes larger, i.e. inversely proportional to the distance. Nonetheless, it is still more efficient than the WPT system, even at 30mm.

Fig. 13. Efficiency vs Air Gap Distance

The load is varied from 1 Ohm to 50 Ohm and the efficiency of the simulated system is computed using the circuit quantities generated by EMS, as shown in Figure 17. The efficiency rises until reaching a maximum of 11% at a load of 10 Ohm then decreases. Therefore, the load must be carefully selected.

**Comparison of EMS Against Powersim [5] results**

In this section, the results computed by EMS are compared to those obtained from and Powersim. The RWPT circuit is modeled in Powersim. Figure 15 shows the equivalent circuit of the system in Powersim. The parameters of the coupled inductor, used to model the wireless coils in Powersim, are given by EMS, as shown in Table 2.

Fig. 15. Equivalent Circuit of RWPT System in Powersim

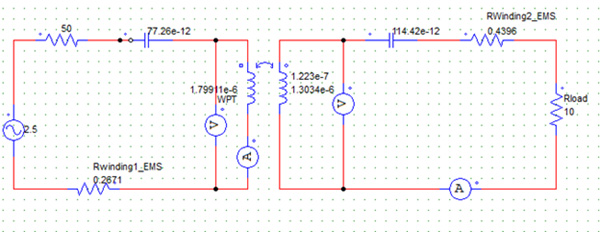


Figure 16 shows the comparison of the computed efficiency calculated via EMS and Powersim. Clearly, the results show a very good agreement; actually matching results.

Fig. 16. Efficiency Results Comparison

The system response as a function of frequency is analyzed using Powersim and the results are plotted in Figure 17. Bode diagram shows that the amplitude output curve has a maximum value of -16dB around the resonant frequency.

Fig. 17. Bode Diagram of the System Extracted from Powersim

1. Cheah WC, Watson SA, Lennox B. Limitations of wireless power transfer technologies for mobile robots. Wireless Power Transfer. 2019;6(2):175-189. doi:10.1017/wpt.2019.8
2. Shadid, Reem (2018) Thesis, UND, Wireless Power Transfer For Biomedical Applications, <https://commons.und.edu/cgi/viewcontent.cgi?article=3344&context=theses>
3. None
4. Samnan Haider et al 2013 IOP Conf. Ser.: Optimization of wireless power transmission for two port and three port inductive link, Mater. Sci. Eng. 53 012026, <https://iopscience.iop.org/article/10.1088/1757-899X/53/1/012026/pdf>
5. <https://powersim.com/>

**Design Challenges of Wireless Power Transfer Technology**

WPT technology poses several significant design challenges related to the charging process, primarily encompassing the following aspects:

The effect of air gap distance on the WPT efficiency

The effect of misalignment on the WPT efficiency

Electromagnetic Interference and Compatibility

The size and weight of the charger

The generated losses and Heat

The effect of the shielding material on the field distribution

Design adaptability and integration to power applications

**Wireless charger for Implantable Pacemaker Application**

The model investigated [2] employs inductive coupling to recharge a pacemaker battery. Illustrated in Figure 2, the simulated setup comprises transmitter and receiver coils, alongside two aluminum plates and ferrite cores. Operating at a low frequency of 20kHz to adhere to EMF standards poses efficiency challenges for WPT. To enhance efficiency, aluminum plates, and ferrite cores are integrated into the design.

Fig. 2. 3D Model of WPT Design used in Pacemaker Application

***Air Gap and Misalignment Effect on Field Distribution***

To evaluate the effect of air gap distance and the misalignment on the magnetic field distribution, a parametric AC Magnetic analysis is used.

The following animation plots show the variation of the magnetic flux density for the different scenarios.

Fig. 3. Animation of the Magnetic Flux vs Airgap

Fig. 4. Animation of the Magnetic Flux vs Lateral Misalignment

Fig. 5. Animation of the Magnetic Flux vs Angular Misalignment

***Air Gap Effect on Coil Parameters (R, L, and K)***

One of the primary challenges is improving the efficiency of the inductive wireless power transfer system which increases with the coupling coefficient of the transmitter-receiver coils. This coefficient depends in turn on the resistance and the inductance of the used coils and it is defined by the following relation:

The following figures show the variation of the coil and coupling parameters versus the air gap distance between the transmitter and receiver sides.

Fig. 6. Self and Mutual Inductances Results versus Air Gap

Fig. 7. AC Resistance Results versus Air Gap

Fig. 8. Coupling Coefficient versus Air Gap

***Shielding Effect on Field Distribution***

Shielding is pivotal in wireless power transfer systems, containing and directing electromagnetic fields. It confines fields to desired regions, optimizing efficiency. Shielding materials concentrate, reflect, or deflect fields, enhancing coupling between transmitter and receiver coils. Simulated scenarios demonstrate shielding's role in improving effectiveness and efficiency, controlling field distribution, and minimizing energy loss. Field distribution in the WPT design reveals metallic shielding's efficacy in confining and concentrating fields between transmitter and receiver coils.

Fig. 9. Magnetic Flux Density Distributions with and without Shielding

1. Air Cored WPT
2. Aluminum Shielded WPT
3. WPT with Ferrite Plates
4. ALuminum Shielded WPT with Ferrite Plates

A second visualization of the field distribution within the human body with and without the shielding is shown in the following plots:

Fig. 10. Magnetic Flux Density Distributions with and without Shielding across the Human Body

**Wireless Power Charger for Electric Vehicle Application**

The second WPT design is a wireless charging system for an electric vehicle made of a double-sided bipolar pad which is presented by two overlapped coils for transmitter and receiver sides made of 5 turns each and operates at the frequency of 85 kHz. The coils are carried by Ferrite support bars and shielded with Aluminum plates.

Fig. 11. 3D Design of Bipolar Pad for WPT EV Charger

The following figure shows the EMS Equivalent circuit used for the LCC Compensation Network presented in [3].

Fig. 12. Equivalent EMS Circuit Schematic for LCC Network

***Shielding Effect on Field Distribution***

The wireless power transfer (WPT) system's frequency significantly influences its efficiency, range, size, and compatibility. Higher frequencies entail higher energy losses and shorter ranges but enable compact designs. Lower frequencies offer longer-range power transfer but demand larger components. Choosing the optimal frequency is crucial to prevent interference and comply with regulations, balancing performance and practicality. Analyzing the operating frequency's impact on efficiency using a parametric AC Magnetic study with circuit coupling yielded the following insights:

Fig. 13: Input and Output Power versus Frequency

Fig. 14. Power Efficiency versus Frequency

The results obtained enabled the determination of the resonant frequency of the investigated WPT design, which operates at 85kHz. This frequency corresponds to a maximum power efficiency of 96%, calculated based on the maximum input and output power values.

The following animation plot shows the vector distribution of magnetic flux lines between the transmitter and receiver WPT sides.

Fig. 15. Vector Plot Animation of the Magnetic Flux Density

***Heat and Loss Analysis***

An investigation of the loss quantities generated within the studied WPT device allowed us to compute and visualize the different loss distributions across the Aluminum shielding, Ferrite bars, and copper coils, as shown below.

Fig. 16. Solid Loss Distribution in the Al Shield

Fig. 17. Core Loss Distribution in the Ferrite Support

Fig. 18: Winding Loss Distribution in the Coils

Lastly, the heat generated is determined by the temperature distribution throughout the entire WPT design, reaching a maximum steady-state temperature of 67°C.

Fig. 19. Temperature Distribution across the WPT System

Fig. 20. Temperature Variation versus Time

1]- <https://eps.fiu.edu/inductive-power-transfer-systems/>

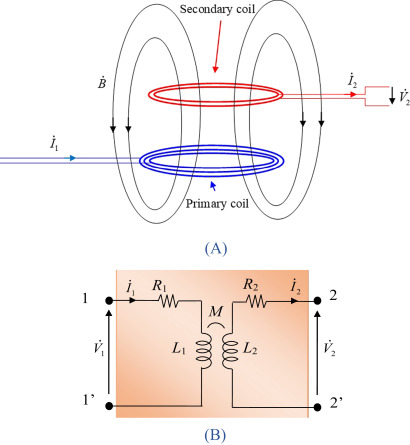
[2]- Wireless power transfer for a pacemaker application, Vladimir Vulfin, Shai Sayfan-Altman & Reuven Ianconescu, Journal of Medical Engineering & Technology

**Wireless Power Transfer**

1. Wireless Power Transfer for E-mobility
2. Inductive WPT
3. Magnetic Field in a WPT System
4. Circuit Models of a WPT System
5. Magnetic couplers for automotive WPT systems
6. Compensation networks of automotive WPT system
7. Power electronics in WPT systems
8. Stationary and dynamic WPT systems for electric vehicles
9. Electromagnetic field safety of automotive WPT systems
10. Electromagnetic compatibility of automotive WPT systems

**1.3.1. Inductive power transfer**

Figure 1.5. Two coupled coils (A) and equivalent circuit (B).



1.3.2. Magnetic resonant coupling

Magnetic resonant coupling (MRC) is an important improvement of the traditional IPT technology to extend the range, i.e., separation distance between the transmitting coil and the receiving coil, and improve electrical performance which are very important features in WPT applications (Kurs et al., 2007; Budhia et al., 2013; Wang et al., 2005; Sibué et al., 2013; Tang et al., 2018; Li et al., 2018; Pinuela et al., 2013; Seo et al., 2016; Dai et al., 2018a; Puccetti et al., 2013; Cruciani, 2014; Campi et al., 2019a; Triviño-Cabrera et al., 2020). The basic idea is to force the system to work under resonant conditions. As a result, the currents flowing in the coils are increased and so is the magnetic coupling (Rim and Mi, 2017; Hui et al., 2014; Wang et al., 2004; Mayordomo et al., 2013; Sohn et al., 2015; Zhang et al., 2017; Budhia, 2011; Budhia et al., 2011; Dai et al., 2018b; Li et al., 2012; Campi, 2017a,b). To meet the resonant condition requirement, compensation networks consisting mainly of capacitors are used to compensate for the inductive reactance of the coils (Li et al., 2015, 2016; Deng et al., 2017; Hao et al., 2014; Choi et al., 2015, 2016; Bertoluzzo et al., 2022; Ibrahim et al., 2015; Pacini et al., 2017). The general scheme of a magnetic resonant WPT is shown in Fig. 1.6. The simplest compensation network includes just one capacitor that can be connected in series (S) or in parallel (P) to the coils. The series-series (SS) compensation is shown in Fig. 1.7. An extensive discussion on compensation topologies is provided in Chapter 7.

Figure 1.6. Equivalent circuit of an MRC system.

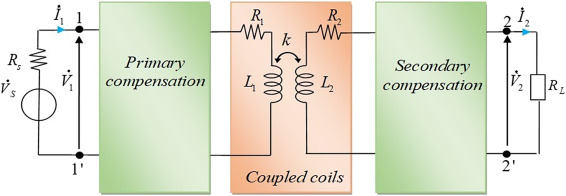
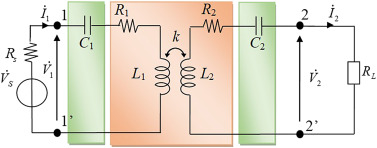


Figure 1.7. Equivalent circuit of an MRC system with SS compensation.

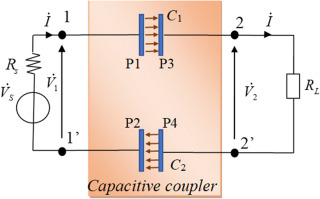


MRC is extremely sensitive to metallic obstacles that may be present between the transmitter and receiver (Mahesh et al., 2021; Triviño et al., 2021).

1.3.3. Capacitive power transfer

WPT technology based on capacitive coupling is known as capacitive power transfer (CPT) and adopts an electric field to achieve power transfer (Wang et al., 2022; Kline et al., 2011; Theodoridis, 2012; Kumar et al., 2015). A general circuit of the CPT system is shown in Fig. 1.8, where two pairs of metal plates are connected in series, forming a capacitive coupler. The capacitive coupler is composed of aluminum or copper plates indicated as P1, P2, P3, and P4.

Figure 1.8. General scheme of a CPT circuit.



When the AC voltage excitation is applied between plates P1 and P2 on the transmitting side, the electric [flux density](https://www.sciencedirect.com/topics/engineering/flux-density) between the electrode plates changes to form a displacement current and achieves a CPT. To increase the values of capacitances C1 and C2 high permittivity [dielectric materials](https://www.sciencedirect.com/topics/materials-science/dielectric-material) are generally used between the capacitor plates ([Wang et al., 2022](https://www.sciencedirect.com/science/article/pii/B9780323995238000047#bib106); [Lu et al., 2017](https://www.sciencedirect.com/science/article/pii/B9780323995238000047#bib71)).

In order to describe the working principle of the capacitive coupler, the mesh current

İ will be obtained as the ratio between the coupler input voltage and the impedance given by the series of C1, C2 and the load resistance RL. Thus, the real power transferred to the load, Pout, is given by:

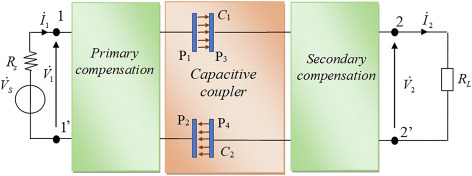
where is the equivalent capacitance. As clearly highlighted in Eq. (1.1) the power transfer capability of the capacitive coupler depends on the operational frequency. At high frequency the full power of the source is transferred to the load as the capacitors behave as short circuits, while at low frequency, the power transferred to the load depends on several electrical parameters. Thus, higher operational frequency is typically preferable.

The major challenge for CPT is the low coupling. This has been partially solved by using compensation circuits, as will be explained in the next section.

1.3.4. Resonant capacitive power transfer

The use of compensation networks in the transmitter and receiver sides according to the scheme shown in Fig. 1.9 allows to reduce the circuit impedance and increase the power transfer efficiency. The simplest compensation network includes just one inductor that can be connected in series or in parallel to the coupler in order to compensate capacitive reactance.

Figure 1.9. Equivalent circuit of a resonant CPT system.

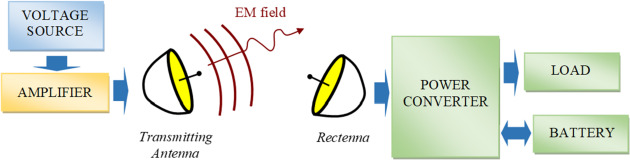


The advantages of this technology are the lower cost of the transmitter and receiver, the reduced impact of metal objects (Lu et al., 2015b, 2017; Xia et al., 2022; Liu et al., 2022, 2023; Vincent et al., 2021; Lian and Qu, 2022), and reduced size compared to IPT systems.

1.3.5. Microwave power transfer

WPT technology based on microwaves is also known as microwave power transfer (MPT) and belongs to the far-field techniques for transmitting power at large distances (Mahesh et al., 2021; Shinohara, 2014). The block diagram of an MPT system is shown in Fig. 1.10. A microwave signal, generated by a magnetron (vacuum-based oscillator) powered by a high voltage DC generator, is sent through one (or more) transmitting antenna. The receiving antenna can be a rectenna made up of both an antenna and a rectifier to convert the received signal in DC to properly charge a battery or power a load. EM fields at radiofrequency are used to transfer power according to the block diagram of Fig. 1.10. This technology permits to transmit energy over a significant distance, with quite good efficiency (Pacini et al., 2017; Costanzo and al, 2014; Monti et al., 2013; Zhu et al., 2021; Passafiume et al., 2022; Microwave Cost Action IC1301 Team, 2017). Several applications of this system have been developed to power or to recharge mobile devices like smartphone, smartwatch, etc. The challenge in MPT is to increase the transmitted power and range while maintaining high levels of EMF safety (Boaventura et al., 2015). RF WPT is similar to MPT.

Figure 1.10. Block diagram of a microwave or radiofrequency power transfer system.

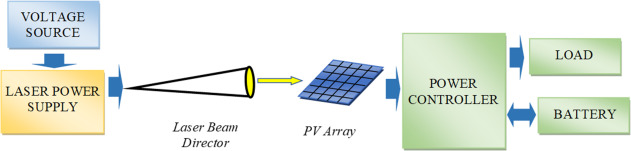


1.3.6. Optical power transfer

WPT technology based on electromagnetic fields at optical frequencies is known as optical power transfer (OPT) or laser power transmission (LPT) (Mahesh et al., 2021; Jin and Zhou,

2018). As the frequency is in the THz range, the EM field is in the form of light. The block diagram of an OPT system is shown in Fig. 1.11. According to this technique, the transmitter consists of a laser diode that generates a light beam of particular power and wavelength. The beam director is used to adjust the laser diode to control the direction of the light beam. The receiving side consists of a photovoltaic (PV) cell and a power controller. The photovoltaic cell converts the received light beam into a power signal which is adjusted by a power controller to properly charge a battery or power a load.

Figure 1.11. Block diagram of an optical power transfer system.



The OPT to be effective requires that the power transmitter and its receiver are in the line of sight and therefore no intermediate obstacles are allowed as the wave cannot pass through them. If this condition is valid, the gap can be up to several kilometers (Passafiume et al., 2022; IEEE Approved Draft Guide for Safety Specification of Laser Transmission in High-Power Industrial Laser System, 2021; He et al., 2021).

1.4. Performance of WPT technologies

Wireless power transfer can be achieved using different technologies operating in the near or far field according to the classification reported in the previous section.

The power to be transferred and the distance between transmitter and receiver are the most important parameters that lead to the choice of the most appropriate WPT technology for a specific application. To this aim, the performance of different WPT technologies in terms of power level, airgap, frequency, and efficiency are summarized in Table 1.1, while strengths and weaknesses for each technology are highlighted in Table 1.2 (Triviño et al., 2021). From Table 1.1 it can be noted that the range for inductive and capacitive WPT is lower with respect to the microwave- and optical-based technologies. The field of validity of the different WPT technologies is also summarized in Fig. 1.12 (Niu et al., 2019). An overview of some WPT applications, different in power and frequency, is schematically shown in Fig. 1.13. Nowadays the MRC technology is the most popular for the wireless charging of EV, due to the high level of efficiency, almost comparable with plugged connection, and for the good tolerance to possible coil misalignment. Furthermore, the problems related to the EMF safety can be controlled by adopting adequate field mitigation techniques.

Table 1.1. Performances of different WPT technologies.

| **WPT Technology** | **Power** | **Range** | **Frequency** | **Efficiency** |
| --- | --- | --- | --- | --- |
| Magnetic resonant coupling | Up to MW | mid | kHz to MHz | Very high |
| Capacitive power transfer | Up to kW | short | MHz | High |
| Microwave power transfer | Up to kW | long | MHz to GHz | Medium |
| Optical WPT | Up to MW | long | >THz | High |

Table 1.2. Advantages and drawbacks of different WPT technologies.

Pros- Numbers; Cons- Alpha

**Resonant Inductive**

1. High efficiency
2. Low EMF safety issues
3. Good misalignment tolerance
4. Medium costs (the cost of the system increases with power)
5. Limited transmission distance

**Resonant capacitive**

1. Low cost
2. Very low EMF safety issues
3. Medium misalignment tolerance
4. Very low transmission distance

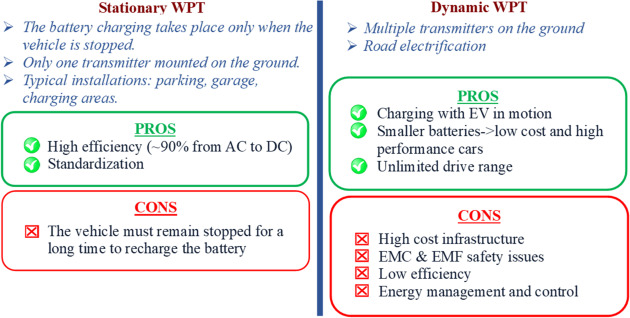
**Microwave**

1. High transmission distance (up to several km)
2. Focused beam
3. Medium efficiency
4. High EMF safety issues
5. Low misalignment tolerance

**Optical**

1. Very high transmission distance (up to several km)
2. Very high safety issues
3. Extremely low misalignment tolerance
4. Low power (in safety conditions)
5. High cost

Figure 1.18. Main features of stationary and dynamic WPT.



Key factors for an effective e-mobility system are:

1. Strategic location of the charging facilities network;
2. Strategic sizing of power supply charging stations with buffers for fast charging and for storing energy from external energy sources;
3. Communication system network;
4. Vehicle-User-Infrastructure;
5. User-friendly vehicle–infrastructure interaction.

Wireless charging of EVs can be essentially achieved by two modes:

1. Stationary or static wireless charging
2. Dynamic wireless charging also called dynamic wireless power transfer (DWPT)

**Chapter 2**

This chapter explains the principles of wireless power transfer system based on magnetic resonant technology. The working principle of inductive coupling is described and resonant architecture is introduced. In particular, the possible compensation techniques to improve the electrical performance of the system are briefly described. Subsequently, the main electronic units necessary for the operation of a WPT system are introduced with the description of the functionality and architecture of each unit. The last paragraph provides an overview of the basic design of the system in terms of possible operating frequency, coil design, and possible EMC and EMF safety problems related to the magnetic field emission of the system.

**2.1. Wireless power transfer**

The idea behind wireless power transfer (WPT) technology is the elimination of galvanic connections such as wires, cables, traces, etc., to power electrical and/or electronic devices. The popular motto of this emerging technology is “cut the cord” (see Fig. 2.1). The simplest configuration of a wireless power transfer system consists of a power transmitter and a power receiver coupled not by a traditional wired connection but by a wireless link (Tesla, 1914), as schematically shown in Fig. 2.2. The coupling path between a transmitter and a receiver is mainly or exclusively in air and therefore can be capacitive (Theodoridis, 2012; Zhang et al., 2019), inductive (Covic and Boys, 2013), or radiative (Popovic, 2013). Capacitive coupling is based on electric field and is described by quasi-static-electric field equations. Inductive coupling is based on magnetic field and is described by quasi-static magnetic field equations. Radiative coupling is based on electromagnetic field and is described by Maxwell's complete equations. WPT based on the capacitive and inductive couplings is often referred to as near-field WPT, while that based on radiative coupling is referred to as far-field WPT. Note that radiative coupling is very popular as it is widely used in radio communications for data transfer and not electrical power transfer!

WPT Power Transmission



The main characteristics of a WPT system are:

1. Amount of power wirelessly delivered to the load (How much power?);
2. Efficiency, which is a very important parameter especially for high power applications or when available electric energy is poor (How efficient?);
3. Maximum separation distance (range) between transmitter and receiver to ensure good power supply to the load (At what distance?).

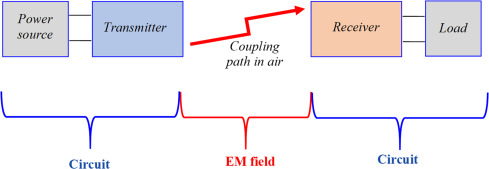
Other important aspects of the electrical/electronic design of a WPT system in terms of safety and sizing are:

1. the voltage and current levels in the transmitter and receiver circuits;
2. the operational frequency;
3. the emission control of electromagnetic fields into the environment that can cause electromagnetic compatibility (EMC)/electromagnetic interference (EMI) or electromagnetic field (EMF) safety issues.

A WPT system includes several components depending on the technology adopted, the power level, the range, the frequency, etc., (Kim et al., 2019, Rim and Mi, 2017, Shinohara, 2018, Triviño-Cabrera et al., 2020). In the most used architecture, the transmitter is connected to a power source and the receiver is connected to the load, as shown schematically in Fig. 2.3. A WPT system can be schematized in two parts:

1. wireless link/coupling path in air described by electromagnetic field equations;
2. electrical/electronic circuitry of transmitter and receiver.

Figure 2.3. Basic architecture and stages of a WPT system.



The design of the first part requires a field approach, while the second requires a circuit approach. The design of a WPT system based on inductive coupling starts with the definition of the magnetic coupler and then deals with the electrical/electronic circuitry of transmitter and receiver.

In automotive WPT applications, the transmitter is usually mounted on the road in a fixed position, while the receiver is mounted on the vehicle and therefore is mobile (Kim et al., 2016; Bi et al., 2016; Shin et al., 2014).

**2.2. Inductive power transfer**

WPT based on inductive coupling is also known as inductive power transfer (IPT). IPT is now a well-established and efficient technology. It is based on Faraday's law of induction as in the electric transformer, with a big difference due to the presence of an airgap which leads to a weak magnetic coupling between the transmitting (primary) coil and the receiving (secondary) coil.

**2.3. Magnetic resonant coupling**

Magnetic resonance coupling is an important improvement of the traditional IPT technology to extend the range, i.e., separation distance, between the transmitting coil and the receiving coil (Kurs et al., 2007; Budhia et al., 2013; Wang et al., 2005; Sibué et al., 2013). The basic idea is to increase the magnetic flux in Faraday's law by increasing the currents flowing in the coils. This is possible by minimizing the impedance of the coils which by their nature have a considerable self-inductance. It should be noted that at the operating frequency the reactance XL = ωL is much greater than the resistance R. In fact, the inductors are generally designed to maximize the quality factor Q defined as (Kiani and Ghovanloo, 2013):

**2.5. Compensation topology**

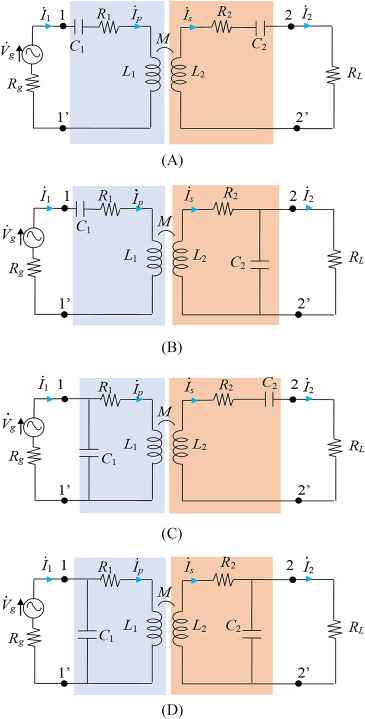
As mentioned above, to get resonance it is necessary to fully compensate the inductive reactance of the coupled inductors (Zhang and Mi, 2016; Wang et al., 2004; Li et al., 2015; Lu et al., 2020; Deng et al., 2014; Li et al., 2016; Li et al., 2016). In the previous sections the SS compensation was discussed, given by the introduction of a series capacitor C1 in the primary circuit and a series capacitor C2 in the secondary circuit. The SS compensation is probably the simplest topology for a WPT system and can lead to very good electrical performance. However, there are other possibilities to achieve resonance condition using different topologies (e.g., a capacitor can be connected in parallel with the inductor). More complex compensation topologies can also be adopted, based on the use of a combination of reactive devices such as inductors and capacitors according to different configurations. Complex compensation schemes will be presented in the Chapter 7. Here, only compensation topologies based on the use of a single capacitive component for the considered circuit are discussed. In this case the circuit presents a single resonance (mono-resonant circuit) when it is excited by a voltage source. It means that there is only one resonant frequency in the considered circuit (primary or secondary) and the resonance can be achieved by using only one capacitor for each side. The capacitor can be connected in series or in parallel with the inductor.

The compensation scheme based on the use of two capacitors (one in the primary and one in the secondary) is the simplest topology to separately compensate the inductive reactance of the two coils. It is extremely convenient in terms of manufacturing cost, complexity, size, and weight (Cho et al., 2013; Zhang et al., 2014).

Four basic mono-resonant compensation topologies are available as shown in Fig. 2.8 (Wang et al., 2004):

1. series-series (SS);
2. series-parallel (SP);
3. parallel-series (PS);
4. parallel-parallel (PP).

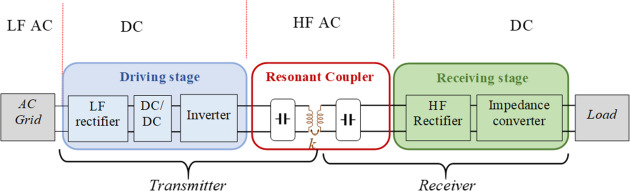
Figure 2.8. Compensation topologies: (A) series-series, (B) series-parallel, (C) parallel-series, and (D) parallel-parallel.



The driving stage is designed to deliver high power at high frequency to the input port of the resonant couplers. It is generally composed by several components cascaded in series as shown in Fig. 2.10:

1. AC/DC converter (low frequency rectifier—LF rectifier) which rectifies the AC sinusoidal wave of the AC power supply at low frequency (power frequency at 50/60Hz);
2. DC/DC converter which changes the voltage level of the DC power;
3. DC/AC converter (inverter) which produces the high frequency power at the operational frequency to the input port of the compensated primary inductor.

Figure 2.10. Block diagram of a WPT system with detailed description of the driving and receiving stages.



The receiving stage is generally composed by several blocks cascaded in series:

1. AC/DC converter (high frequency rectifier—HF rectifier) which rectifies the high frequency power coming from the output port of the coupled inductors;
2. impedance converter which is a DC/DC regulator adopted to match the load with the system.

The described architecture is designed for a power supply at power frequency and for a load in DC. However, it can be easily adapted for other kind of power supply and loads, e.g., DC power supply and/or loads that require AC feeding (Musavi and Eberle, 2014).

In the following, the descriptions of the most important converters used in WPT applications are summarized. More details on power electronic converters can be found in Chapter 8.

**2.6.4. Power regulation**

A very important aspect of a generic charging system is the management and regulation of the power supply. A battery is known to require careful charging. For example, a lithium battery, which is the most widespread today, requires an initial charge phase at constant current and a final charge phase at constant voltage. Furthermore, the system must adapt the power delivered to the battery to variations in geometric conditions such as the misalignment of the coils. To ensure an accurate control of the output power it is therefore necessary to introduce a control system that allows the fine regulation of the system parameters.

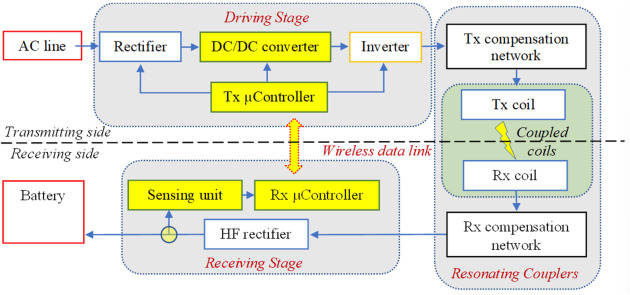
Three configurations can be adopted to create a power regulation system:

1. Regulation on the transmitting side;
2. Regulation on the receiving side;
3. Regulation on both transmitting and receiving side.

In transmitting side regulation, the main concept is to adjust the input power on the WPT transmitter in order to regulate the output power (Miller et al., 2015). The power regulation is based on a feedback from the receiver unit (through a wireless communication channel, e.g., Bluetooth) as shown in Fig. 2.14, or an estimation of the delivered output from the transmitting side parameters. The information of the output power, voltage, and current is used to regulate the input parameters of the system, in order to achieve the output target power. The primary side regulation can be mainly performed in two ways:

1. Adjusting the operational frequency;
2. Adjusting the input voltage.

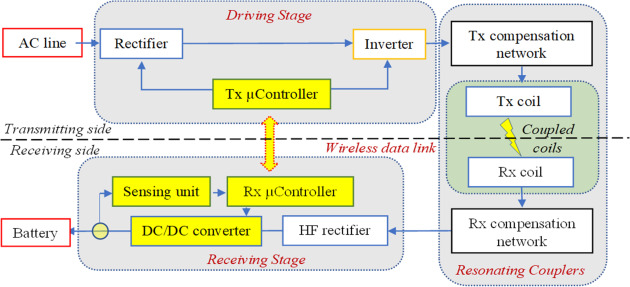
Figure 2.14. Power regulation on transmitting side.



A microcontroller is used to implement a control algorithm that varies the duty cycle of the converter or the frequency of the inverter, to obtain the target output power/voltage.

The power regulation on the receiving side is based on the application of a control voltage unit (DC/DC) on the receiving side of the WPT system. The converter is placed between the high frequency rectifier and the load as shown in Fig. 2.15. The main advantage of this architecture is the simplicity of the system, since it is not necessary any communication between the transmitting control unit and the receiving control unit. However, the variation of the voltage level on the output side leads to a variation of the input resistance seen by the transmitter.

Figure 2.15. Power regulation on receiving side.



Finally, with the combination of power regulations on the transmitter and receiver side, it is possible to have total control of the system, but there will be an increase in losses due to the presence of two converters. These techniques are discussed in detail in Chapter 7.

**2.7. Basic WPT design**

**2.7.1. System specifications**

The design procedure for a WPT system starts from specifications. There are two categories of specifications: electrical and geometric. The main electrical specifications include:

1. power level;
2. Efficiency;
3. range (distance across an air gap).

Other important electrical specifications are:

1. voltage levels on primary and secondary coils and ports;
2. current levels on primary and secondary coils and ports.

The main nonelectrical specifications are:

1. Size;
2. Weight;
3. mechanical robustness.

Beside electrical and geometrical specifications, a key aspect is the system cost.

**2.7.2. Operational frequency**

Operational frequency is a key aspect in the design of a WPT system since ω0 appears in Q1 and Q2 via Eq. (2.19) and in the figure of merit (FOM), defined as FOM = k2Q1Q2. Ideally to increase the FOM, the frequency should be increased. However, an increase of frequency leads to an increase of losses for commutation and conduction in electronic circuits of transmitter and receiver, but also in coupled inductors and compensation circuits due to parasitic elements and skin effect. Therefore, the selection of the frequency range suitable for WPT operations depends on the cost-benefit ratio.

Furthermore, the use of the frequency spectrum is not free, as it is regulated by national and international plans. Although the standardization process of WPT applications in automotive is not completed, at the moment the admissible frequencies are in the low frequency range or in the ISM (industrial, scientific, and medical) bands which are reserved internationally for ISM purposes, excluding applications in telecommunications.

The frequencies used by some bodies or alliances are:

1. SAE: 79–90 kHz for light-duty vehicles in automotive applications (SAE International, 2017);
2. Qi: 110–205 kHz;
3. AirFuel: 277–377 kHz.

The central frequencies of ISM bands for frequencies up to 6 GHz are:

1. 6.78 MHz;
2. 13.56 MHz;
3. 27.12 MHz
4. 40.68 MHz
5. 433.92 MHz
6. 915 MHz
7. 2.450 GHz
8. 5.800 GHz

**2.7.3. Coil design**

As previously described, at least a magnetic coupler is required to transfer electric power wirelessly using the inductive-based WPT technology. To get good performance, it is important to have a high coupling factor k and a high quality factor Q. The challenge is therefore the design of coils with high k and Q, but with low costs, dimensions, and weight (Mohamed et al., 2018).

Although coils can take on different shapes with different sizes, those for stationary WPT automotive applications with small gap are generally planar. The most popular geometries are circular, rectangular, DD, DDQ, and bipolar DD (Guangjie et al., 2016). Each of these geometries presents pros and cons.

The coil wire is generally made of copper. Typically litz wires are used. They are composed of many thin wire conductive strands, individually insulated and twisted, to reduce AC power losses, i.e., skin and proximity effects (Umetani et al., 2021).

To enhance the WPT performance, k and Q must be maximized and this is generally achieved by maximizing inductances and minimizing losses. It is therefore of paramount importance to reduce as much as possible the leaked magnetic flux in air and the power losses in conductive materials. To confine the magnetic field and to avoid magnetic flux leakage the use of magnetic materials such as ferrite is highly recommended (Campi et al., 2014). Ferrite has a high permeability and low losses at the frequencies of interest for automotive WPT, and therefore its use is very popular. However, ferrite is very expensive, fragile, and very heavy, so the optimal configuration of ferrite (blocks and/or layers) is a challenging issue in coil design. A good design of the ferrite configuration allows to guide the magnetic flux and to divert it in a suitable way in order to avoid eddy currents in metallic regions near the coils, such as, for example, the vehicle body (Budhia et al., 2009; 2011). Hence the right use of ferrite can limit magnetic flux leakage and eddy current power loss. In the equivalent circuit it leads to an increase of the inductance values and to a decrease of the resistance values, improving k and Q values.

Finally, the magnetic field generated by the currents in the coils must not produce eddy currents in the vehicle body and must not disturb the electrical and electronic devices of the road and vehicle systems (Kim et al., 2013; Cruciani et al., 2019; Campi et al., 2017a; Campi et al., 2020; Mohammad et al., 2019). Therefore, high conductivity shields, typically in aluminum, are used to prevent the magnetic field from producing undesirable effects in the environment. The use of aluminum shields can mitigate the magnetic field impinging on passengers and pedestrians (Campi et al., 2019).

The planar copper coil, the ferrite, and the aluminum layer form a pad. A detailed description of these devices is reported in Chapter 6.

**2.7.4. EMC/EMI and EMF safety**

The choice of operating frequency has a strong impact on EMC/EMI and EMF safety (Laakso et al., 2012; Christ et al., 2013; Chakarothai et al., 2018). EMC is the ability of electrical equipment and systems to correctly operate in the electromagnetic environment. EMC is not only important for functional performance; legal requirements must also be met for the commercialization of systems (Asa et al., 2020). The critical EMC issues are related to conducted and radiated emission from power electronic circuits and coils, produced not only by the fundamental frequency but also by high order harmonics in the circuits that produce conducted and radiated emissions (Pichon, 2020). These problems generally increase as the frequency increases. Therefore it is often necessary to limit the frequency although the magnetic coupling improves with frequency (Kim et al., 2014).

A very critical aspect of the high power WPT system is related to EMF safety (Campi et al., 2017b,c). One of the most significant problems in the application of WPT inductive systems is the large emission of the time-varying magnetic field into the surrounding environment, especially at the fundamental frequency. It is well established that high intensity AC magnetic fields can produce biological effects in living beings. Currently, only short-term effects on human health are known, but there is also concern about possible long-term effects. Emissions of magnetic fields are limited by national and international standards and guidelines to protect the human exposure to electromagnetic fields. The most popular regulations are the IEEE C.95 standards and the ICNIRP guidelines for protection against short-term effects (International Commission on Non-Ionizing Radiation Protection, 1998; 2010, 2020; IEEE, 2019). They have set limits for exposure to magnetic fields at different frequencies and periodically these limits are revised by monitoring the state-of-the-art in this topic. The ICNIRP limits are given in terms of external fields (reference levels) and internal quantities (basic restrictions). If the reference levels are exceeded, then a dosimetry analysis must be carried out to assess the compliance with the basic restrictions. In WPT automotive applications the main problem is due to the magnetic field produced by the coil currents at the fundamental (operational) frequency that can produce internal electric fields in the human body. The EMF limits can be easily exceeded in the area between the transmitting and receiving coils where the magnetic field is maximum, therefore areas restricted to humans can be often defined. The magnetic field strength can exceed limits also in other areas near the WPT coils beside the vehicle body due to a significant magnetic flux leakage. Magnetic field reduction (based, for example, on the correct EMC design of WPT coils or the use of mitigation techniques such as passive and active shields) is another key aspect to solve for the successful deployment of WPT technologies (Moon et al., 2015; Buccella et al., 2002).

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