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Wireless Power Transfer Technologies Applied to Electric Vehicles: A Review

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Abstract: The expansion on the use of Electric Vehicles demands new mechanisms to ease the charging process, making it autonomous and with a reduced user intervention. This paper reviews the technologies applied to the wireless charge of Electric Vehicles. In particular, it focuses on the technologies based on the induction principle, the capacitive-based techniques, those that use radiofrequency waves and the laser powering. As described, the convenience of each technique depends on the requirements imposed on the wireless power transfer. Specifically, we can state that the power level, the distance between the power source and the electric vehicle or whether the transfer is executed with the vehicle on the move or not or the cost are critical parameters that need to be taken into account to decide which technology to use. In addition, each technique requires some complementary electronics. This paper reviews the main components that are incorporated into these systems and it provides a review of their most relevant configurations.

Keywords: wireless power transfer; electric vehicle; inductive; capacitive; laser; optical; dynamic; stationary; charge

1. Introduction

Electric Vehicles (EVs) represent a sustainable mode of transportation, which will help reduce greenhouse gas emissions. This statement is supported by some reported data. The United States Environmental Protection Agency informed that nearly 28% of the greenhouse gas emissions in this country in 2018 were produced from the transportation sector [1]. In particular, if we study which type of vehicle contributed more to this pollution, we observe that 69% of these gases were caused by light-duty vehicles whereas 23% was related to medium and heavy-duty trucks. A similar conclusion can be derived when studying the data about Europe for the same year where 25% of the greenhouse gases were due to the transport sector [2].

In addition, EVs are expected to become a relevant actor in the Smart Grids. It is expected that a group of vehicles will behave as mobile batteries with a low response time when activated or deactivated. They can compensate the intermittency of the renewable energy sources [3]. For this purpose, the batteries can be generators or they can also act as controllable loads in the Vehicle-to-Grid (V2G) context [4].

Even if EVs will help to the integration of renewable energy sources and to reduce the greenhouse emissions, driver still tend to acquire fuel-based vehicles as they fear that the autonomy of EVs is not sufficient to guarantee a drive without problems. This shortcoming has been identified for electric cars [5] or even for other low-power vehicles [6]. One of the reasons for this belief is the charging time. Table 1 summarizes the charging modes defined in the International Standard IEC 61851-1 [7]. Mode 1 charging is the most popular solution for domestic appliances due to its power requirements and reduced cost.

The charging process is limited by the batteries' physical constraints, such as the maximum charging current, power and voltage [8]. To comply with these restrictions and avoid damaging the battery, charging is usually carried out following a Constant

Current (CC)/Constant Voltage (CV) strategy [9], which guarantees that both the voltage and the current do not exceed the maximum values recommended by the manufacturer in a two-phase process. In addition, the C-rate and the Depth-of-Discharge (DoD) of the charge directly affect the lifetime of the battery [10], so it is not advisable to use the fast charge regularly.

Table 1. Charging modes according to IEC 61851-1 [7].

Charging Mode	Charging Type	Maximum Current	Maximum Power	Charging Time for 50 kWh	Kilometers from a 15 min Charge [1]
Mode 1	Slow	16 A, AC, Single-Phase	3.7 kW	14 h	5 km
Mode 2	Fast	32 A, AC, Single-Phase	7.4 kW	7 h	9 km
		32 A, AC, Three-Phase	22 kW	>2 h	27 km
Mode 3	Rapid	62 A, AC, Three-Phase	43 kW	>1 h	54 km
Mode 4	Ultra-Rapid	400 A, DC	200 kW	15 min [2]	250 km [2]

[1] Using an average consumption of 0.20 kWh/km. [2] Batteries cannot be fully charged at maximum power.

Moreover, DC chargers are only available in specific locations presently for safety concerns. The high charging time of most popular wired chargers and the care of batteries prompt the need for developing other charger types or other mechanisms, which could also ease user interaction with the grid. Wireless Power Transfer (WPT) outstands as an alternative technology to improve the user perception about the charging process of the EVs [11]. Although DC charging are still a quicker option, we can already find some 11-kW wireless chargers commercially available, which could provide a convenient charging time too. The advantages provided by this technology are multiples, being the following features the most relevant ones.

- Automatic operation without driver intervention. The process can be scheduled, and it can happen even without the presence of the vehicle owner. This feature reveals itself as convenient to promote the participation of the EVs in the V2G operations. Some software appliances can be designed and implemented to program the charges and set the user preferences.

- Safer charge. In case of electric cars, conductive charge is supported by cables carrying high electrical current. This could become a serious risk, especially when adverse weather conditions take place. As this conductor is avoided by wireless chargers, this type of charger becomes safer from the driver's point of view. As a counterpart, magnetic or electric fields involved in the wireless power transfer must be restricted to the controlled levels to guarantee that they are not harmful.

- Dynamic or on-the-move charge. As the power source and the receiver are not physically connected, the EVs can be charged in more situations if they use wireless chargers. Thus, the use of wireless chargers extends the possibility of performing a static charge (when the EV is parked) to scenarios where the car is temporally stopped (e.g., waiting for a traffic light) or on the move. If this kind of charge are available in more road sectors, this will imply that the battery of the EVs can be charged more frequently while moving and it could be smaller and cheaper.

These advantages are significant for all types of EVs. As a consequence, we can find implementation of wireless chargers in cars [12], bicycles [13], buses, trains [14], boats [15], scooters, wheelchairs [16] and Unmanned Aerial Vehicles (UAV). Some of these implementations are commercially available but others are mere proofs of concept.

Currently, there are different technologies associated with the WPT. When deciding about which WPT technology to employ and how to adapt it to the system, the following criteria should be considered:

- Transferred power. WPT technology can be used to transmit up to 1 kW for light-duty vehicles, to transfer 1–100 kW for medium power EV or even to send more than 100 kW for high-power EVs. For very-low-power requirements, the system may directly power the vehicle instead of recharging the battery. In addition to this tendency, the power level impacts on two main issues. First, the devices on the power electronics need to support the switching frequency and the demanded power levels. Second, the power levels involved in the transfer usually sets the criterion to follow in the design. In this sense, the maximum power transfer theorem is applied for low-power applications whereas the efficiency is more relevant for high power levels.
- V2X-enabled power transfer, i.e., the compliance or not with the Vehicle-to-Everything (V2X) context. By this criterion, we define the sense of the power flow leading to unidirectional or bi-directional chargers. The traditional chargers have a power transfer with a unique sense from a power system to the battery but it is also possible to discharge the EVs to support the grid, another vehicle or device. In this last case, the power electronics must be designed to be bi-directional.
- Gap, i.e., the distance separating the power source and the receiver. In EV wireless chargers, we can find a wide range for the gap. In [17], the receiver is installed in the kickstand of a bicycle and the transmitter is on the pavement. Both power extremes are in contact with 0 cm as the gap. For electric cars, SAE establishes the term coil ground clearance as the gap. In particular, the organization defines three types of classes according to this parameter: Z1-class (100 mm < gap < 150 mm), Z2-class (140 mm < gap < 210 mm) and Z3-class (170 mm < gap < 250 mm). For aerospace applications, the gap can reach up to several meters [18].
- Capability to work with misalignment. During the design of a charger, the transmitter and the receiver are assumed to be in a predefined position. However, the conventional use of the charger may be in situations where the transmitter and/or the receiver are not in those expected placed. As a result, both extremes are misaligned. Some WPT technologies are still able to work with misalignment. However, other technologies need to reconfigure the transmitter to modify the power beam so it is adjusted to the current position of the receiver.
- Potential existence of intermediate objects. The WPT technologies operate with different ranges of wavelengths. This makes them capable or not to transmit the power when intermediate objects are in the gap. Safety issues may arise when this eventuality takes place.
- Stationary/Mobile receiver, if we set the requirement that the WPT system should be able to transfer power when the receiver is in an unspecific position before or during the charging process. This feature is especially relevant for on-the-move charge.

WPT refers to a set of technologies [11], which comprises magnetic resonant chargers, capacitive-based WPT, laser beam powering or microwave-based chargers. So far, wireless chargers based on resonant transmission have reached a commercial status for static EVs [19]. Several prototypes have also been implemented and tested for dynamic charge and they are supported by magnetic resonant transmission. Capacitive power transfer has been extensively studied for its potential application in EVs. So far, the power levels and gap of capacitive WPT experiments are lower in comparison with the potentials of magnetic resonant chargers [20]. However, this tendency may change as recent works defend the fact that capacitive charging is more convenient for charge on the move. There are also other implementations based on microwave power transmissions, for electric cars but they are not a commercial product [21]. Optical power transfer is revealing as an appealing technology to powering drones, but the efficiency and the power levels are still low.

This paper presents an overview about how WPT technology is applied in the EV sector considering different vehicles and power transfer techniques. It also includes the

description of some prototypes or experiments, which have demonstrated the feasibility of these techniques. From the analysis of the already implemented systems, we conclude some limitations that the technology has for a fully convenient application in the EV context.

The rest of the paper is structured as follows. Section 2 overviews the EV conditions on which the WPT can happen. Section 3 deeply describes the application of the most relevant WPT techniques to the charge/discharge of EVs. Section 4 addresses the analytical comparison among the technologies to offer a convenient operation for EVs. Finally, Section 5 describes the main conclusions of this work and outlines some future trends.

2. Charging Operation Modes: Static, Stationary and Dynamic

Wireless chargers avoid the restriction of being connected to a cable increasing the EV charging mode options. Due to the flexibility that wireless charging offers, the EV charging process can also take place at temporal stops or even while driving, and thus, allowing reduced energy capacity for the batteries.

It can be identified three wireless charging operation modes: static, stationary or quasi-dynamic and dynamic. They are represented in Figure 1.
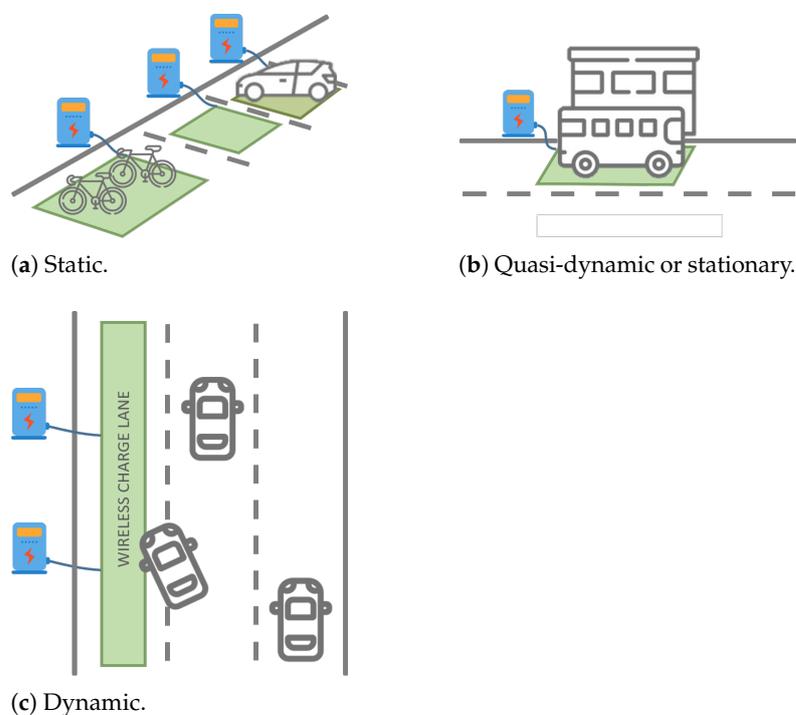

(**a**) Static.

(**b**) Quasi-dynamic or stationary.

(**c**) Dynamic.

Figure 1. WPT operation modes.

Static WPT takes place when the EV is at parking position and engine is off to proceed to full charge. This is the usual charging mode at public parking or homes. Some complex functions can be incorporated to these chargers in order to minimize coil misalignments. Taking into account charging infrastructure and time, static WPT is similar to conventional conductive charging [22,23].

On the other hand, dynamic and stationary (or quasi-dynamic) wireless charging operation modes enable EVs to be charged while in transit. This new paradigm poses technical design and operational challenges that were not present for classical conductive charging.

Stationary WPT charge occurs with the following two particularities (i) the vehicle is stationary, but the engine is still running and (ii) this situation holds over a short period of time that is not sufficient to reach a full charge. This type of charge is useful for public transport vehicles to charge when stopping at passenger stops. This was one of the charging operation modes of the Victoria project in city of Málaga (Spain) in 2018 [24]. Without

affecting the bus service at stops, the battery can be charged. For private vehicles and at traffic lights stops, the stationary charge can also take place.

The most challenging operation mode is the dynamic mode, which allows an EV to charge wirelessly as it is driving along the road. In this case, certain sections of the road are equipped with WPT transmitters and power electronic equipment to enable WPT for EVs. This type of charging promotes the roadway powered electric vehicles [25]. Although the cost of the infrastructure is high, its benefits of this infrastructure are expected to be notable due to the low number of chargers available in highways [26].

There are several cities where dynamic charging has already been tested. For instance, in some cities in South Korea under the OLEV project) [27], in Malaga (Spain) in the Victoria project [24] or in the city of Douai in France with the FastinCharge project [28]. In Torino (Italy), Conductix-Wampfler has implemented a prototype to charge a bus when stopping and at the end of the bus route with magnetic resonant technology [29].

The Unplugged project [30] whose objective is to design and develop inductive chargers for EVs in urban environments improves comfort and sustainability of car-based mobility. Another relevant project on dynamic charge is The Fabric Project [31]. It was completed in June 2018 and it performed a comparison among different modes of electromobility, including wireless and uninterrupted charging of electric vehicles on the go. This comparison has been carried out on urban, interurban (metropolitan) roads and highways. Alternatively, the Smartroad Gotland project [32] connects the municipality and Visby airport on the island of Gotland (Sweden). It has developed a reserved test section for electric bus with continuous service (shuttle service) of 1.6 km of the total of 4.1 km of the road axis.

In a similar way to conductive chargers, wireless chargers can be implemented in such a way that they allow bi-directional power flows. V2G wireless chargers are being of interest for the research community in recent years. We can find some studies addressing the V2G procedures even for dynamic charge [33].

3. WPT Technologies

Wireless power transfer encompasses a group of technologies. As we will study next, their application differs for each one.

3.1. Magnetic Resonant WPT

The most mature technology for WPT in EVs is based on the induction principle with a pair of air-core coils. As defined by Ampère's Law, when the transmitter coil (also referred to as the primary coil) is powered with a time-varying current, it generates a dynamic magnetic field around this structure. If a receiver or secondary coil is able to concatenate some of the flux, a induced voltage is observed . Since the secondary coil is electrically connected to the EV battery, the current on the primary coil is able to induce some voltage on the secondary coil and, in turn, to transfer power to the battery. An illustrative coupler for EV applications is shown in Figure 2. This corresponds to the coupler used by the authors in their prototypes.

Figure 2. Illustrative implementation of two coils for a magnetic resonant WPT.

As stated by Faraday's Law, the amount of the power transferred is due to the capacity of the secondary coil to concatenate as much magnetic flux as possible. The magnetic field involved in these systems are related to the primary current and the relative position between the transmitter and the receiver coil [34]. In EV wireless chargers, two main strategies are mainly applied to maximize the magnetic flux traversing the secondary coil: (i) advanced coil design and (ii) inclusion of compensation networks. Power converters and their control system are also relevant in these chargers, as illustrated in the generic diagram of Figure 3.
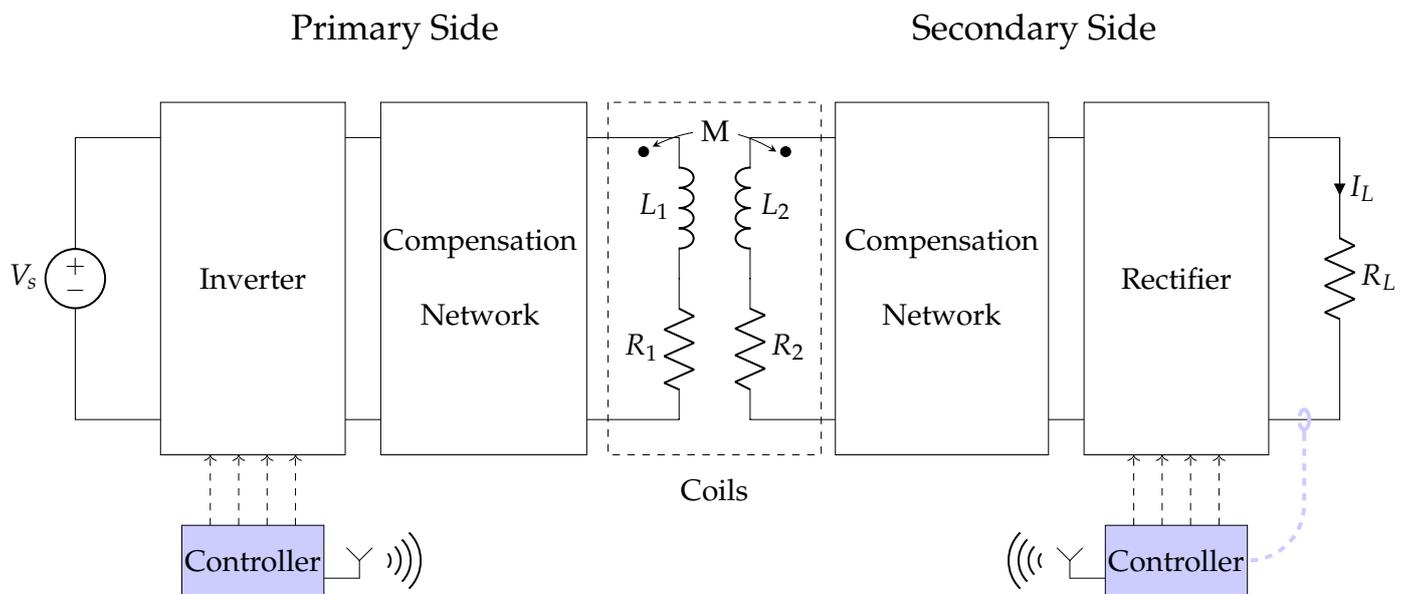

Figure 3. Generic structure of an EV wireless charger.

As for the coil design, the simplest structures are the circular and the rectangular/square ones. Their simplicity can be a plus for low-cost applications. However, some other vehicles require that their charge is not degraded with misalignment, and the use of this type of coil may not fulfill this requirement. This need has prompted the use of alternative coil topologies in the context of electric cars. Double-D or DD coils are composed of two equal D-shaped (rectangular) subcoils with a shared side. They are electrically connected in parallel but wound in such a way that they concatenate the magnetic field as if they were in series. Basing on the DD coils, the DD quadrature or DDQ is implemented. It has two independent windings: one is a DD pair of coils and another is the quadrature or quad (Q) coil. The Q-coil is placed over half of the area of each D coil. Ferromagnetic and conductive materials are included to prevent coupling between the DD and the Q coils. Bipolar coils are similar to DD coils but one of the coils overlaps half of the area of the D-shape coil. Among these three topologies, it is said that DDQ coils are the ones that can concatenate more magnetic flux. Bipolar coils represent an intermediate solution and DD coils can concatenate less magnetic field than the other two [35]. To confine the magnetic field in the area of interest, advanced coils are usually equipped with ferrite plates which set a preferential path for the magnetic field [36]. In addition, shielding may be used to prevent the magnetic field to traverse determined zones. For instance, they could be placed underneath the transmitting coil so that the magnetic field will not circulate in this unproductive area. Using ferrite and shielding will increase the efficiency of the system and it will help to comply with the safety restrictions imposed in this kind of system.

The previous coil topologies are more convenient for static applications. The approach for dynamic charging alters the structure of the transmitter coils. In particular, we can find a series of coils with a dimension similar to the pickup coil. This structure is usually called lumped or segmented. It is also possible to a rail-based solution with stretched transmitter coils, in which the longitudinal dimension is much larger than the one of the

receiver coil. In this category, we can find the E-type, U-type, W-type, I-type or S-type coils. The first letter on this term refers to the resulting geometry once the ferromagnetic material is included in the stretched coil. In comparison with the lumped structure, the rail-based solution presents some advantages, such as higher losses, lower efficiency and higher installation and maintenance costs [37].

When efficiency is a goal, the material of the coils must be carefully selected for the operational frequency. If the cost is feasible, Litz wire can be used as it minimizes the losses due to eddy currents [38].

Inductive WPT applied to EVs are usually resonant systems. In resonant WPT, the electrical system is designed to work under at resonance so that reactive networks (referred to as the compensation networks) are incorporated on the primary and the secondary sides. Mono-resonant topologies are composed of only one capacitor. One capacitor is connected to the primary coil and another to the secondary coil. The connection can be series or parallel. When referring to them, the connection with the primary coil is first specified and then the connection to the secondary coil so that the configurations are: Series-Series, Series-Parallel, Parallel-Series or Parallel-Parallel compensation networks. Figure 4 shows the schematics for these connections. Table 2 specifies the value for these capacitors (C_1 on the primary side and C_2 on the secondary side). It also includes the efficiency that can be achieved taking into account the resistances of the coils (R_1 and R_2 for the primary and secondary coils) and the equivalent resistance of the load R_L. The efficiencies of the SP and PP topologies are affected by the mutual inductance M, which also depends on the coil misalignment. Due to their simplicity, they are easy to control and implement. However, they do not provide a high performance when they coils are misaligned. Multi-resonant compensation topologies, which contain more than one reactive component, are more adequate under these circumstances. In addition to improving system efficiency against misalignment, multi-resonant topologies offer other additional benefits, such as reduced bifurcation phenomenon [39], improved stability and efficiency with dynamic charging [40] or using a single primary coil to charge multiple vehicles [41] and feasibility of bi-directional systems[42].

The most popular multi-resonant structures for EV wireless chargers are the LCL and the LCC topologies. The schematics are illustrated in Figure 5.
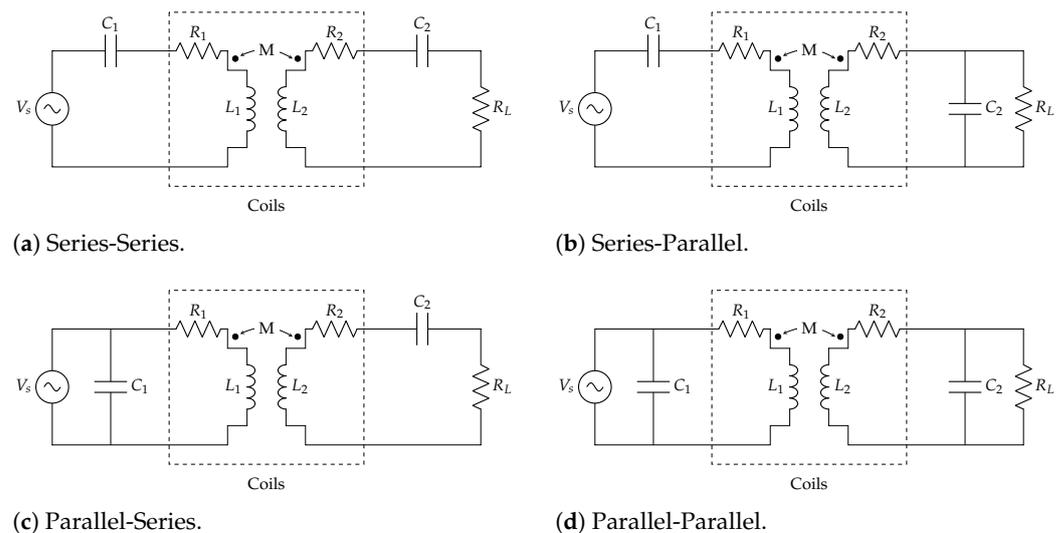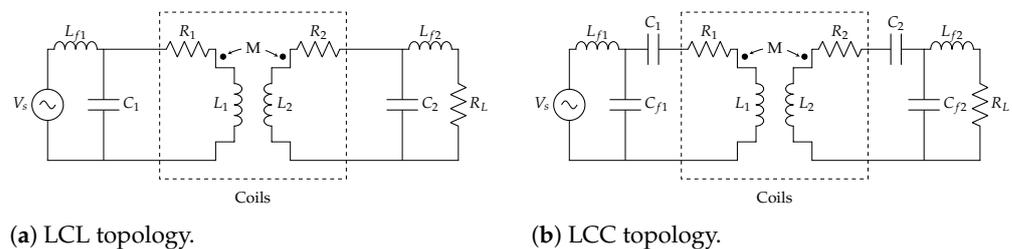

(**a**) Series-Series.

(**b**) Series-Parallel.

(**c**) Parallel-Series.

(**d**) Parallel-Parallel.

Figure 4. Mono-resonant compensation topologies.

Table 2. Capacitor values and AC efficiency for mono-resonant compensation topologies [43].

Topology	C_1	C_2	Efficiency
SS	$\dfrac{1}{L_1\omega}$	$\dfrac{1}{L_2\omega}$	$\eta \cong \dfrac{R_L}{R_2+R_L}$
SP	$\dfrac{L_2^2 C_2}{L_1 L_2 - M^2}$	$\dfrac{1}{L_2\omega}$	$\eta \cong \dfrac{R_L}{R_2+R_L+\frac{R_1 L_2^2}{M^2}}$
PS	$\dfrac{L_2 C_2}{L_1 + \frac{M^4}{L_1 L_2 C_2 R_L^2}}$	$\dfrac{1}{L_2\omega}$	$\eta \cong \dfrac{R_L}{R_2+R_L}$
PP	$\dfrac{\left(L_1 L_2 - M^2\right) L_2^2 C_2}{\frac{M^4 R_L^2 C_2}{L_2^2}\left(L_1 L_2 - M^2\right)^2}$	$\dfrac{1}{L_2\omega}$	$\eta \cong \dfrac{R_L}{R_2+R_L+\frac{R_1 L_2^2}{M^2}}$

(**a**) LCL topology.　　　　　　　　　　　　　　(**b**) LCC topology.

Figure 5. Multi-resonant compensation topologies.

A third issue related to magnetic resonant WPT is the power electronics. To concatenate more variation of the magnetic flux, inductive power transfer usually relies on high-frequency signals. The generation and process of these signals are done by the power converters. The devices in these converters must be selected according to the power they have to support and the switching frequency. International standards regulate the nominal operation frequency at 85 kHz [44]. Traditional Si IGBTs are not suitable to deal with this frequency and high power, so Silicon Carbide (SiC) MOSFETs are recommended instead. Despite their higher cost, they present lower on-state resistance in comparison with Si IGBTs [45], which allows higher switching frequencies and a reduction of losses and cooling requirements.

The typical diagram of a resonant wireless charger is depicted in Figure 3. The inverter converts the direct current to high-frequency alternating current. This conversion is usually performed using a full-bridge inverter [46–49], although some authors suggest other topologies such as single-ended converters [50] or multi-phase systems [51,52]. If the charger is designed to be bi-directional, the power converters must be designed to be bi-directional too. Other diagrams also opt for including a DC/DC converter on the secondary side [53,54].

Associated with the power electronics, these chargers include the control system. This system is in charge of switching the power devices according to different criteria. We can find some proposals in which the control adjusts the operational frequency, others in which they tune the reflected load or even some that act on the frequency and on the compensation networks at the same time [55]. The control strategy used has a direct effect on the selection of the charger topology, since depending on the actuation point, specific converters may be required. In systems controlled on the primary side, the control acts on the inverter of the charger, which can be regulated by adjusting the phase-shifting and the frequency. Chargers that use this topology reduce the number of components installed in the vehicle since the secondary power electronics are simpler, but they require a system that communicates both sides of the charger. On the other hand, chargers controlled on the secondary side do not have this need for communication, but they require a greater number of components in the vehicle, such as a controlled rectifier or a DC/DC converter. This entails an increased weight. It is also possible to find chargers controlled from both sides of the charger, in which all the power electronics work in coordination with the aim of

achieving maximum efficiency [53]. Furthermore, this configuration allows bi-directional operation if the power electronics allow the power flow in both senses.

The efficiency of resonant wireless chargers is due to the efficiency of the power converters, the compensation networks and the coils. They will be highly affected by the coil misalignment. A deep study about the efficiency of resonant wireless chargers can be found in [56].

Today, there are commercial wireless chargers based on magnetic resonant technology. ORNL, Witricity, Qualcomm or Efacec are providers of this product [57]. These chargers are oriented to static charge. ORNL has been able to build a 120-kW charger with a 97% efficiency. Witricy states that their wireless chargers can provide up to 11 kW with a 90–93% of efficiency. Qualcomm defines for their wireless an efficiency level over 97% across the airgap and over 90% from primary DC to battery DC [58], although their technology was acquired by Witricity in 2019. Efacec presents similar efficiency than Qualcomm technology. SAE J2954 is the standard for inductive wireless chargers applied to light-duty vehicle [44]. This standard imposes some limitations on the dimensions of the coils, the gap or the efficiency [46]. The International Electrotechnical Committee (IEC) [59] and the International Organization for Standardization (ISO) [60] also have documents to regulate commercial wireless chargers.

3.2. Capacitive WPT

Capacitive WPT is supported by an electrical field generated in the area between two capacitors (the forward and return capacitors). These capacitors are constructed between the transmitter and the receiver with two parallel and close plates. The coupling capacitance of these elements is usually of the order of a few picofarad [61]. In an analogous way to resonant WPT, when the plates are close, an electric field is generated, and an induced current appears in the receiver. As the capacitors are connected to the battery, the power transfer is effectively performed to the EV. Although this arrangement of the plates is the most common one, there are variants that provide improvements [62], such as the Four-Plate Stacked structure [63], which is more compact and reduces the external capacitances, and the Six-Plate Stacked structure [64], which includes two larger external plates that act as shielding and reduces electric field emissions. The induced current is proportional to the variation of the electric field, so power converters are also used in this type of charger to increase this variability.

Conversely to resonant wireless chargers, capacitive WPT can realize an effective power transfer even with metallic barriers [62] as this condition does not lead to relevant losses. Capacitive wireless chargers are a competitive option because the electric field is confined in the volume comprised between the two plates of the capacitors. This restriction makes capacitive wireless chargers safer when compared with the magnetic-based counterparts.

Compensation networks and power converters are also part of these chargers, as shown in Figure 6.
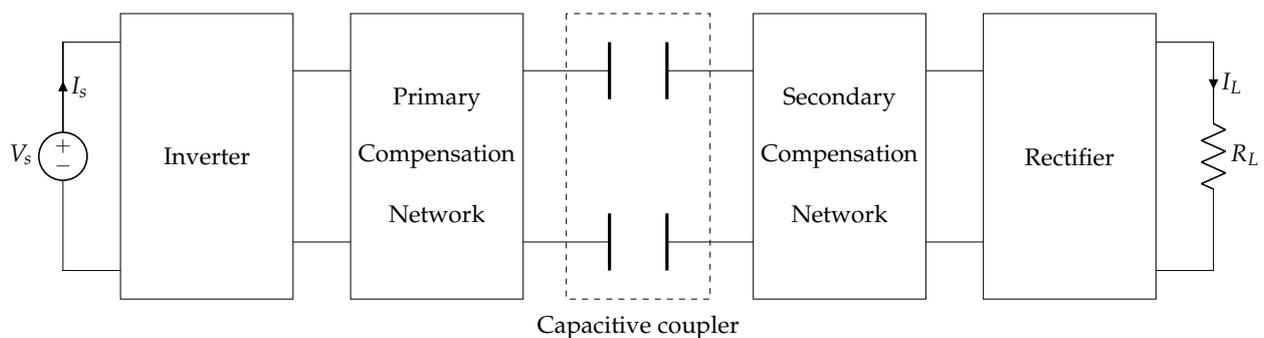

Figure 6. Generic diagram for capacitive wireless chargers.

The mono-resonant compensation topologies are coils, which may be connected in series or in parallel. We can also talk about the Series-Series, Series-Parallel, Parallel-Series or Parallel-Parallel structures, as in the magnetic-based chargers. As for the multi-resonant compensation topologies, double-side LCL [63], double-side LCLC and double-side LC are the most popular ones in capacitive chargers [65]. The schematics of the most popular compensation topologies in capacitive power transfer are depicted in Figure 7.
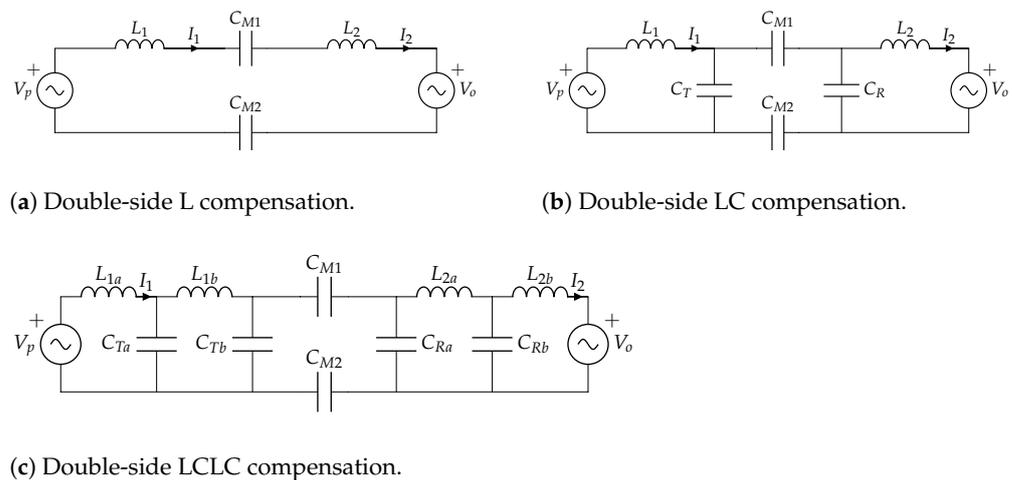

(**a**) Double-side L compensation.

(**b**) Double-side LC compensation.

(**c**) Double-side LCLC compensation.

Figure 7. Compensation topologies for capacitive WPT.

As with inductive power transfer, power electronics play a fundamental role, since the operating frequency of the system is directly related to the capacitance requirements. Most of the prototypes developed in the literature use an operating frequency of 1 MHz [14,63,65], although there are also prototypes that work at other frequencies such as 530 kHz [66], 4 MHz [62] and 13.56 MHz [67]. To deal with these high-frequency values, SiC MOSFETs is usually the selected technology thanks to its previously mentioned advantages, but Gallium Nitride (GaN) technology is used for the highest frequencies due to lower switching losses [68,69]. The DC current is converted to high-frequency alternating current using a full-bridge inverter (most usual) [14,63,65], buck converter [70], Class *E* converter [62,71], Class ϕ converter [67] or even with a three-phase inverter [72], although the latter requires a special six-plate topology.

The first prototypes of capacitive wireless chargers were restricted to low-power and low-gap applications [20]. However, this technology has evolved in recent years and we can find some implementations reaching several kilowatts and gaps up to 300 mm. Switching frequency is usually higher than in resonant chargers as the coupling capacitance is very small. As previously commented, it is usually a MHz signal [61,63]. Both the gap and the misalignment also affect the efficiency. The authors in [73] analyze the drop in the efficiency and the study does not show significant efficiency drops with horizontal misalignments lower than 50% of the plate length, although increments in the gap do produce steeper drops in efficiency from a certain distance. The study in [65] presents similar results, but with a higher efficiency drop in horizontal misalignment. The plates topology also affects to the efficiency under misalignment. For example, Four-Plate Stacked structure is more robust under angular misalignment than the simple parallel structure.

The main advantages of capacitive WPT to charge an EV are:

- Restricted electric field to the zone comprising the plates. This particularity eases the role of preserving the electromagnetic emissions in potentially dangerous areas.
- Reduced size and cost when compared with resonant wireless charger. Resonant chargers rely on expensive coils made of Litz wire in order to reduce the losses at high-frequencies. However, capacitive wireless chargers just require aluminum plates. This is cost-efficient material, with good conductivity and low weight.

As for the disadvantages, the most relevant ones for capacitive wireless chargers are:

- Difficulty to build the bulky capacitors due to the small area available underneath the vehicle chassis, specially for light-duty vehicles such as bicycles or scooters.
- Parasitic capacitances are common in the vehicle, which may affect in the performance of the wireless charger [61].

Recently, there is a new approach for building inductive and capacitive wireless chargers [14,74]. These hybrid systems are design so that the vehicle is charged with the inductive technology while it is parked. Alternatively, for on-the-move charge the capacitive WPT is preferred.

Developed prototypes can transfer up to a few kWs with an efficiency higher than 90%. Focusing on the bibliography, ref. [73] with 2.4-kW output power and 90% of efficiency, ref. [63] with 1.8 kW and an efficiency of 86%, ref. [65] with 1.5 kW and an efficiency of 85% and [66] with 1 kW at an efficiency of 88% stand out. On the other hand, there is a commercial solution from Murata [75], which has available a low-power solution with a power capacity of 10 W, and the Equus platform from Solace Power Inc.(located in Canada) [76], which can reach a maximum power level of 250 W at greater than 75% efficiency.

3.3. Microwave Power Transfer

Microwave Power Transfer (MPT) is a far-field WPT technique working with microwaves. The basis of this technology works as follows. The microwave is generated by a magnetrom, which is powered by a high-voltage DC generator. The microwave passes through a waveguide and it is then radiated by the transmitting antenna. The transmitting antenna may be designed to be able to orientate the radiated power to the collection region [77]. For that, a phase-shifter array is used in the transmitter. Then, the receiver uses a rectenna to convert the microwave signal into a DC signal. The DC signal is connected to the battery of the EV, so that this element can be charged. This generic structure is represented in Figure 8. The power is usually transferred with 2.4 GHz or 5.8 GHz. Some recent works also employ 28-GHz signals [78].
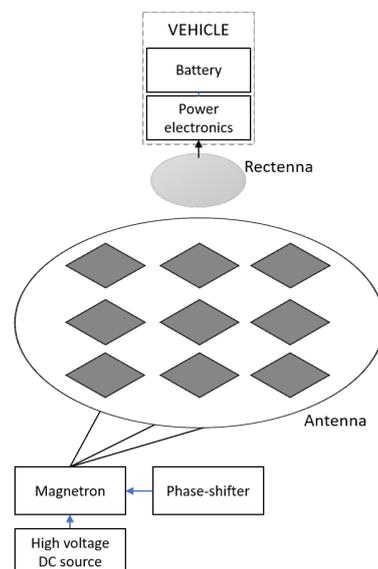

Figure 8. Generic diagram of a MPT system.

There are some implementations for MPT in home environments [79–81] but the current experiments on EVs are limited. The work in [82] develops a model for recharging an electric agricultural vehicle with MPT. The prototype reaches 44% efficiency in the DC-DC conversion for a 250-W power level. The system requires a robust tracking algorithm to control the beamforming as the MPT is very sensible to the relative misalignment between

the transmitter and the receiver. The authors in [83] addresses the most suitable material for the substrate of the transmitting antennas in order to maximize the power transfer.

More than terrestrial vehicles, the applicability of MPT is expected to be oriented to the aerospace field with a separation of several meters from the power transmitter and the receiver. The group led by William Brown conducted the first relevant MPT experiment on which they powered a model aircraft in 1964. In 1968 Peter Glaser defined the Space Solar Power/Satellite (SSPS). The idea behind this renewable energy system is that geostationary satellite collects the solar energy through a condenser. Then, it converts this energy into electricity by the solar arrays. With a MPT circuit, it reflects the energy to the Earth. A more recent approach can be found in [84]. In 1975 they also transmitted 450 kW to a receiver placed 1 mile away from the transmitter via microwaves. In the 1980s, small aerial vehicles flying at 21 km of altitude received 500 kW via a 5.4-GHz microwave. These airplanes were part of the Stationary High Altitude Relay Platform (SHARP) project, in which the airplanes provided telecommunication services. Presently, MPT is gaining attention for the powering of UAVs. In [85], a microwave beam radiation is used to power a Microaerial Vehicle. As described in this work, the process has three phases: (i) tracking the receiver by means of a pilot 2.45-GHz signal, (ii) transmitting the power at 5.8 GHz and (iii) processing the power. The work addresses how to configure an active-phased array of antennas to orientate the beam conveniently. In [86], the authors propose the use of the bus network in a city to charge the EVs, when they are close enough. Buses and EVs are equipped with a MPT system. It is a theoretical study which does not include implementation details.

Taking into account the generic circuits of the MPT, this technology suffers from the following three main limitations in the EV context:

- The transmitter and the receiver are designed to work in only one power flow direction. The adaptation of these chargers for V2G operations requires the replication of a dual system in the MPT.
- For high power levels, it requires bulky antennas which may avoid its applicability in some scenarios.
- The efficiency of MPT is lower than the one obtained by inductive or capacitive coupling [21]. This term is usually referred to as the beam collection efficiency.

3.4. Optical WPT

Optical WPT or laser power beaming systems work with waves in the THz range for the power transfer. Figure 9 presents a generic diagram of an optical WPT.
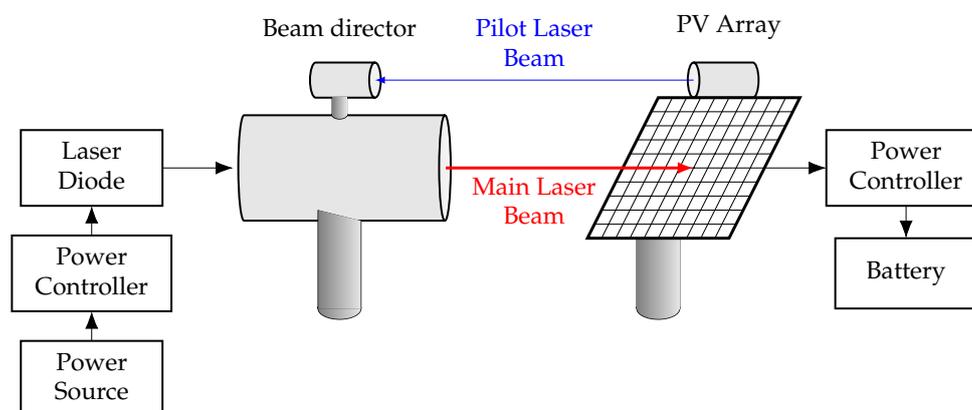

Figure 9. Generic diagram of an optical WPT system.

The optical wave is generated by a laser diode, which is powered by the grid in the transmitter. A laser generates a concentrated beam of light of a particular wavelength and power. To adjust the direction of the light, a beam director is incorporated into these systems so that the light can reach the receiver. The receiver is equipped with photovoltaic cells which convert the received laser light into power. This power is transferred to the

battery by power converters. The transmitter or the receiver can rely on a maximum power point tracking device to maximize the received power beam and, consequently, the efficiency of the power transfer. The beam director is an essential element as in the range of wavelengths the power transmitter and its receiver must keep the line-of-sight and no intermediate objects should be allowed. Under this circumstance, the receiver may be up to several kilometers from the power source. It is important to take into account that lasers are considered potentially dangerous for humans [87]. In particular, the risks increase with the power levels. Consequently, beam powering is restricted to specific environments with scarce human activity nearby and low-power transmissions.

There requirements can be identified in the beam-powered prototypes. The first experiment of beam powering in the EV context was designed by EADS Space Transport. The source was a distance up to 280 m to the vehicle, which was a Mini Rover. The efficiency of the system was under 25% as the laser was powered with 5 W, but the vehicle only received 1 W [18]. In NASA was able to remotely power 6-W drone flying at an altitude of 15 m with a 1-kW laser beam [88]. Lasermotive demonstrates the feasibility of beam powering with a prototype at 9 m from the source. It could keep its flight during 48 h with only the received laser power. Other experiments with UAVs have been described in the related literature but the power and efficiency of the transfer are reduced [18]. In [89], the authors describe how they designed and implemented a 180-W UAV to be powered by laser beams. It run for 12 h continuously with this WPT technology.

The efficiency of laser power beaming is quite poor. We could quantify the overall efficiency (η_{sys}) as the product of the efficiencies of the intermediate elements. So that:

$$\eta_{sys} = \eta_{DC} * \eta_{PS} * \eta_{Diode} * \eta_{Atm} * \eta_{PV} * \eta_{PCR} \tag{1}$$

where $\eta_{DC}, \eta_{PS}, \eta_{Diode}, \eta_{Atm}, \eta_{PV}$ and η_{PCR} are the efficiencies associated with the DC source, the power source, the diode, the propagation through the atmosphere, the photovoltaic cells in the receiver and the power converter to connect to the battery, respectively. Typical values for the components are presented in [18].

Atmospheric attenuation is modelled by Beer's Law as follows

$$P = P_o * e^{-\alpha_{ext} * R} \tag{2}$$

where P_o is the output power at the laser diode, P is the power received by the photovoltaic cells, which are separated R meters from the diode, and α_{ext} corresponds to the attenuation due to gas or aerosol.

As a conclusion, the use of this WPT technology is appropriate for specific scenarios with controlled conditions (no human or obstacles nearby). The power levels must be also reduced. UAVs are the most promising candidates to benefit from this technology [90]. Its application to other EV systems is not recommended as it suffers from the following limitations:

- Low efficiency. As previously explained, these systems suffer rom from a poor efficiency (<25%) [91]. The advances on laser technology and photovoltaic cells could increase this metric in the near future.
- Low power levels due to the potential risks of reaching a human being.
- Difficulty to orientate the laser beam via a software control, being the passive elements (e.g., lens or mirrors) the current devices to perform this task. It is worth noting that the orientation of the laser is usually a strong requirement as the beam must be oriented to the area where no human beings are in the path between the power source and the receiver.
- Unidirectional power flow. Due to the specific and different components that are present in the transmitter and in the receiver, V2G operations are not possible with this technology.

3.5. Comparison

WPT can be implemented via multiple technologies. The previous sections have explained the fundamentals of the resonant, capacitive, microwave-based and optical power transfer when they applied to the EV charge. Table 3 summarizes the main features and metrics of these technologies in the studied context.

Table 3. Comparative study of the WPT technologies applied to EVs.

Technology	Power Level	Efficiency	Bi-Directional Flow	Gap	Intermediate Objects	On the Move	Cost
Resonant	High (Up to 100 kW)	90–95%	Yes	< 30 cm	Yes	Yes	Medium
Capacitive	Medium (Up to 7 kW)	80–85%	Yes	< 30 cm	Yes	Yes	Low
Microwave	Low (<250 W)	40–50%	No	up to 1 km	No	No	High
Laser	Low (<500 W)	1–15%	No	up to 1 km	No	No	High

Although inductive technology is mature, it is expected that conductive and wireless chargers will be implemented jointly in a vehicle to offer the possibility of using each one in the most convenient way and situation. Some hybrid chargers have been proposed for this type of implementation [92].

3.6. Safety Issues

WPT technologies rely on electromagnetic fields to realize the power transfer. For health and safety reasons, the flux of these fields must be restricted as has been established by the international institutions. Specifically, International Commission on Non-Ionizing Radiation Protection (ICNIRP) has published a guideline about this issue, which has been transposed into regulation by more than 100 countries. It sets the limits for non-ionizing radiation, i.e., the radiation derived with a photon energy lower than 10 eV and a frequency lower than $3 \cdot 10^{15}$ Hz. These limits were established as a measurement of protection for general and occupational public from short- and long-term exposures to artificial electromagnetic fields.

For these restrictions, this organization divides the electromagnetic waves into six groups:

- Ultraviolet radiation, with a wavelength comprised between 200 and 400 nm.
- Visible light, with a wavelength in the interval from 100 to 400 nm.
- Infrared Radiation, in which the wavelength is greater than 400 nm but lower than 780 nm.
- Radiofrequency, in which the frequency is in the interval from 100 kHz to 300 GHz.
- Low frequency, for waves in the range from 1 Hz to 100 kHz.
- Static electric and magnetic fields with 0 Hz of frequency.

According to this classification, resonant EV wireless chargers should comply with the restrictions associated with the low frequency group. In this group, there is an additional sub-classification. For those chargers supported by electromagnetic waves in the range from 3 kHz to 10 MHz (this also includes some radiofrequency-based chargers), the imposed restrictions are in Table 4.

Table 4. Electromagnetic restrictions set by ICNIRP in the range 3 kHz–10 MHz.

Public	E-Field Strength E (kV m^{-1})	Magnetic Field Strength H (A m^{-1})	Magnetic Flux Density B (*T*)
Occupational	$1.7 \cdot 10^{-1}$	80	$1 \cdot 10^{-4}$
General	$8.3 \cdot 10^{-2}$	21	$2.7 \cdot 10^{-5}$

Another concern related to resonant wireless power transfer is the compatibility of these systems with internal medical devices (e.g., pace-markers). These devices are carefully designed to be safe with external interfering sources. However, some limits should be

considered for the charger. Specifically, they could be in the drivers, passengers or even in a bystander. According to X, the field reaching to them should be lower than 15 µT so that the devices are unaffected. When this field is 29.4 µT, then the device may be in reversion mode but with no permanent damage. Touch current must be restricted too due to the potential damages it could provoke [93].

MPT and capacitive-based systems should comply with the restrictions in the radiofrequency range. ICNIRP specifies the SAR (Specific Absorption Rate) for different parts of the body and for general and occupational public too. Evaluating these metrics and considering the power levels implied in the EV wireless chargers, no human being should be allowed to be in the area comprised between the power transmitter and the receiver.

As for lasers, the safety concerns are related to the diode types, which are also linked to the amount of the power transfer. Class 1, 2 or 3R lasers are safe for humans as they do not provoke skin burn hazards. Class 4 lasers are not safe for humans posing risks of skin burns or eye damage. Consequently, they should be used with the guarantee that no human being will be in the power transfer path. For that, an additional system that detects this eventuality could be necessary.

4. Additional Technologies for EVs Wireless Charge

To get commercial WPT products, the components for the power transfer must also count on some control electronics and software to fulfill the safety and operational requirements. In addition, some extra electronics and control must be included in order to effectively integrate the product with other systems or infrastructures. Data communication is necessary to exchange data to a convenient integration of the charger with the infrastructure (e.g., electrical grid or data bases for vehicle identification). Moreover, the primary and the secondary sides of the wireless chargers must exchange some measurements to ensure that the charge/discharge process is being accomplished correctly, to ease the alignment of the transmitter/receiver or for load detection [94]. This must be done to prolong battery lifetime as they have to be charged in a controlled way. In this sense, Ion-Lithium batteries, which are the most common batteries in EVs, are usually charged with a Constant-Current-Constant-Voltage scheme [95]. Therefore, the primary side must generate the electrical signals according to the status of the battery. Under some given circumstances, the primary side can infer how the power is being received [47,48,96], but in a broad view, the results of some measurements (current, voltage) must be transferred to the primary controller. For this purpose, a wireless communication channel must be set. It can be based on well-known technologies such as IEEE 802.11, IEEE 802.16 or 3G. In magnetic resonant chargers and microwave-based WPT systems, some experimental prototypes make advantage of the installed coils to use them as the communication components [97]. When the data and the power systems rely on a common channel, some configuration parameters must be taken into account. First, it is important to decide if the power and the data can be transmitted simultaneously or timeslots may be set to separate both processes (they could even share the same carrier). The most common implementation is to use two different carriers (one for the power transfer and another for the data transmission) so that they do not interfere each other [94]. Concerning the data transmission, the modulation technique and the protocol should be carefully selected in order to have an effective communication with the sufficient Signal-to-Noise Ratio and the bit rate needed for this application [98].

In some WPT applications, the power receiver can move or be in a random position. Under these circumstances, a receiver localization algorithm must be included in the product so that the electromagnetic wave is generated with the correct beam direction. Far-field WPT opt for controlling the difference in the current phase of the transmitting antennas. An array of antennas is common to increase the transmitted power and to control the beamforming. Near-field WPT techniques try to estimate the coupling between the transmitter and the receiver in order to adjust the transmitted power [99]. The work in [100] develops an autonomous alignment system for a dynamic wireless charge with a random position for the receiver.

Magnetic resonant technology and laser-beaming are especially sensible to the presence of intermediate objects in the zone between the transmitter and the receiver. These objects can cause a diminution of the efficiency and even unexpected accidents due to the induced eddy currents (with resonant systems) or reflections (with beam powering). The Foreign Object Detection (FOD) algorithms are oriented to detect the situations in which these objects/beings are in the intermediate zone between the transmitter and the receiver. Some proposals for this algorithm can be found in [101,102].

An additional algorithm is the scheduling, which controls and defines when the charge or the discharge occurs for a set of chargers. It is supported by network models and some optimization problems. The goal of the optimization problem may be reducing the peak loads [103], reducing the greenhouse emissions [104] or improving the integration of the renewable energy sources [105]. Scheduling can also be performed with routing. In this way, the drivers receive recommendations about when and where to charge and discharge their EVs [106].

There are few works dealing with scheduling and/or routing for wireless chargers. If we consider only static wireless chargers, the scheduling algorithms are similar to a minor reduction on the efficiency. However, quasi-dynamic and dynamic charging do impact on how the recommendations about the charge/discharge process should take place. Dynamic charge poses a new challenge for scheduling algorithms. The work in [86] proposes the use of the buses to charge the EVs when they are close. The algorithm is designed to maximize the total residual energy subject to all EVs can arrive to their destinations before a predefined deadline. Trying to minimize the charging costs, the work in [107] defines the scheduling for online buses charged via wireless. To do so, a two-stage optimization problem is proposed, and the day-ahead electricity market is considered. As for routing, we can find a specific work about dynamic wireless charge in [108].

5. Conclusions

It is clear that the Electric Vehicles can benefit from Wireless Power Transfer technology as it eases the charge/discharge process and it even extends the scenarios in which these processes can happen. When considering the electromobility context, four main technologies are applied for wireless chargers. They differ on the physical principle on which they rely: induction, capacitance, radiofrequency and laser. In this paper, we have analyzed some application of these technologies specifically intended for EVs. The review reveals that the convenience of these technologies depends on several parameters such as the gap, the power level, the potential presence of intermediate objects or how the power flow could be. The most mature technology for EV wireless charger is the one based on the magnetic resonant technology, which also allows V2G operations. However, there are still some open challenges in which the industry and research community need to align efforts so that new approaches and solutions are developed. Among the most important ones, for the resonant chargers, we can highlight the following ones: (i) transmission and receiver pad misalignment minimization strategies to achieve higher efficiencies, (ii) compact and reduced coil designs for high-power transfer rates and (iii) optimized designs for EM fields shielding and mitigation. The capacitive WPT technology shows some relevant limitations such as limited efficiency, low-power density, intense electric fields and parasitic capacitances. A deep effort must be addressed to mitigate these shortcomings. Similar limitations are found to radiofrequency and optical WPT. The microwave is not practical for high power levels as it requires bulky antennas while the optical-based technology is restricted to low power levels due to the potential risks of reaching a human being. The efficiencies for the latter two technologies are lower than the one obtained by inductive or capacitive coupling. They are only of interest when there is a certainty that no human being may be in the path between the transmitter and the receiver and both components are separated a long distance.

Concerning charging operation modes, the static charge can be accomplished safely with the four technologies presently but quasi-dynamic and dynamic charge still requires

some advances. Other adjacent technologies must be also developed in order to guarantee a correct performance of the chargers.

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