



UNIVERSIDAD DE MÁLAGA

Simultaneous wireless power and data transfer system for V2G inductive power chargers

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Simultaneous wireless power and data transfer system for V2G inductive power chargers

Inmaculada Concepción Casaucao Tenllado

Tesis dirigida por la Dra. Dña. Alicia Triviño Cabrera.

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Abstract

The electric vehicle (EV) is currently growing due to the unquestionable need to reduce emissions of CO_2 into the atmosphere. Their integration into the market is taking place progressively, however, in recent years the number of EV sales has increased exponentially. These vehicles are equipped with plug-in charging technology, where the user has to manipulate the charging cable to plug an unplug the EV. Considering that the charging power of EVs is in the order of kW, it is interesting to explore other alternatives that allow the charging process to be carried out in a simpler and safer way. This is the motivation behind research into wireless power transfer (WPT) systems. The technologies proposed for wireless charging are varied, but inductive-resonant systems is the most efficient solution for this type of application.

Additionally, the increase in the number of EVs on the market and, therefore, the increase in energy consumption from the grid, has led to the development of Vehicle-to-Grid (V2G) algorithms that allow the electric vehicle to transfer energy to the grid when necessary. This task is carried out through energy distribution strategies that enable the optimal power flow, taking into account variables such as energy prices or the charging state of the vehicle.

In order to carry out these control algorithms and, additionally, to monitor the vehicle status during the charging process, communication between the EV and the charging station is required. In plug-in chargers, this communication is done through the charging cable itself. However, in the proposed inductive-resonant charging solutions, this communication must take place wirelessly. For this reason, it is intuitive to consider the use of commercial communication technologies such as Bluetooth, Wi-Fi, ZigBee or Radio Frequency. Although these technologies are widely deployed, they can lead to serious drawbacks such as communication delays, pairing problems or cybersecurity issues. As a major alternative, simultaneous power and data transfer (SWPDT) systems are emerging, in which communication is generally carried out through the power system itself.

This doctoral thesis aims, first, to analyse the SWPDT system proposals offered by the scientific community, in order to identify design criteria that may be useful for future implementations. Likewise, through an in-depth analysis of this technology, it is possible to identify the optimal solution that fits the charging requirements of each specific application. This is one of the main contributions of this doctoral thesis.

During the analysis of the design criteria, it has been found that one of the most studied parameters is the compensation system, used to make the system work in resonance. However, the analyses carried out on this subject show a significant gap in terms of the performance of these systems during data transmission. In order to provide the scientific community with a detailed study of this behaviour, this doctoral thesis has proposed a comparative study of the two most widely used compensation systems in the literature, Series-Series (SS)

and LCC-LCC. This comparative study focuses on the mathematical analysis of the data channel in SWPDT systems.

Additionally, the study of bidirectional control algorithms has led to the conclusion that one of the strategies that facilitates the integration of the EV in the network is the control of P and Q during the charging process. Therefore, in order to implement a bidirectional wireless charger, the research of this thesis has led to the implementation of a V2G algorithm, with control of P and Q in four quadrants, allowing up to 8 modes of operation. This control has been designed for both SS and LCC-LCC systems. All these studies have been experimentally validated on a working prototype with charging power up to 1 kW.

The implementation of this V2G control system, together with the study of SWPDT charging technology, has led to the analysis of synergies between both subjects. In this way, one of the ideas carried out in this doctoral thesis is the implementation of a SWPDT system, whose communication is oriented towards sending information related to the V2G control technique. This prototype has been carried out for an LCC-LCC system, including misalignment and data rate studies.

Finally, the last study of this work is related to energy distribution strategies, through which the EV can carry out its charging or discharging according to variables such as the price of electricity or the battery state of charge (SoC). For this purpose, a distributed algorithm approach is proposed that obtains satisfactory results, achieving a global optimum and efficient computation times.

The completion of this PhD thesis is expected to provide a significant contribution to the scientific literature on wireless charging of electric vehicles.

Keywords: Electric vehicle, wireless charging, SWPDT systems, communication, V2G, data

Resumen

En la actualidad, el vehículo eléctrico (VE) se encuentra en auge debido a la indiscutible necesidad de reducir las emisiones de CO_2 a la atmósfera. Su integración en el mercado está teniendo lugar de manera progresiva, sin embargo, en los últimos años el número de ventas de VEs se ha visto incrementado de manera exponencial. Estos vehículos cuentan con una tecnología de carga enchufable, en la que el usuario debe manipular el cable de carga tanto para su conexión como para su desconexión. Considerando que la potencia de carga de los vehículos eléctricos se encuentra en el orden de los kW, resulta interesante buscar otras alternativas que permitan realizar el proceso de carga de manera más sencilla y segura. De esta motivación nacen las investigaciones centradas en los sistemas de carga inalámbrica. Las tecnologías propuestas para la carga sin cables son variadas, sin embargo, los sistemas inductivo-resonantes se posicionan como la solución más eficiente para este tipo de aplicaciones.

Por otra parte, el aumento en el número de vehículos eléctricos en el mercado y, por tanto, el incremento de consumo de energía de la red, ha dado lugar al desarrollo de algoritmos de carga bidireccionales (*Vehicle-to-Grid*, V2G) que permiten que el vehículo eléctrico ceda energía a la red cuando sea necesario. Esta tarea se lleva a cabo a través de estrategias de distribución de energía que posibilitan el flujo de potencia de forma óptima, atendiendo a variables como el precio de la energía o el estado de carga del vehículo.

Para llevar a cabo estos algoritmos de control y, adicionalmente, contar con una monitorización del estado del vehículo durante su proceso de carga, es necesario que exista una comunicación entre el VE y la estación de carga. En los cargadores enchufables, esta comunicación se realiza a través del propio cable de carga. Sin embargo, en las soluciones propuestas de carga inductivo-resonante, esta comunicación se debe producir de manera inalámbrica. Para ello, es intuitivo considerar el uso de tecnologías comerciales de comunicación como Bluetooth, Wi-Fi, ZigBee o Radiofrecuencia. A pesar de que estas tecnologías están ampliamente extendidas, pueden presentar serios inconvenientes como retardos en la comunicación, problemas de emparejamiento o problemas de ciberseguridad. Como alternativa principal, surgen los sistemas de transmisión simultánea de potencia y datos (*SWPDT systems*), en los que la comunicación se lleva a cabo, generalmente, a través del propio sistema de potencia.

En esta tesis doctoral se pretende, en primer lugar, analizar las propuestas de sistemas SWPDT que la comunidad científica ofrece, de manera que se puedan identificar criterios de diseño que puedan ser de utilidad para futuras implementaciones. Del mismo modo, a través de un análisis en profundidad de esta tecnología, es posible identificar la solución óptima que se ajusta a los requisitos de carga de cada aplicación en concreto. Esta es una de las contribuciones principales de esta tesis doctoral.

Durante el análisis de los criterios de diseño se ha podido comprobar que uno de los parámetros más estudiado es el sistema de compensación, utilizado para que el sistema trabaje en resonancia. Sin embargo, los análisis realizados de esta temática muestran un vacío significativo en cuanto al comportamiento de estos sistemas ante la transmisión de datos. Con el fin de aportar a la comunidad científica un estudio detallado de este comportamiento, en esta tesis doctoral se ha planteado el estudio comparativo de los dos sistemas de compensación más utilizados en la literatura, Serie-Serie (SS) y LCC-LCC. Este estudio comparativo se centra en el análisis del canal de datos en sistemas SWPDT.

Adicionalmente, el estudio de algoritmos de control bidireccionales ha permitido concluir que una de las estrategias que facilita la integración del VE en la red es el control de P y Q. Por ello, con el fin de implementar un cargador inalámbrico bidireccional, la investigación de esta tesis ha dado lugar a la creación de un algoritmo V2G, con control de P y Q en cuatro cuadrantes, permitiendo hasta 8 modos de funcionamiento. Este control ha sido diseñado tanto para un sistema SS como para un sistema LCC-LCC. Todos estos estudios han sido validados experimentalmente en un prototipo funcional con potencia de carga de hasta 1 kW.

La implementación de este sistema de control V2G, junto con el estudio de sistemas de carga SWPDT, ha propiciado el análisis de sinergia entre ambas temáticas. De esta manera, una de las ideas llevadas a cabo en esta tesis doctoral es la implementación de un sistema SWPDT, cuya comunicación esté orientada al envío de información relacionada con la técnica de control V2G. Este prototipo se ha llevado a cabo para un sistema LCC-LCC, incluyendo estudios de desalineamiento y velocidad de transmisión.

Finalmente, el último estudio de este trabajo está relacionado con las estrategias de distribución de energía, a través de las cuales el VE puede realizar su carga o su descarga atendiendo variables como el precio de la electricidad o el estado de carga de la batería. Para ello, se plantea una aproximación de un algoritmo distribuido que obtiene unos resultados satisfactorios, consiguiendo un óptimo global y unos tiempos de computación eficientes.

La realización de esta tesis doctoral espera contribuir significativamente a la literatura científica dedicada a la carga inalámbrica de vehículos eléctricos.

Contribución 1

La carga inalámbrica de vehículos eléctricos (VEs) se mantiene en constante evolución, permitiendo mejoras significativas en la tecnología. Esta constante evolución ha propiciado la aparición de nuevos métodos de carga, lo que permite dar el salto desde la carga conductiva tradicional, a la carga inalámbrica. De los métodos de carga inalámbricos existentes, el método inductivo-resonante es el que presenta mejores resultados, convirtiéndose en la solución más extendida.

Durante el proceso de carga de un vehículo eléctrico, es necesario que la transmisión de potencia, unidireccional o bidireccional, se realice de manera efectiva y segura, por lo que numerosos estudios se centran en la mejora de esta funcionalidad. Sin embargo, durante la carga de un VE, también es ne-

cesaria la comunicación entre el vehículo y la estación de carga. A pesar de la existencia de numerosas tecnologías comerciales para realizar esta función (Bluetooth, Wi-Fi, ZigBee o Radiofrecuencia), se ha demostrado que su uso puede acarrear consecuencias negativas en los procesos de carga inalámbrica: pérdidas de conexión, errores de emparejamiento, retardos en la transmisión o problemas de ciberseguridad. Como alternativa al uso de estas tecnologías comerciales, nacen los sistemas de transmisión simultánea de potencia y datos (*SWPDT systems*). En la literatura se pueden encontrar revisiones del estado del arte de este tipo de sistemas integrados en aplicaciones biomédicas o aplicaciones de electrónica general. Sin embargo, no existe un análisis en profundidad de los sistemas SWPDT aplicados a vehículos eléctricos. En esta contribución, se pretende aportar a la literatura un estudio exhaustivo de estos sistemas, analizando su viabilidad en vehículos eléctricos.

En esta revisión del estado del arte, se ha presentado una clasificación de seis criterios de diseño que han sido identificados en la literatura previamente existente. Estos criterios han permitido estudiar en detalle las ventajas e inconvenientes que presentan las diferentes soluciones propuestas en literatura. De esta manera, el artículo creado como resultado de esta contribución ofrece una guía en profundidad que puede ser de utilidad para el proceso de diseño e implementación de un sistema SWPDT. Además, se proponen numerosos casos de estudio que permiten visualizar de forma clara las aplicaciones reales de los sistemas SWPDT en un cargador de vehículos eléctricos.

Contribución 2

Uno de los elementos más importantes en un sistema de carga inalámbrica con tecnología inductivo-resonante es el sistema de compensación. El sistema de compensación permite que el sistema trabaje en resonancia a la frecuencia de trabajo elegida, permitiendo, de esta manera, que se maximice la transmisión de potencia y, por tanto, se mejore la eficiencia de esta transmisión. De entre todos los sistemas de compensación que pueden ser utilizados en los sistemas de carga inalámbrica, existen dos que son los más empleados por las ventajas que presentan: Serie-Serie (SS) y LCC-LCC. Estos sistemas de compensación cuentan con un buen comportamiento ante sistemas de desalineamiento, así como unos valores adecuados de eficiencia. En la literatura, existen numerosos análisis comparativos de estos sistemas de compensación, sin embargo, todos estos análisis son realizados atendiendo al estudio de variables relacionada con la transmisión de potencia.

El objetivo principal de esta contribución es la creación de un análisis comparativo de los sistemas de compensación SS y LCC en términos de transmisión de datos. Este análisis resulta interesante, ya que en los sistemas SWPDT la transmisión de información cobra una importancia similar a la transmisión de potencia. Para este estudio comparativo, es necesario analizar variables diferentes a las estudiadas típicamente en sistemas WPT. Estas variables son la relación señal/ruido (*SNR*), la capacidad del canal y el ancho de banda. Además, ya que el desalineamiento entre bobinas es una problemática ampliamente abordada en literatura, es interesante analizar el efecto de estos sistemas de compensación en condiciones de desalineamiento, estudiando las posibles

variaciones ocasionadas en las variables relacionadas con la transmisión de datos. Por otra parte, es destacable que, en este estudio, todos los análisis se han llevado a cabo considerando las resistencias parásitas de todos los componentes, las cuales son importantes en las funciones de transferencia que rigen los sistemas.

Contribución 3

La integración de vehículos eléctricos en la red puede presentar un desafío significativo en la infraestructura y métodos de gestión de energía. Principalmente, las consecuencias esperadas de esta integración son un aumento en la demanda de energía, inestabilidades en la red eléctrica debido a la simultaneidad en la carga de vehículos y la necesidad de implementación de nuevas estrategias de carga. Para aliviar estas consecuencias, se propone la tecnología Vehicle-to-grid (V2G), en la que el vehículo eléctrico puede tanto ceder como demandar energía, dependiendo de la estrategia de carga adoptada. Esta tecnología se implementa, inicialmente, en vehículos eléctricos enchufables, sin embargo, cada vez son más los estudios que relacionan el control V2G con cargadores inalámbricos de vehículos eléctricos.

En esta contribución se propone un sistema de control V2G adaptado a un cargador inalámbrico SAE J2954. En este control, se proponen ocho modos de funcionamiento, considerando todas las posibles combinaciones de potencia activa (P) y potencia reactiva (Q). El control de la potencia activa transmitida es importante para realizar una correcta regulación de la frecuencia, mientras que el control de la potencia reactiva es ampliamente utilizado para regular la tensión del bus en sistemas eléctricos. En esta propuesta se analizan los 8 modos de funcionamiento, aportando para cada uno de ellos una validación experimental. Además, se implementa un sistema de sincronización que permite ajustar de manera precisa la fase entre las señales de activación de los convertidores de potencia.

Contribución 4

La creciente demanda de fuentes de energía renovables ha llevado a un aumento en el uso de vehículos eléctricos, lo que plantea retos para las redes eléctricas a la hora de acomodar esta demanda. Este capítulo del libro se ofrece una visión global de las posibles soluciones para gestionar el uso de vehículos eléctricos en zonas residenciales. Partiendo de un análisis inicial de los tipos de estaciones de carga que pueden instalarse en los hogares, se realiza un análisis en profundidad de los servicios que los vehículos eléctricos pueden proporcionar a la red y a la gestión de la energía doméstica, incluyendo la regulación de la frecuencia, el apoyo a la tensión y la reducción de los armónicos de corriente.

Por otra parte, una de las contribuciones principales de este capítulo es la propuesta de dos estrategias descentralizadas de carga óptima para un agregador de vehículos eléctricos en el contexto de las aplicaciones residenciales. La primera estrategia considera el estado de carga y las características eléctricas de los cargadores domésticos para optimizar el horario de cada vehículo eléctrico, mientras que la segunda estrategia establece la conveniencia de contribuir a la potencia objetivo en función de las demandas domésticas previstas,

la capacidad de energía renovable o el estado de carga. Finalmente, se propone una solución descentralizada que permite a todos los cargadores de vehículos eléctricos actualizar sus acciones de carga/descarga en paralelo sin comunicaciones adicionales entre los cargadores implicados.

Palabras clave: Vehículo eléctrico, carga inalámbrica, sistemas SWPDT, comunicación, V2G, datos



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List of Abbreviations

ASK	Amplitude Shift Keying
BPC	Bidirectional Power Converter
BPSK	Binary Phase Shift Keying
BFSK	Binary Frequency Shift Keying
BLE	Bluetooth Low Energy
BT	Bluetooth
CCS	Combined Charging System
CSMS	Charging Station Management System
DL-DC	Double Link - Double Carrier
DPSK	Differential Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
	EMI Electromagnetic Interference
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FDM	Frequency Division Multiplexing
FSK	Frequency Shift Keying
GA	Ground-assembly
G2V	Grid-to-Vehicle
ISO	international organization for Standardization
JSON	JavaScript Object Notation
OCA	Open Charge Alliance
OCPP	Open Charge Point Protocol

OOK	On-Off Keying
PP	Parallel-Parallel
PS	Parallel-Series
PSK	Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RT	Resonant Tank
SAE	Society of Automotive Engineers
SL-DC	Single Link - Double Carrier
SL-SC	Single Link - Single Carrier
SNR	Signal-to-Noise Ratio
SOAP	Simple Object Access Protocol
SoC	State of Charge
SP	Series-Parallel
SS	Series-Series
SWPDT	Simultaneous Wireless Power and Data Transfer
TDM	Time Division Multiplexing
VA	Vehicle-assembly
V2G	Vehicle-to-Grid
WPT	Wireless Power Transfer
ZPA	Zero Phase Angle
ZVS	Zero Voltage Switching

List of Symbols

Symbol	Description	Unit
B	Bandwidth	Hz
C	Channel capacity	bps
C_1	Primary side series capacitor	F
C_2	Secondary side series capacitor	F
C_{f1}	Primary side filter capacitor	F
C_{f2}	Secondary side filter capacitor	F
C_{RT}	Resonant tank capacitor	F
DR	Data rate	bps
f	Frequency	Hz
k	Coupling coefficient	-
L_1	Primary side main inductor	H
L_2	Secondary side main inductor	H
L_{f1}	Primary side filter inductor	H
L_{f2}	Primary side filter inductor	H
L_{RT}	Resonant tank inductor	H
M	Mutual inductance	H
ω	Angular frequency	rad/s
ω_d	Angular frequency for data transmission	rad/s
P_{in}	Input Power	W
P_{out}	Output Power	W
R_1	Primary coil internal resistance	Ω
R_2	Secondary coil internal resistance	Ω
R_{BAT}	Battery equivalent resistance	Ω
V_{in}	Input voltage	V
V_{out}	Output voltage	V

Chapter 1

Introduction

In this chapter, a brief presentation of the content developed in this doctoral thesis will be introduced. First, the main motivation of this line of research will be presented, which is directly related to the communication requirements of wireless chargers for Electric Vehicles (EV). In EVs with conductive charging, this communication is carried out through the wired connectors. However, in wireless charging alternative methods must be studied to transfer data without cables.

The objectives of this doctoral thesis and the contributions achieved with the completion of this research will be described in this chapter. As a final section, the structure of the document will be outlined.

1.1 Motivation

A growing number of countries are joining the movement to switch from fuel-based vehicles to Electric Vehicles (EVs) for sustainability-related reasons. Furthermore, it has been demonstrated that CO_2 emissions in urban areas have direct effect on the allergic respiratory diseases [1] and may compromise human health [2]. The main motivation is that there is a great need for reducing CO_2 emissions, 23 % of which comes from transportation, according to the International Energy Agency [3]. In 2015, in the midst of a climate crisis, the Paris Agreement was established with the goal of keeping the global average temperature increase below $2^\circ C$ above pre-industrial levels [4]. Using EVs is considered as one of the sustainable solutions to reduce CO_2 emissions [5] and align with the recommendations set in the Paris Agreement. The reduction of CO_2 has a direct consequence on the inhabitants of urban environments, which are expected to be denser in a future. With this diminution, the improvement of human health could be achieved with reductions in respiratory illnesses. In addition to contributing to the reduction of air pollution, EVs also have advantages of low noise emissions, which significantly reduces noise pollution in cities and thus improves mental and physical health of their inhabitants [6].

The above-mentioned reasons, together with the economic incentives proposed by some countries to encourage a transition to electric vehicles, have led to an increase in the number of sales of electric vehicles during last years [7], as can be observed in Fig. 1.1. The growth in the stock of vehicles in recent years is practically exponential, which makes the adoption of EVs a reality. As this is a contemporary topic, it is interesting to carry out a study of its technology, as well as the possible technical advances that can be achieved in this field.

Traditionally, the EV charging has been carried out through cables (type 1, type 2, type 3 or type 4 [8]). However, in recent years, wireless EV charging has gained popularity due to the advantages it presents. Through wireless EV charging, the driver's intervention in the charging process is reduced, as it can be carried out automatically. In addition to being a simpler process, it could be safer since the conventional charging cable that must be handled in conductive chargers carries high-value current, which could pose a danger to the driver [9]. For this reason, much research is focused on implementing a design that replaces the conventional conductive charging method with wireless charging. To be a competitive EV charging technology, the wireless chargers must be highly efficient.

There are different Wireless Power Transmission (WPT) technologies that could be used in the EV charging process. Inductive-resonant transmission, capacitive transmission [10], microwave-based transmission [11] and optical or laser transmission [12] are the main WPT technologies employed for these applications [9], [13]. The most robust

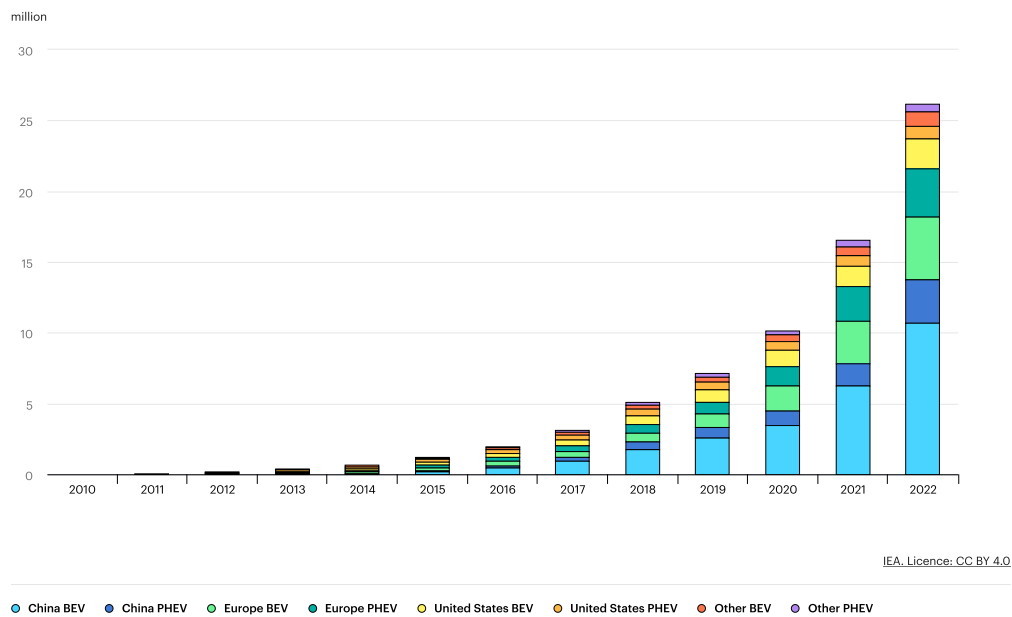


Figure 1.1: Car stock from 2010 to 2022. Source: [7]

technology used in the implementations that have been carried out up to now is inductive-resonant. In fact, companies such as WiTricity [14] or InducTEV [15] are developing prototypes with the aim of commercialising inductive wireless chargers.

In both conductive charging of EVs and inductive charging, it is necessary that a communication exchange takes place during the charging process [16], as shown in Figure 1.2. Data such as battery status, user identification or warning messages must be sent. But the communication is not only necessary for user management, it can also be used to control the chargers. One of the direct control applications related to vehicle charging is Vehicle to Grid (V2G) control, which enables a two-way energy exchange between the electric vehicle and the grid [17]. With V2G charging, the power flow is bi-directional, allowing energy to be exchanged between the vehicle and the grid in both directions. This technology has direct advantages, such as supporting grid decongestion, making the grid more flexible and helping the integration of renewable energies. Services in the V2G context are expected to grow in the near future [17]. Consequently, conductive and wireless charging for EVs must be designed to support these new services with bidirectional power flow and the corresponding communication requirements for a controlled transfer.

The most straightforward methodology of wireless information transmission is the use of existing commercial technologies such as Bluetooth, Bluetooth Low Energy (BLE), Zig-Bee, Radio Frequency (RF) and IEEE 802.11 (Wi-Fi). These technologies have the advantage that, due to their inclusion in the market many years ago, they are under constant improvement, so that variables such as transmission rate (in the order of kbps for ZigBee [18] and Mbps for Bluetooth [19], BLE [20] and Wi-Fi [21]) or interoperabil-

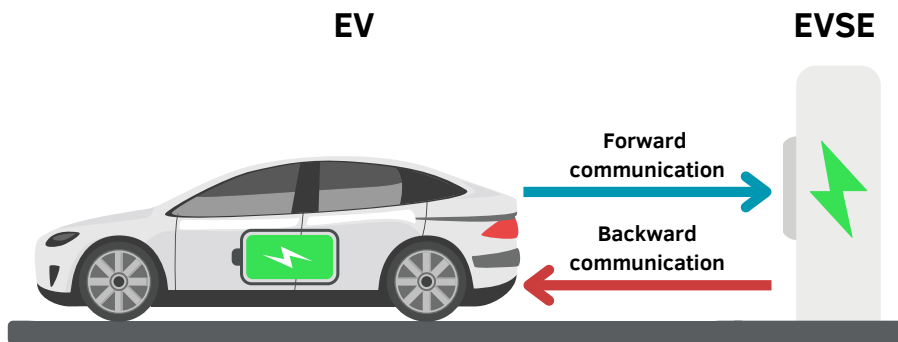


Figure 1.2: EV communication scheme for conductive charging

ity are being improved. Although these technologies are the most immediate solution for wireless charging, there are issues that need to be highlighted, such as those illustrated in Figure 1.3. Among all these issues, one of the most critical is cybersecurity [22], [23], as during the wireless charging process, user data can be compromised due to the numerous vulnerabilities of commercial technologies.

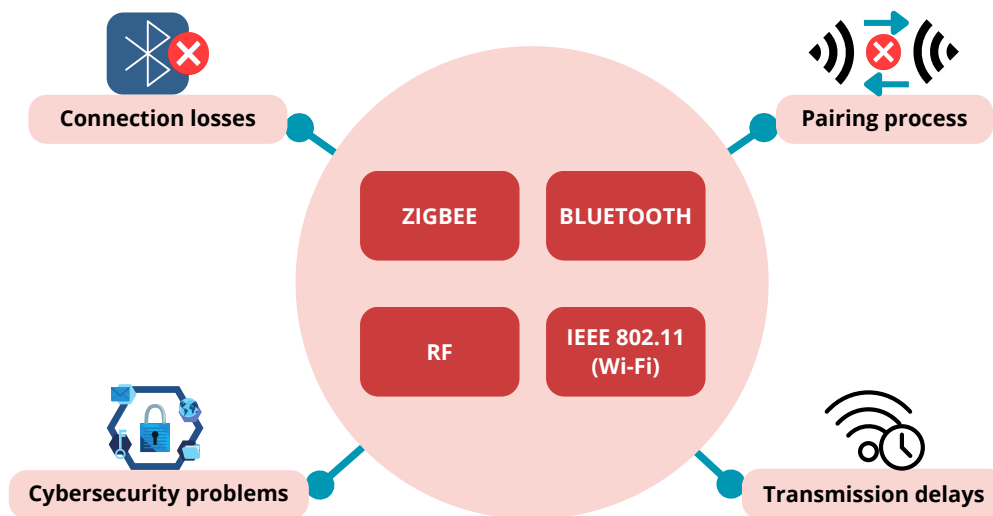


Figure 1.3: Issues associated to commercial communication technologies

In view of this problem, the scientific community is committed to a clear solution to avoid the use of commercial communication technologies for wireless charging of electric vehicles: simultaneous wireless power and data transfer (SWPDT) systems [24]. In these systems, data transmission is carried out via the power transmission circuit, without the need for external communication systems. In this way, the data transmission system is integrated into the power transmission circuit, making the wireless charger more reliable.

Although the use of SWPDT is convenient for other scenarios (medical implants [25], [26], general applications [27]), the interest for this technology in the context of EVs is growing, as analysed during the development of this doctoral Thesis.

1.2 Objectives

This doctoral thesis has the objective of designing and implementing an inductive wireless charger with an integrated simultaneous data transmission system. This communication exchange during the charging process can be used to realise diverse control strategies. Specifically, it is analysed the feasibility of this kind of system to support the communication related to V2G wireless charging under realistic conditions.

The specific objectives that have been developed during this work will be detailed below:

- O1.** Review of the state of the art. In this initial stage, an in-depth study of WPT and SWPDT systems will be carried out, analysing the solutions proposed in the literature, as well as the specific design criteria for each topology. This study will be performed in order to cover the lack of studies related to SWPDT systems for EVs in literature. Throughout the development of this objective, numerous useful criteria will be considered in order to carry out a classification of each topology, studying their advantages and disadvantages. Additional studies, such as case studies applied to SWPDT systems and the integration of SWPDT with OCPP and ISO 15118 protocols are included.
- O2.** Design and implementation of V2G control techniques. The possibility of implementing a control for a V2G wireless charging system will be studied. Specifically, both the active and reactive power flows will be considered. This control will be carried out in the four quadrants. Synchronisation systems will be used for the correct operation of the converters in the primary and secondary sides.
- O3.** Analysis of the effect of compensation systems in data transmission. A comparative study will be carried out about the effect of the compensation system on the data transmission system in SWPDT. This comparison will be made with two of the most commonly used compensation systems in wireless charging chargers due to their advantages: Series-Series and LCC-LCC compensation topologies. In this comparative study, variables such as bandwidth will be analysed, and a three-axis misalignment study will be carried out for each topology.

- 04.** Study of the relation of the misalignment and power level effects on data rate. This analysis will conclude how misalignment and transmitted power level in a SWPDT circuit affect the data rate of the communication system. For this purpose, the results will be validated experimentally, studying misalignment in all three axes.
- 05.** Design and implementation of a SWPDT system. The design of a SWPDT system that will be integrated into a SAE J2954-compliant wireless electric vehicle charger is carried out. First, the system will be designed based on the analysis of the compensation system and the misalignment effect. Then, a simulation study will be carried out to check the validity of the design. Finally, it will be implemented in an experimental prototype in the laboratory.

1.3 Contributions

The first contribution of this doctoral thesis is the elaboration of an in-depth review of the state of the art of SWPDT systems in electric vehicles, which had not yet been addressed in the previous literature, as shown in Fig. 1.4. Then, different contributions related to V2G control and distributed algorithms are presented. Going deep into SWPDT systems, a comparative analysis about SS and LCC-LCC compensation systems is carried out, highlighting their effect on the data channel. Finally, in order to promote synergy between the above contributions, a SWPDT system for V2G chargers is proposed.

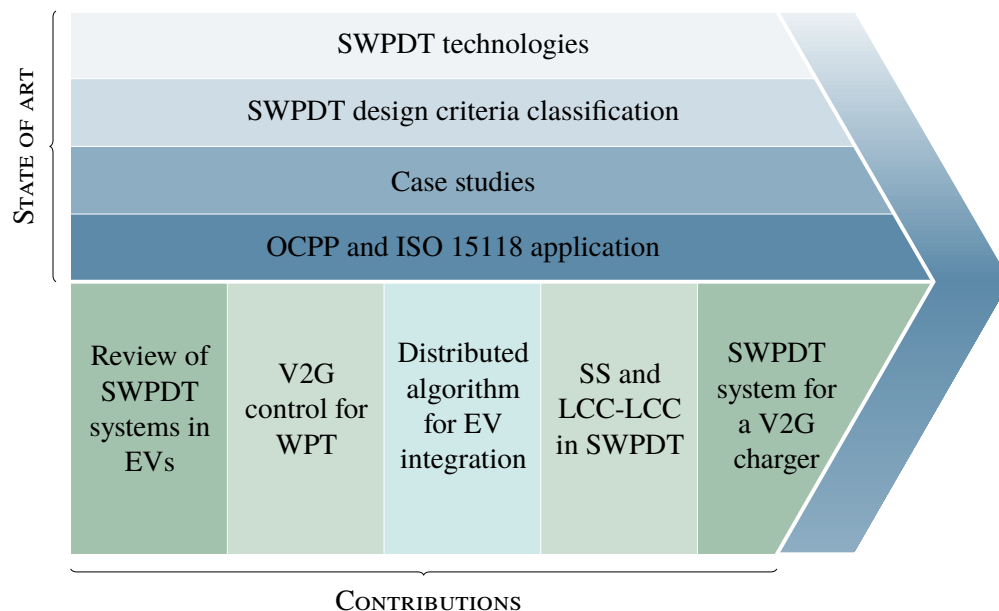


Figure 1.4: Developmental stages of the Thesis.

Table 1.1: List of contributions and relationship with objectives.

Contribution	Objective
A. Triviño, I. Casaucao and M. Castilla, "Flexible Regulation of Active and Reactive Power for a Fully-controllable V2G Wireless Charger" in IEEE Transactions on Transportation Electrification, doi:10.1109/TTE.2023.3265189 JCR Impact Factor (2022): 7 (Q1) .	O2
I. Casaucao , A. Triviño and Z. Lin, "Simultaneous Wireless Power and Data Transfer for Electric Vehicle Charging: A Review," in IEEE Transactions on Transportation Electrification, doi:10.1109/TTE.2023.3309505. JCR Impact Factor (2022): 7 (Q1) .	O1
A. Triviño, I. Casaucao , J.C. Quirós, P. Pérez and A. Rojas, "Novel sustainable magnetic material to improve the wireless charging of a lightweight drone", in RSC Advances, https://doi.org/10.1039/D2RA07800G JCR Impact Factor (2022): 3,9 (Q2) .	O1
A. Triviño, I. Casaucao and J.A. Aguado (2023). "Distributed Operation of an Electric Vehicle Fleet in a Residential Area". In Energy Smart Appliances (eds A. Moreno-Munoz and N. Giacomini). https://doi.org/10.1002/9781119899457 Book chapter .	O2
I. Casaucao , A. Triviño Cabrera, "Inductors", Editor(s): Jorge García, Encyclopedia of Electrical and Electronic Power Engineering, Elsevier, 2023, Pages 229-246, ISBN 9780128232118, https://doi.org/10.1016/B978-0-12-821204-2.00019-2 . Encyclopaedia chapter .	O1
I. Casaucao and A. Triviño. Sistema de Transmisión Inalámbrica Simultánea de Potencia y Datos. In IBEMOB'22. Proceedings of 1 Iberoamerican Workshop on Electromobility, 2022. International conference .	O3

Continued on the next page

Table 1.1: List of contributions and relationship with objectives (continued)

Contribution	Objective
I. Casaucao and A. Triviño. SS and LCC compensation system for SWPDT: comparative analysis. In 4th IEEE International Conference on Advances in Magnetism - IEEE AIM 2023, 2023. International conference.	O4
I. Casaucao and A. Triviño. A Simultaneous Wireless Power and Data Transfer System for an SAE J2954 compliant EV Charger. In Global Conference on Wireless and Optical Technologies (GC-WOT'23), 2023. International conference.	O3
I. Casaucao , A. Triviño, F. Corti and A. Reatti, "SS and LCC-LCC in Simultaneous Wireless Power and Data Transfer: a Comparative Analysis for SAE J2954-compliant EVs" in IEEE Transactions on Industrial Informatics, doi: 10.1109/TII.2024.3360510 JCR Impact Factor (2022): 12.3 (Q1).	O5

1.4 Structure of the document

The structure of this document is divided into 4 chapters, in which the following concepts are addressed:

- **Chapter 1** presents the motivation for this doctoral thesis, analysing the objectives established during its development, as well as the final contributions achieved throughout the process.
- **Chapter 2** develops the theoretical basis and the state of art of all the concepts addressed in this doctoral thesis, such as wireless charging of electric vehicles, SWPDT systems, the V2G control algorithm, as well as communication protocols in electric vehicle chargers.
- **Chapter 3** contains the contributions achieved during the development of this doctoral thesis, providing a brief summary of each one of them, which includes the most relevant concepts and achievements.
- The document of this doctoral thesis ends with **Chapter 4**, where the conclusions obtained throughout the whole process are presented, as well as the future lines identified.

Chapter 2

STATE OF ART

In this chapter, a description of the state-of-the-art of communication systems in wireless electric vehicle chargers as well as the V2G control strategy is developed. First, the concept of wireless charging is briefly defined, followed by the definition of SWPDT systems. Second, the existing topologies in SWPDT systems, which offer different solutions in their design, are analysed. Furthermore, the variables analysed in these systems, which are important to meet the requirements of the application, are studied in depth. In this chapter, special mention is made to the V2G control algorithm, analysing the state of the art and its integration in SWPDT systems. Finally, the most commonly used communication protocols in wireless charging of electric vehicles are mentioned, highlighting the use of OCPP and ISO 15118.

2.1 Wireless power transfer charging

In order to address the topic of SWPDT chargers, the basics of wireless charging must be first introduced. The initial concept to be defined is the used wireless charging technology. Chapter 1 of this document briefly mentions the many technologies available for wireless charging of electrical devices. The most common ones are [9]:

- Inductive-resonant. This technology is based on the transmission of power through a pair of coupled coils. As explained throughout this section, the principle of operation of this technology is based on Faraday's Law and Ampère's Law.
- Capacitive. In a capacitive charger, the power transmission is performed by generating an electrical field between two capacitors. These capacitors consist of two parallel and close plates, constructed between the transmitter and the receiver sides.
- Microwave-based. In this case, a magnetron generates microwaves, which pass through a waveguide and then are radiated by the transmitting antenna. Then, in the receiver, a rectenna converts the microwave into a DC signal, which feeds the battery.
- Optical or laser. Finally, this technology uses a laser diode to generate the optical wave. This beam of light is of a specific wavelength and power. Additionally, a beam director is included to correctly adjust the direction, in order to reach the receiver. In the receiver side, photovoltaic cells are placed to convert the laser light into power.

Among all these technologies, the most robust and widely used in electric vehicles is the **inductive-resonant** technology.

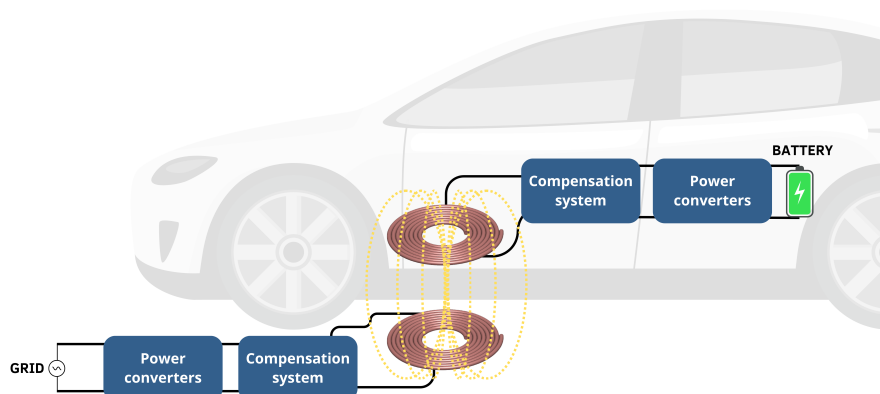


Figure 2.1: WPT Generic system scheme.

The structure of an inductive-resonant charger is illustrated in Figure 2.1. The power transmission is carried out through a pair of air-core coupled coils, being divided into the

transmitter coil (included in the primary circuit) and the receiver coil (included in the secondary circuit). For EV charging, the primary circuit would be located in the Electric Vehicle Supply Equipment (EVSE), and the secondary circuit in the EV. The operation of this technology is mainly governed by the principle of electromagnetic induction, explained through two Laws: Ampère's Law and Faraday's Law [28], [29]. As can be seen in Figure 2.1, the generic scheme consists of a set of power converters (an AC-DC rectifier and a DC-AC inverter, typically) that provides a variable current that travels through the compensation circuit and the primary winding (modelled as the inductance L_1 and its internal resistance R_1). By Ampère's Law, this variable current generates a magnetic field across the conductor. Since the primary coil is coupled with the secondary one (as indicated by the mutual inductance, M), the variable magnetic flux will be received by the secondary winding (represented by the self-inductance, L_2 , and the internal resistance, R_2). The voltage induced in this part of the circuit is transmitted to the battery through an AC-DC rectifier. The amount of power transferred in the charging process will depend, according to Faraday's Law, on the variation of the magnetic flux received by the secondary winding. The variation increases with the frequency of the magnetic field involved in this process, which is set by the power converters. Typically, the frequency ranges from 22 to 25 kHz and from 79 to 90 kHz.

Additionally, in resonant inductive systems, a compensation system is used to improve the power transfer between the primary and secondary circuits. The function of these compensation systems is to make the circuit work in resonance at a given frequency. The most basic form of a compensation system consists of the inclusion of a capacitor in series or in parallel with the main coil in both the primary and secondary circuits. This results in 4 different topologies, named as mono-resonant systems: Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP). Figure 2.2 shows the equivalent circuits of these topologies, being C_1 and C_2 the compensation capacitors, L_1 and L_2 the primary and secondary inductors, and R_1 and R_2 the primary and secondary coil resistances, respectively. These circuits are represented by considering the equivalent AC input voltage (V_{in}) and the equivalent battery resistance (R_{BAT}).

In the basic structures represented in Figure. 2.2, the capacitor is calculated to force the circuit to work in resonance at the working frequency. The relation between the capacitor value and the inductor value is given in Table 2.1 for each compensation system. The efficiency (η) is measured as the relation between the output power (P_{out}) with respect to the input power (P_{in}). Considering that the circuit works in resonance at the selected operation frequency, the values for η in mono-resonant circuits are presented in Table 2.1.

In addition to these basic topologies, more complex topologies such as LCL or LCC can be found in the related work. The LCL system consists of the inclusion of a coil in

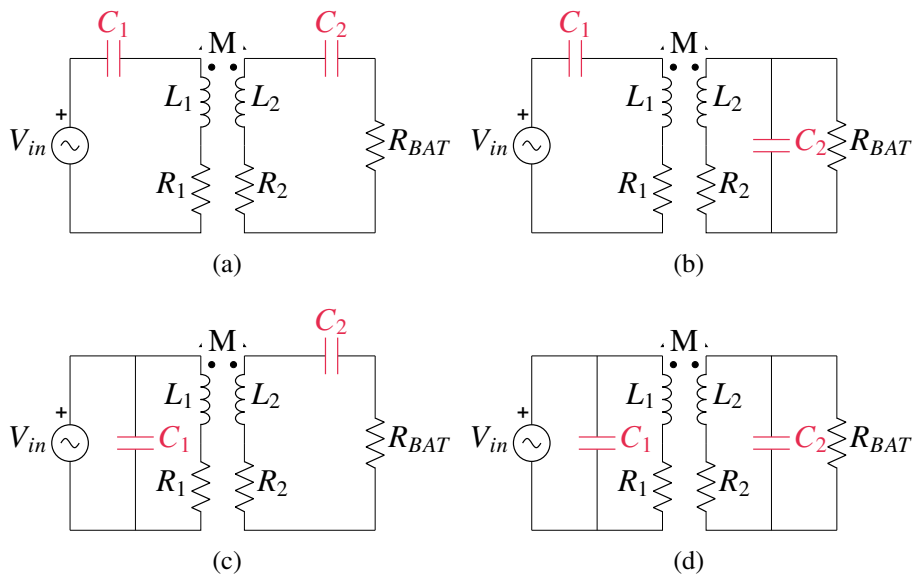


Figure 2.2: Mono-resonant Compensation systems (a) Series-Series (SS), (b) Series-Parallel (SP), (c) Parallel-Series (PS), (d) Parallel-Parallel (PP).

Compensation system	Primary Capacitor Value	Secondary Capacitor Value	Efficiency
SS	$C_1 = \frac{1}{L_1 * w^2}$	$C_2 = \frac{1}{L_2 * w^2}$	$\eta \approx \frac{R_L}{R_2 + R_L}$
SP	$C_1 = \frac{L_2^2 C_2}{L_1 L_2 - M^2}$	$C_2 = \frac{1}{L_2 * w^2}$	$\eta \approx \frac{R_L}{R_2 + R_L + \frac{R_1 * L_2^2}{M^2}}$
PS	$C_1 = \frac{L_2 C_2}{L_1 + \frac{M^4}{L_1 L_2 C_2 R_L^2}}$	$C_2 = \frac{1}{L_2 * w^2}$	$\eta \approx \frac{R_L}{R_2 + R_L}$
PP	$C_1 = \frac{(L_1 L_2 - M^2) L_2^2 C_2}{\frac{M^4 R_L^2 C_2}{L_2} + (L_1 L_2 - M^2)^2}$	$C_2 = \frac{1}{L_2 * w^2}$	$\eta \approx \frac{R_L}{R_2 + R_L + \frac{R_1 * L_2^2}{M^2}}$

Table 2.1: Efficiency and capacitor values of compensation systems

series with the PP structure described above. The LCC technology adds a new element to the LCL system, which consists of a capacitor connected in series with the main coils. These two systems are named multi-resonant systems, and can be seen in Figure 2.3.

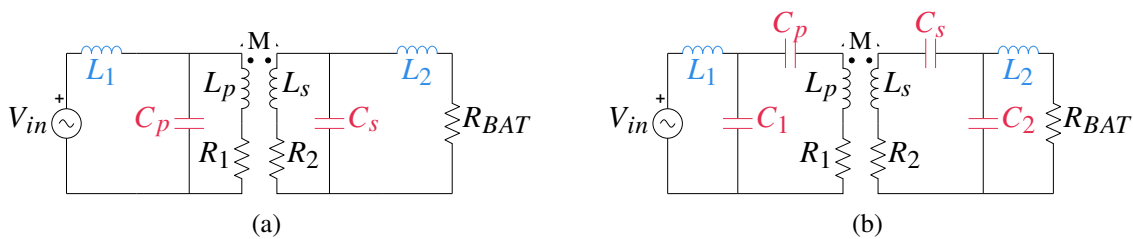


Figure 2.3: Multi-resonant compensation systems (a) LCL (b) LCC.

The convenience of each compensation topology depends on the application requirements to be fulfilled, such as efficiency maximization, simplification of control techniques or the tolerance to the non-ideal position between the power coils, known as misalignment, as shown in Fig. 2.4.

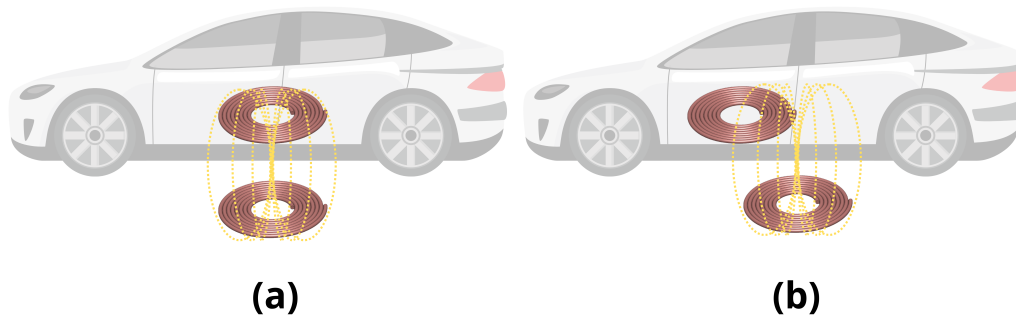


Figure 2.4: Position between coils (a) ideal, (b) with misalignment.

On the other hand, special attention should be paid to the regulation of inductive WPT chargers. The main standard is *SAE J2954: Wireless Power Transfer for Light-Duty Plug-In/Electric Vehicles and Alignment Methodology* [30], whose latest version was released in 2022. This standard regulates the interoperability of light-duty vehicles with different universal wireless chargers in static charge. This standard is focused on static charging, where the EV is positioned in a fixed place during the entire charging process. Although the EV does not move, the position may not be exactly the one considered in the design process.

There are three design criteria for WPT chargers that can be deduced from this standard:

- **Coil geometry.** This standard proposes the dimensions, geometry and gap between coils according to the type of charger implemented. These chargers can be classified according to the gap between coils and the transmitted power level, as can be seen in Table 2.2. However, the common suggested solution for all classes is a rectangular coil on primary side (ground assembly-GA), and a square inductor for the secondary side (vehicle assembly-VA), as can be observed in Fig. 2.5.

Table 2.2: SAE J2954-2022 power and classes classification.

Range of input Volt-Amps	WPT1	WPT2	WPT3
	0 to 3.7 kVA	0 to 7.7 kVA	0 to 11.1 kVA
Class	Z1	Z2	Z3
	100 to 150 mm	150 to 200 mm	200 to 250 mm

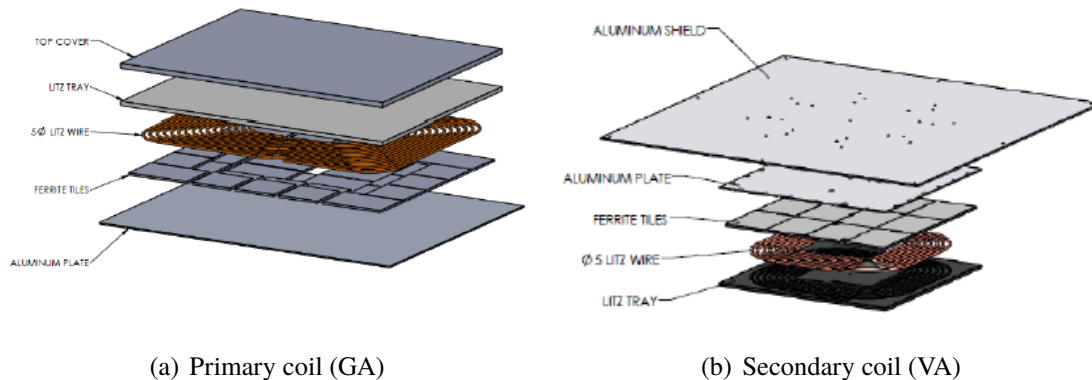


Figure 2.5: SAE J2954 proposed coils. Source: [30]

- **Operation frequency.** As stated in SAE J2954 standard, the working frequency range at which the system reaches the resonance is from 79 kHz to 90 kHz. According to the reviewed literature and the proposed solutions, the nominal value is 85 kHz.
- **Misalignment margins.** The misalignment margins are proposed for each axis, giving the maximum tolerance for each case and considering, in addition, the minimum target efficiency that must be fulfilled. The acceptable misalignment values for each axis are shown in Table 2.3.

Table 2.3: Positioning tolerance requirements for Test Stand VAs and Product VAs.

Axis	Value (mm)
ΔX	± 100
ΔY	± 100
ΔZ	Specified by manufacturer

Although SAE J2954 is oriented to static charging, there are other options which can be applied to wireless charging, such as stationary and dynamic charging. In stationary charging, the EV charges its battery during short periods of time, that it, in a non-continuous way. This can be useful for buses, which can be recharged in bus stops during its itinerary. On the other hand, in dynamic charging the EV battery can be recharged while moving. In Fig 2.6, these three technologies are shown. These wireless charging options are not exclusive of inductive charging, but they are more mature with this technology.

The basic concepts outlined in this section provide an understanding of the foundations on which simultaneous power and data transmission circuits are based.

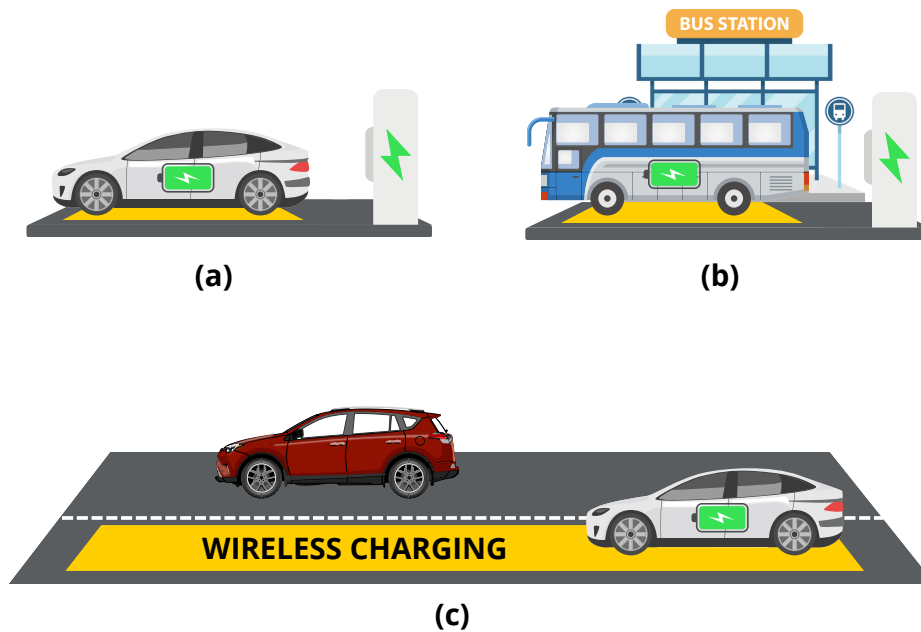


Figure 2.6: Wireless charging methods (a) static, (b) stationary, (c) dynamic.

2.2 Simultaneous wireless power and data transfer systems

As in traditional charging, communication plays a critical role in wireless charging systems. The establishment of a continuous and robust communication framework between the charging infrastructure and EVs stands as the basis of a correct and controlled charging process. The information that needs to be transmitted during the charging process of an electric vehicle is diverse and it depends on the use of the charging station (i.e. the data involved is different if the charging station is intended for multiple users previous payment or if it is domestic). The communication exchange in WPT may include data related to:

- **Control.** Communication allows the EV and the charging station to exchange information about the availability of power in the grid and other relevant factors, such as the participation of the EV in controlled charging algorithms. This leads to a more precise and efficient control of the charging process.
- **Identification and authentication.** The EV must be authenticated and identified, so that the charging station allows only authorised vehicles to access charging. This prevents unauthorised use of public charging stations.
- **Vehicle status.** Bidirectional communication between the vehicle and the charging station enables the exchange of status data in real time. The vehicle can report its

current charging status, State of charge (SoC), battery temperature and other relevant data.

- **Payment.** After the charging of the electric vehicle has been completed, payment for the energy consumed is required. Consumption and charging data, as well as information related to the vehicle owner, are transmitted to the charging station.

Communication during charging of plug-in electric vehicles is an area that has been addressed not only as a research topic, but also at the commercial level. These vehicles use communication protocols that have been created specifically for this application. There are mainly two protocols: OCPP and ISO 15118. ISO 15118 is used for the information exchange between the EV and the EVSE, while OCPP is required to transmit information between the EVSE and the central system.

As an initial solution, SAE J2847/6 [31], included in SAE J2954 standard, establishes that the communication technology that can be used in wireless charging for EVs is IEEE 802.11 (Wi-Fi). However, this technology, as well as Bluetooth (BT), Zig-Bee, or Radiofrequency (RF), presents some drawbacks related to the following issues:

- The connection between the vehicle data controller and the charging station may experience difficulties during the pairing process. Throughout this process, both devices register their information in order to create a link between them. This is a crucial step during the beginning of communication since the absence of pairing between devices prevents the data exchange.
- Potential connection loss during information exchange may occur due to multiple reasons (i.e. interference from other devices, a weak connection, or deterioration of the antennas used), thereby hindering proper system functionality. The frequencies used by these technologies are widely employed in common applications, so relevant interference can appear in the data carrier wave.
- The transmission delays are noticeable (up to 6 ms in the case of RF [32] and up to 46 ms in the case of BLE [33]).
- Since these technologies are highly extended, cybersecurity problems are commonly identified and published, so they can be easily found in the physical implementation, making information more vulnerable to attackers [22], [23].

As an alternative to the use of commercial technologies, researchers are deeply investigating a new solution known as Simultaneous Wireless Power and Data Transfer (SWPDT) systems. The consideration of SWPDT systems involves a paradigm change in electric vehicle communication, in which the aim is to modify the current communication scenario

depicted in Figure 2.7.a into the scenario shown in Figure 2.7.b. The definition of this technology is the simultaneous transmission of power and information by using, in most cases, the same inductive link. This approach has several beneficial applications for many scenarios, such as V2G control systems.

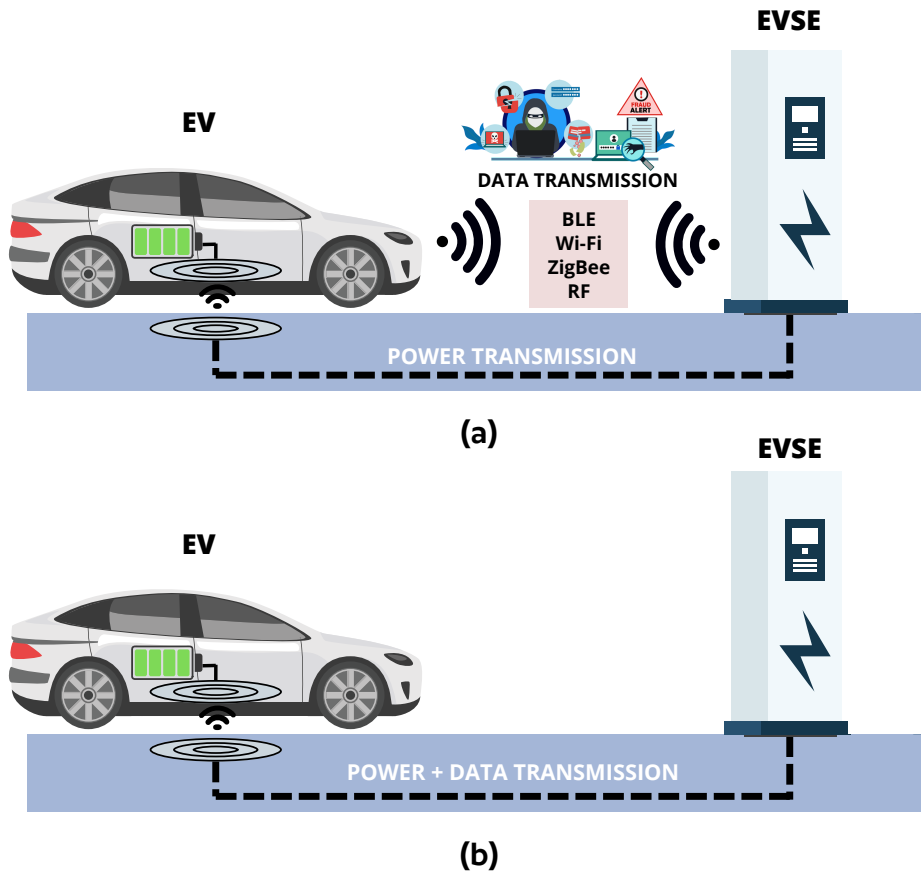


Figure 2.7: Communication scheme with (a) commercial technologies, (b) SW-PDT technology.

SWPDT topologies

The proposed solutions for SWPDT systems are diverse and do not adopt an unique configuration. In literature, there are numerous proposals that opt for different methods to implement SWPDT chargers. Specifically, six design criteria have been identified in this Thesis:

- **Number of links and number of signal carriers.** A pair of coupled inductors is considered as a wireless link in inductive WPT systems. In this case, it is necessary to determine the number of links and signals needed to perform the power and data transmission. This simultaneous transmission can be performed through one link

and one signal, through one link and two or more signals and, finally, through, at least, two links and two signals.

- **Data communication type.** The data communication type is classified depending on the direction of the data transmission, as well as the simultaneity of information in both directions. Three categories can be distinguished:
 - With the **simplex** configuration, the information is transmitted only in one direction (from primary to secondary side, or from secondary to primary side).
 - The **half-duplex** technique allows the information to be transmitted in both directions, but not simultaneously (from primary to secondary side and from secondary to primary side at, different time slots).
 - Finally, with **full-duplex** configuration, a data signal can be transmitted simultaneously in both directions (from primary to secondary side and from secondary to primary side at the same time slot).

It should be noted that both half-duplex and full-duplex are bidirectional technologies, while simplex is an unidirectional communication.

- **Signals multiplexing technique.** In the application of wireless charging of EVs with data transmission, it is common that two different signals coexist in the same circuit. There are different multiplexing techniques that allow them to be transmitted simultaneously [34], such as:
 - Frequency Division Multiplexing (*FDM*). Two (or more) different frequencies are used within the available bandwidth for transmitting two signals.
 - Time Division Multiplexing (*TDM*). Two (or more) signals are transmitted in different time slots, following an alternating pattern, using (or not) the same frequency within the available bandwidth.
- **Modulation of data signal.** The data transmitted by the circuit can be modulated through the following techniques [35]:
 - Modulation with amplitude variation, being Amplitude Shift Keying (*ASK*) and On-Off Keying (*OOK*) representative options.
 - Modulation with phase variation. The most popular techniques are Phase Shift Keying (*PSK*), Binary Phase Shift Keying (*BPSK*), Differential Phase Shift Keying (*DPSK*), Quadrature Phase Shift Keying (*QPSK*), Differential Quadrature Phase Shift Keying (*DQPSK*).

- Modulation with frequency variation. Frequency Shift Keying (FSK) and Binary Frequency Shift Keying (*BFSK*) are the techniques used in this category for SWPDT.
- **Data injection/extraction.** Depending on the technique used to inject or extract the data, different methods can be distinguished according to two categories:
 - Depending on the electronics used: transformers, inductors, direct connection or toroidal-core inductor. Each technology is selected according to the advantages offered to the complete system, being the transformer and toroidal-core inductors the most used topologies.
 - Depending on the injector/extractor circuit connection to the power electronics: series or parallel. This connection is made with respect to the primary and secondary main coils.
- **Compensation system.** Different compensation systems can be used, such as SS, SP, PS, PP, LCL or LCC. To determine the appropriate compensation system for the design, the bandwidth tolerance to misalignment must be considered, as this is a factor that varies according to the chosen compensation system.

The number of signals and links is the main classification of SWPDT systems. According to this criterion, three main types can be distinguished in the reviewed literature. These types are named as Single Link - Single Carrier (SL-SC), Single Link - Double Carrier (SL-DC) and Double Link - Double Carrier (DL-DC) [36], as shown in Figure 2.8. In case of SL-SC, the information is transmitted through the variation of the power signal (f_{p1} and f_{p2}), in terms of amplitude, frequency or phase [37], [38]. On the other hand, for SL-DC topology, two different signals are needed: one for the power transmission (f_p), and another one for the data transmission (f_d). In this case, both signals are transmitted through the same inductive link, so the selected frequencies must be at least an order of magnitude apart in order to facilitate the correct interpretation of each of them [39], [40]. Finally, DL-DC topology is found. In this case, there are two (or more) inductive links, one of them intended for power transmission (f_p), and a smaller one for information exchange (f_d) [41], [42]. The literature review performed during this doctoral thesis shows that the most widely used technology is SL-DC, since it is the most flexible with respect to the other options.

With regard to the communication type, it is important to highlight that a high number of solutions propose bidirectional information transmission. Although simplex communication can be found in literature [43], [44], half-duplex [45], [46] and full-duplex [47], [48] are the most commonly adopted solutions by authors. In Fig. 2.9 the three basic topologies

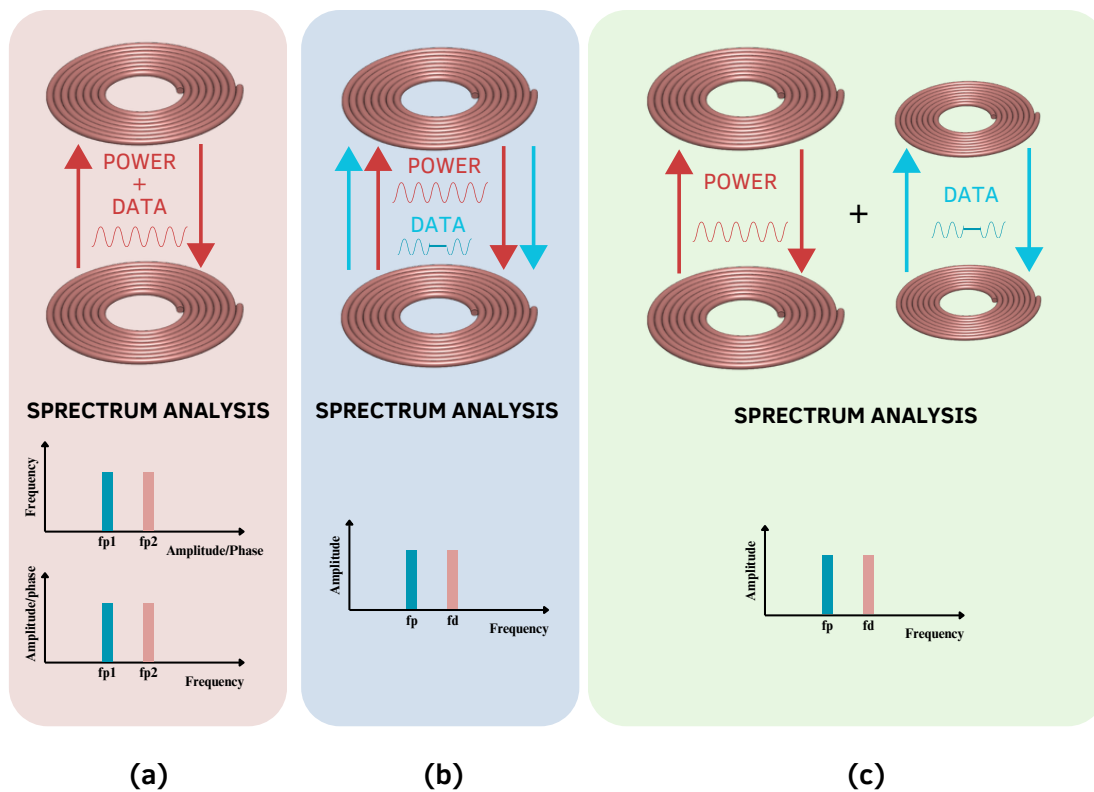


Figure 2.8: SWPDT charger types (a) SL-SC, (b) SL-DC, (c) DL-DC.

are shown. Bidirectional communication is a determining factor regarding to the communication protocol used. Some EV communication protocols, such as OCPP 2.0.1 and ISO 15118, work with a bidirectional message structure, where there is an exchange of information between the EV and the EVSE. Thus, it is important to consider if the final application of the system requires this type of communication. If so, only half-duplex and full-duplex solution can be proposed, while simplex proposals can be used where communication in one direction is needed, thus simplifying the circuit.

On the other hand, in some cases it is necessary that two or more signals coexist through the same channel. Thus, a method that allows to perform the transmission of each signal without problem is required. In communication, there are two main methods: Frequency Division Multiplexing (FDM) and Time Division Multiplexing (TDM), as indicated in Fig. 2.10. In FDM, the available bandwidth of the channel is divided into smaller frequency bands, and each signal is assigned a distinct frequency band for transmission. In case of EV charging, these signals are usually separated by an order of magnitude apart (in the order of kHz for power transmission, and in the order of MHz for data transmission). Then, in TDM, instead of dividing the available bandwidth into frequency bands as in FDM, the channel capacity is divided into sequential time slots. As can be deduced from literature, solutions propose FDM as the preferred technique to perform simultaneous transmission

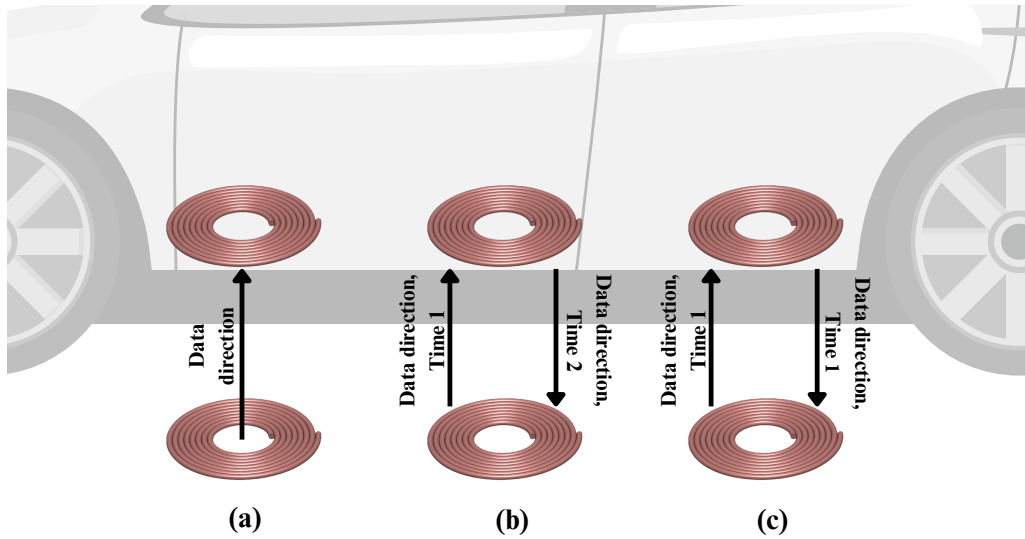


Figure 2.9: Communication type (a) simplex, (b) half-duplex, (c) full-duplex.

of signals [49], [36], [50] although, in some cases, TDM can be found [51].

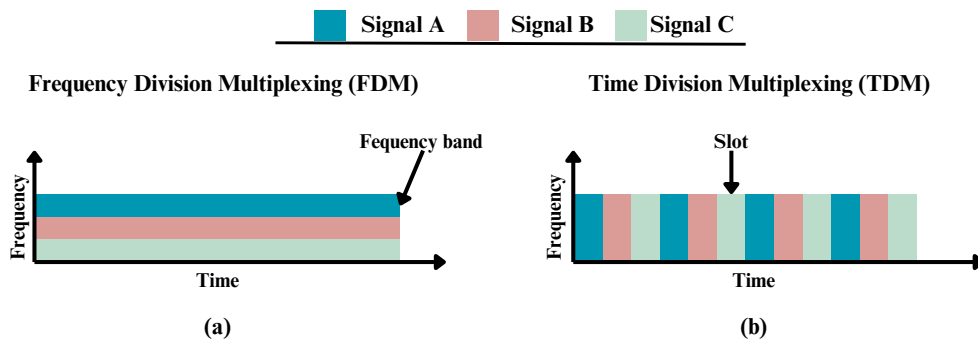


Figure 2.10: Signal multiplexing techniques (a) FDM, (b) TDM.

As mentioned before, the information transmission is usually performed by the inclusion of a second carrier at a different frequency, sufficiently far from the frequency of the power signal (at least an order of magnitude apart). In addition, this data transmission can also be carried out through the variation of the power existing signal. Thus, at this point, it is necessary to mention what is considered information in SWPDT systems. Data exchange in SWPDT systems consists of sending a succession of logic 0's and 1's (bits) which together represent a specific information in the receiving circuit. To do so, it is necessary to decide the optimal alternative to perform the modulation of this information. The most common techniques are Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying (PSK). As shown in Figure 2.11, ASK consists in the transmission of a logic 0 or 1 by modifying the amplitude of the carrier signal. On the other hand, FSK modulation uses the frequency variation to code the bits sequence during the information

transmission process. Finally, in PSK modulation, the phase of the carrier signal is varied to represent different bits. These three techniques are the basis for other more complex methods such as BPSK, DPSK, QPSK, DQPSK or BFSK.

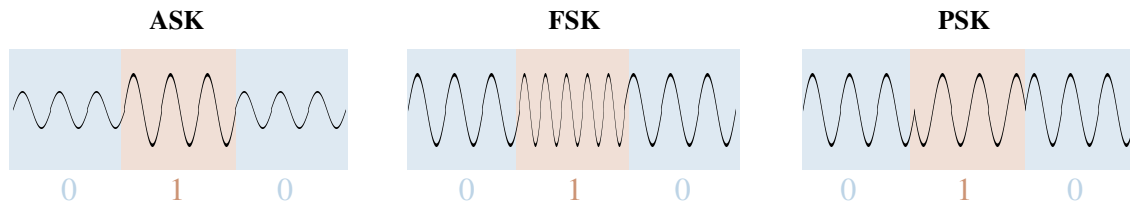


Figure 2.11: Modulation techniques waveforms.

With respect to the manner in which the data is transmitted through the power circuit, it is necessary to mention the specific case of SL-DC. In this technology, the information must be injected and extracted from the power circuit. According to the reviewed literature, there are several methods to perform the injection and extraction process. Considering the used electronics, transformers and toroidal cores can be highlighted. Both topologies allow the isolated injection and extraction of data into the power system. The main difference between them is the complexity of their designs, since authors propose toroidal core as a solution to simplify the design stage. In case of the transformer, the power signal flows into the transformer winding, so this element must be designed considering the main variables from the power circuit, as primary and secondary current or voltage. In contrast, with toroidal core the power signal flows through the existing power line, and the data is injected and extracted into the circuit as a result of the coupling between power line and the toroidal core winding. The main consideration that must be taken into account is the saturation of the selected core, since it is possible that the behaviour of the toroidal transformer changes according to this variable [52].

On the other hand, analysing the connection between the data injection/extraction method, it is found that authors propose both series and parallel connection with respect to the main coil. Throughout this analysis, it can be deduced that authors do not determine which is the optimal method to perform the data extraction/injection, founding proposals both for series connection [53], [54] and parallel connection [55], [56].

Finally, the compensation system used have a high impact on the power channel performance. As for the WPT systems, in SWPDT circuits there are also a high number of proposals that include different compensation topologies according to the application requirements. Thus, it can be found that the four basic structures (SS, SP, PS, PP) are widely used in literature, as can be seen in [57]. However, it can be noted that there is a recent trend of using multi-resonant systems, such as LCC, so that this topology has a good performance under misalignment situations and a similar efficiency values with respect to SS. It should be mention that no specific topologies have been found for SWPDT systems,

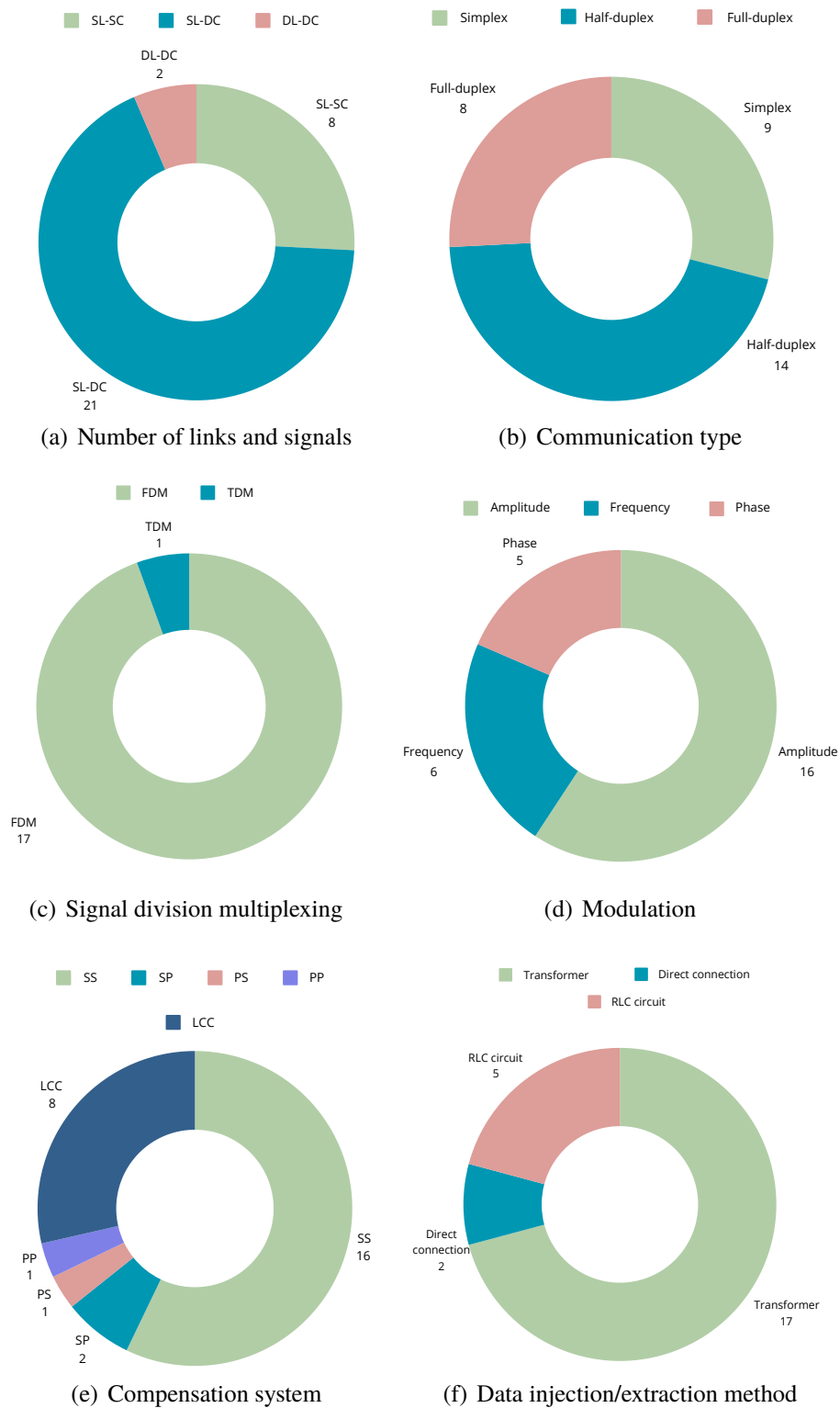


Figure 2.12: Statistics of the most adopted solutions in the literature.

therefore, the literature does not make a differentiation with respect the compensation systems used in WPT.

There is another characteristic to study in the SWPDT reviewed literature: coil geometry. Analysing this variable, it can be found that circular, square, rectangular and DD coils are used. However, this classification has no relevance in this study since, as briefly mentioned in Section 2.1, the standard SAE J2954 defines the coil geometry and dimensions both for primary and secondary side. According to this standard, although different topologies can be found, the typical geometry is a square planar inductor for the secondary coil (VA) and a rectangular planar inductor for the primary coil (GA), as stated in Section 2.1.

In Fig 2.12, the most adopted solutions for each category are represented. By analysing the results, it can be deduced that SL-DC, where two or more signals coexist in the same channel, is the most widely used topology according to the number of signals and links classification. In these systems, the use of transformers to inject and extract the data and to keep the power and data circuits isolated is of particular importance. With regard to the communication type, bidirectional solutions are the preferred topology by authors, with emphasis on half-duplex solution. In the specific case of SL-DC, the signal multiplexing technique that is outstanding is FDM, with a high difference with respect to TDM. On the other hand, analysing the modulation technique employed, there is a high number of solutions that highlight the amplitude modulation method as the simplest proposal to perform data transmission. Finally, it can be noted that SS have been the most widespread compensation topology due to its simplicity and effectiveness. However, there is an actual trend of using LCC structure, since it has numerous advantages for different applications such as misalignment tolerance studies and dynamic charging.

Applications of SWPDT systems

SWPDT systems have potential applicability across several fields related to EV charging. In fact, there are several research lines that study the improvement of wireless chargers functionalities based on a SWPDT approach. Thus, it is possible to highlight different applications that can be suitable for SWPDT implementation in EV wireless chargers, as shown in Fig. 2.13.

The first application that should be considered is **maximum efficiency control**. In EV wireless charging, the power levels involved require a maximum efficiency control [58], [59], [60]. In this way, the inductive charger performance could be equivalent to conductive chargers. In the maximum efficiency control algorithms found in literature, it is typical practice to utilize a communication system that permits the interchange of parameters, such as load voltage, load current, or battery status, between the two components of the circuit (primary and secondary sides). With some data exchange, the algorithms are able to reach the point of maximum efficiency as these variables are known. Therefore, it

can be deduced that a robust communication between the primary and secondary circuits is necessary for these systems, in order to prevent connection losses, pairing issues or latencies. The use of SWPDT systems for maximum efficiency control is conditioned by communication parameters, such as data rate or bandwidth, which must be studied and properly designed in order to meet all requirements.

Second, **synchronisation between power converters** must be mentioned. One of the specific applications of data transmission is the use of information to perform the synchronisation between primary and secondary power converters [61], [62]. Some proposals apply control algorithms both in primary and secondary sides [63], so the synchronization of the signals that activate the power converters is crucial. Additionally, this synchronization can be useful to control the power flows V2G operations based on a phase-delay technique [17]. The basis of this approach is the generation of a delay between the activation of secondary power devices with respect to the primary converter. This delay, known as δ parameter, is transmitted from primary to secondary side via wireless communication. As mentioned before, commercial communication platforms can be used to perform this action. However, the communication delays are variable due to the uncertain number of phases required for the transmission (initial setup, pairing, etc.) and each one takes an unprecise time. In addition, with commercial communication technologies, the system is forced to incorporate complex synchronisation techniques as the ones described in [64]. Thus, these drawbacks allow the consideration of a SWPDT system as a useful alternative.

Another remarkable application is **dynamic charging or charging on-move**. Dynamic charging is a topic of interest in literature in recent years [65], [66], [67], [68]. In this application, data transmission between EV and EVSE is required with the same importance as in static charging. In fact, in case of dynamic charging the robustness of communication must be higher, and the information exchange must be performed faster, since during the charging process the EV is constantly in motion. As communication in these cases is a process that requires precision, in order to avoid connection losses, data loss, delays or inaccuracy, in dynamic charging systems the data exchange is generally performed at the beginning of the charging line [69]. In this way, the entire control system is based on estimations of the variables involved, such as battery status, mutual inductance or the values of voltage and current. As it is an estimation, the values obtained are subject to inaccuracies or errors, which may lead to a misoperation of the charger. Thus, in this line of research, SWPDT systems can potentially lead to a significant improvement. With the integration of a simple communication protocol, SWPDT systems can be considered as a faster alternative to commercial communication technologies, since constant communication can be maintained during the entire charging process without the need for repetitive pairing process.

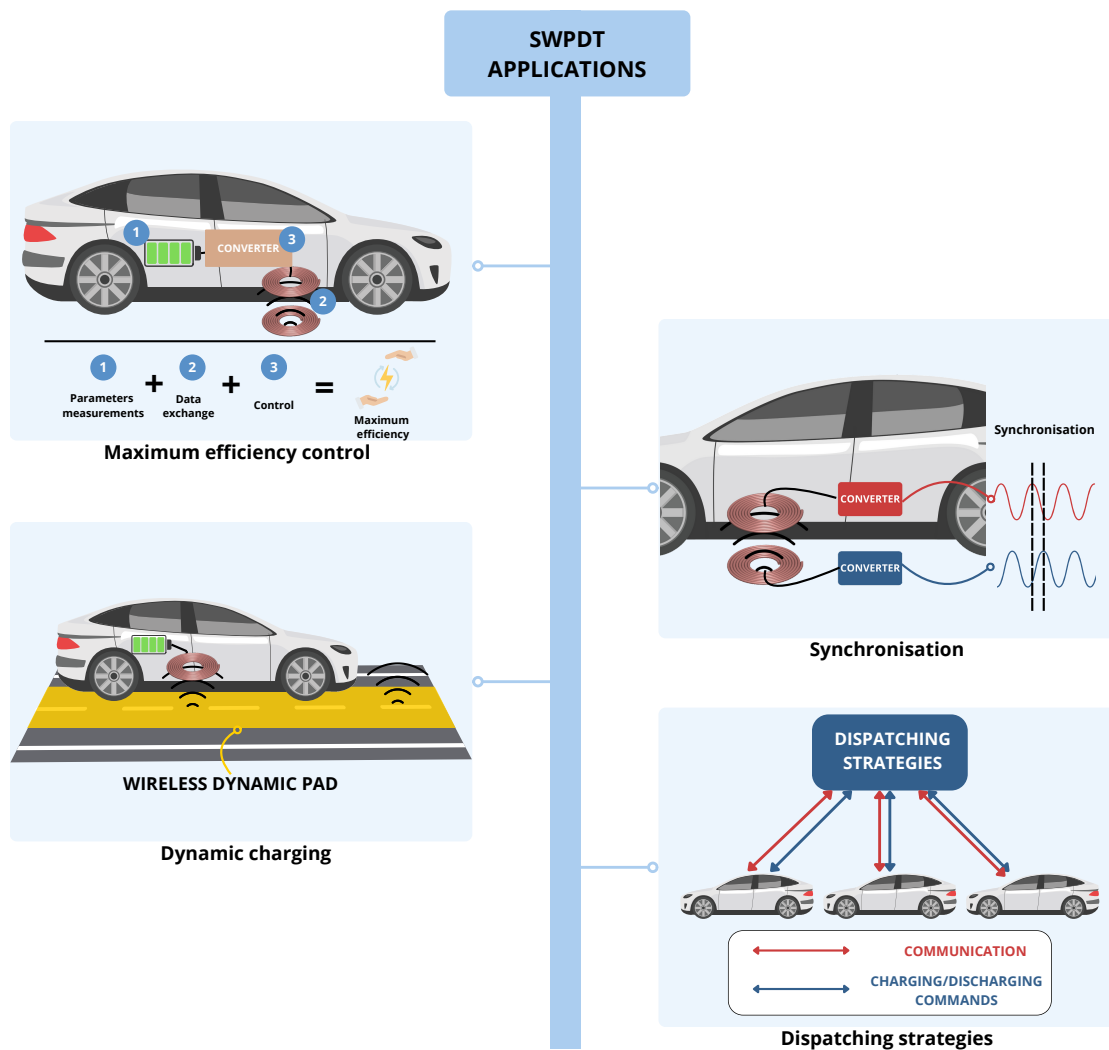


Figure 2.13: SWPDT main applications.

Finally, a fourth case study that is gaining relevance should be mentioned: **EV dispatching strategies**. With the increase of power consumption in recent years, and the growth in the number of sales of electric vehicles, the consumption is estimated to increase by further 15.98 % by 2050 [70]. Considering that most EV users decide to charge the vehicles after work, this problem is aggravated, since the peak demand in more limited time slots increases. Additionally, the emergence of technologies such as V2G or Vehicle to Home (V2H) allow bidirectional power flows. The flexibility of EV charging and the dual role as a power source could be exploited for a better performance of the power grid. As sources, the vehicles can be used as batteries at times of high demand or to provide ancillary services. In addition, constraints such as the price of electricity, or even the State of Charge (SoC) of the battery, can be followed for battery recharging with the corresponding

benefits for the users. For this purpose, optimal management algorithms are developed to determine the charging/discharging scheduling. The implementation of these algorithms requires communication between the electric vehicle and the charging station. Considering the communication requirements involved in this scenario could favour the integration of wireless charging in the market, since it will enable the participation of the EVs with this type of charging in the energy management algorithms. Thus, SWPDT systems are an optimal solution for this application as it allows the integration of a communication system into the power transmission system itself.

2.2.1 Considerations in SWPDT systems

As well as for WPT systems, in SWPDT solutions there are some considerations that should be analysed during the design process. In wireless chargers, variables such as efficiency, gain, misalignment performance or the correct choice of the compensation system have been widely studied. However, these studies are related to the effect of these variables on the power channel. In case of SWPDT systems, it is also necessary to analyse the effects that the circuit parameters can cause in the data channel. Due to the novelty of SWPDT systems in EVs, these studies are still under development, so it is important to understand the relation between system parameters and data transmission performance.

Analysed variables

In the literature, there are several studies that deeply analyse the theoretical basis of the compensation topologies. In terms of power transmission, variables such as voltage gain and efficiency are widely investigated by authors. The gain analysis is noteworthy for its impact in wireless charging systems, since it allows to understand the effect of the system parameters in the voltage ratio of the complete charger.

To perform the gain analysis, it is necessary to define two main related terms: the transfer function and the Bode diagram. The transfer function is the mathematical relation between the system input and system output [71]. This variable is expressed in the frequency domain and provides information about how a system responds to different frequencies. The basic form of a transfer function is $H(s) = \frac{Y(s)}{X(s)}$, being $Y(s)$ the system output, $X(s)$ the system input, and $H(s)$ the value of the transfer function. Both $Y(s)$ and $X(s)$ are calculated by using Laplace transform. The variable s , in frequency domain, represents the complex term $j\omega$.

The mathematical expression of the transfer function can provide a numerical idea of the system performance. However, there is a method that facilitates the understanding of the results obtained in the mathematical relation. This is the Bode plot representation. The

Bode plot representation [72], consists of two different plots: system gain, representing the amplitude response, and system phase shift, representing the phase response. The gain plot shows, in decibels (dB) the magnitude response of the transfer function (Y-axis) as a function of the frequency (X-axis). On the other hand, in phase plot the system phase shift (Y-axis), in degrees, as a function of the frequency (X-axis), can be observed.

Interesting information can be extracted from Bode diagram. One of the most useful conclusions that can be deduced is the gain value of the represented transfer function. The gain value (G) is the relation between the output voltage (V_{out}) and the input voltage (V_{in}), for each frequency, through the equation $G = \frac{V_{out}}{V_{in}}$. In addition, the phase shift between the output signal and input signal can be obtained for each frequency. In case of SWPDT systems, with two carrier signals for power and data transmission, Bode plot representation is also useful to study the predominant frequencies found in the system.

The coexistence of two carrier signals with highly difference frequencies is an important factor to be considered in the analysis of SWPDT systems. The performance of passive components, such as inductors and capacitors, varies significantly under different frequencies due to their inherent electrical characteristics [73]. The factors that can cause an impedance to increase and decrease with respect to frequency are multiple. Variables such as geometry, dimensions, permeability of the core used, and material have a considerable effect on the behaviour of the components. In a SWPDT system with SL-DC topology, there are two (or more) different signals with frequencies an order of magnitude apart, so it can be deduced that the behaviour of the components under each frequency will be different. For this reason, it is necessary to perform an analysis of the system for each of the frequencies considering a precise characterization of the components for each carrier. The study must include the definition of the transfer functions and the interference.

In addition to the transfer function, another variable that characterises a wireless charging system is efficiency (η). Efficiency refers to the ratio of useful power transferred to the EV battery (P_{out}) compared to the total active power consumed by the charging system (P_{in}). It is a crucial parameter that indicates how effectively the energy is transmitted from the charging infrastructure to the vehicle without significant losses. Additionally, higher efficiency in wireless charging systems contributes to faster charging times and better overall performance, making them more practical and interesting to users. The generic equation defining efficiency is given by $\eta = \frac{P_{out}}{P_{in}}$, where P_{out} and P_{in} are the output and input powers, respectively.

This variable is extensively analysed in all the WPT solutions proposed in the literature, as the objective of wireless charging is to achieve an efficiency similar to the efficiency achieved in plug-in EVs.

However, in SWPDT systems the analysis of transfer function, with gain and phase

study, and efficiency, is not enough. Since there are more physical variables involved in the system related to information, the analyses need to be expanded. As mentioned before, in SL-DC systems there are two or more signals that coexist on the same channel. Thus, it is interesting to study the interference between them. To do so, **Signal-to-Noise ratio (SNR)** is considered. SNR is the ratio between the voltage of the desired signal and the voltage background noise [74]. In case of SWPDT systems, data carrier is considered as the main and desired signal, and power signal is considered as the noise. The formula for Signal-to-Noise Ratio is typically expressed in dB, and is given by $SNR_{dB} = 20 \log_{10} \frac{V_{signal}}{V_{noise}}$, being V_{signal} the voltage of the data signal and V_{noise} the voltage of power signal, in the specific case of SWPDT SL-DC systems.

On the other hand, there is another concept that should be mentioned in this part, which is the **bandwidth** of a transmitted signal. The bandwidth is defined as the frequency range in which the gain of a signal is up to -3 dB below peak value. This measurement is useful when analysing the gain in the transmission of a signal, as it is possible to determine in which frequency range an output of a desired value is obtained. If a peak value is calculated for the signal gain, the bandwidth provides the frequency limits to meet that value with a maximum difference of -3 dB, allowing the system certain flexibility with respect to the operating frequency.

Furthermore, it should be mentioned that, through the Nyquist theorem, the data rate is directly related to the bandwidth. Nyquist theorem establishes that the maximum bit rate for a noiseless channel can be calculated through $DR = 2B \log_2(L)$, being DR the data rate, i.e. the number of bits per second, B the bandwidth of the channel and L the number of signal levels. Therefore, a change in bandwidth directly leads to a change in the data rate, which is an important consideration in SWPDT systems.

In addition, another important variable in communication is the **capacity** of the channel. Capacity of a communication channel refers to the maximum rate at which information can be reliably transmitted over that channel [75]. It provides an upper limit on the achievable data rate for a given channel with a specified level of reliability. The concept of channel capacity is formulated by the Shannon-Hartley theorem [76]. This theorem establishes a theoretical upper bound on the channel capacity, which is the maximum rate at which information can be transmitted over a communication channel with a specified bandwidth in the presence of noise. The channel capacity is often denoted by the symbol C and is measured in bits per second (bps), and its formula is given by:

$$C = B \log_2 \left(1 + \frac{V_{signal}}{V_{noise}} \right) \quad (2.1)$$

, being C is the channel capacity in bits per second (bps), B the bandwidth of the channel in hertz (Hz), V_{signal} the voltage of the power signal and V_{noise} the voltage of data signal.

The analysis of all these variables is necessary to have a complete overview of the performance of the system, both in terms of power and data transmission. In this way, it is possible to identify possible errors or inconsistencies in the design and development stage and, in this way, optimise the system based on the results obtained from the previous analyses.

Misalignment

One of the main challenges facing wireless EV charging technology is the non-ideal positioning of the coils during the charging process, known as misalignment. The misalignment, as shown in Fig. 2.4, is given when the secondary coil, found in the EV, is not perfectly aligned with the primary coil in any of the three axes (X, Y and Z). Thus, the secondary coil is not able to collect the entire magnetic field generated by the primary coil, so that the coupling coefficient between the coils decreases, causing the waste of energy. This situation is very common, as it is highly complicated for the positioning between the coils to be ideal in all cases. Misalignment effect have been widely studied in bibliography [77], [78], [79], since it has direct effects on electric vehicle charging, such as loss of efficiency.

Since misalignment is a common problem that the scientific community is trying to reduce, there is a wide range of literature looking for solutions to counteract the effect of misalignment in the charging process. Among these studies is the analysis of compensation systems and their performance with respect to misalignment. As mentioned in Section 2.1, there are four basic topologies (SS, SP, PS, PP) and variations of them generating more complex structures as LCC or LCL. Each of these topologies has a different performance under misalignment conditions. As stated in [9], SS and LCC compensation networks offer a better performance when misalignment is produced between coils. This is one of the main reasons to consider both compensation systems for data transmission. Other research activities focus on how to design the coils and the controllers to achieve a charging process more efficient with misalignment.

Although the effect of misalignment in terms of efficiency has been extensively studied in the literature, not many studies have been found that analyse the effect of misalignment on data transmission. In addition, it is interesting to analyse which compensation system performs better under misalignment, specifically studying the consequences of misalignment on data transmission. If misalignment in power transmission can have direct effects on the charging process such as energy loss and reduced transmission efficiency, it can also cause undesirable disadvantages in data transmission. Misalignment in the coils can lead to errors in the transmission of information caused by poor coupling coefficient. The voltage at which the data signal is transmitted is generally much lower than that of the power

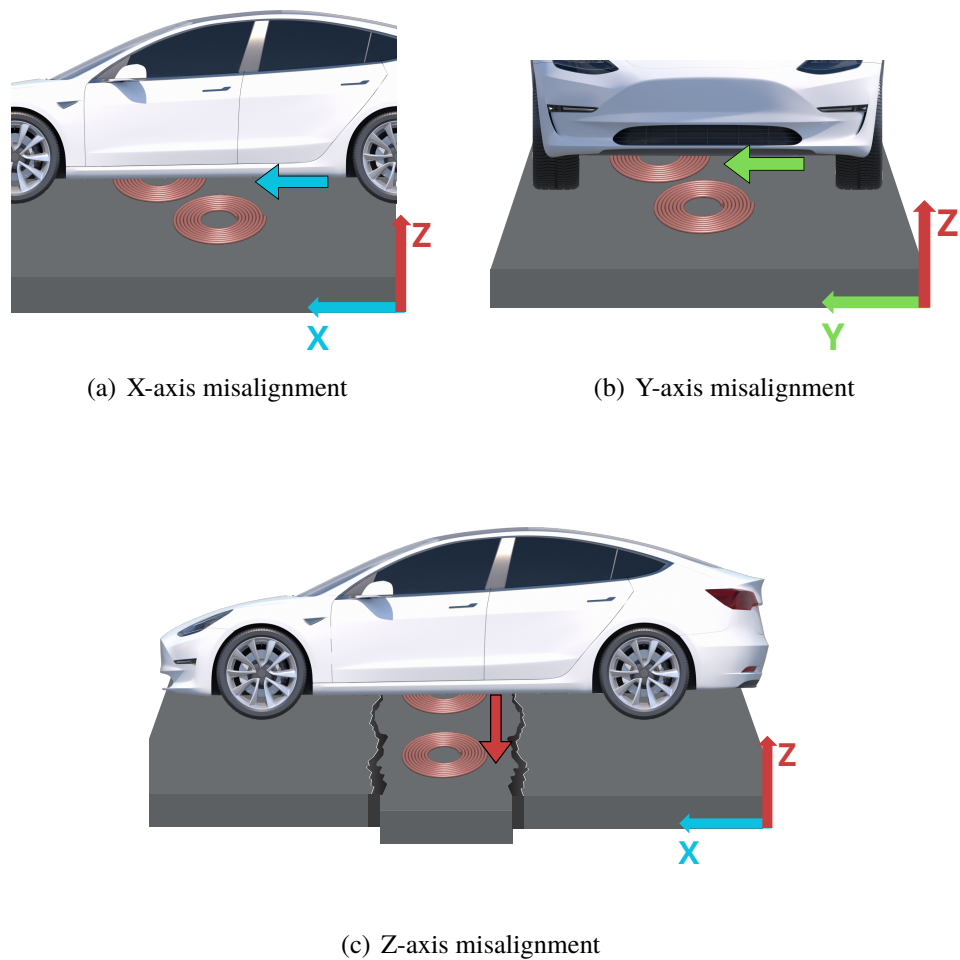


Figure 2.14: Misalignment in 3 main axes.

signal. That is, a data signal of about 10 V_{pp} compared to hundreds of volts for the power signal. A drop in the coupling coefficient can cause a decrease in this received voltage on the secondary side, causing its value to be closer to the noise present during wireless transmission. A data signal close to the voltage value of the noise can lead to misinterpretation of the transmitted information, resulting in significant errors in the charging process such as loss of information or incorrect data transmission. In addition, the relation between the noise level and data signal level is related to the channel capacity, as mentioned in the previous section, and this can affect the data rate achieved during the charging process.

There are some methods that can alleviate the effect of misalignment in wireless power transfer. One of the most outstanding is the use of active inductors [80]. An active inductor is an equivalent system, which may consist on an inductor of small size, an H-bridge, and a DC-link capacitor. The idea with this structure is to achieve, through specific control techniques of the switching frequency, an equivalent inductance with higher value than the initial inductor placed on the circuit. In the application of WPT, this active inductor can

substitute, for example, the passive filter inductor of a double-sided LCC compensation system. Thus, as the output power and, therefore, efficiency are related to the compensation components values, it is possible to find a relation between them. With this variable reactance, it could be possible to improve the overall efficiency according to the measured output parameters, by implementing effective control algorithms acting directly in the power converters. This topic has been addressed during the PhD student's research stay, so future results are expected for its integration in SWPDT systems.

Compensation topologies

In resonant inductive chargers, compensation system are an indispensable element in the charger performance, as discussed in Section 2.1. Specifically, SS and LCC compensation topologies have emerged as two of the most prevalent and extensively studied solutions [81]. Both of these compensation strategies have been thoroughly investigated and widely adopted due to their versatility, effectiveness, and applicability across diverse power electronics applications.

In terms of power transmission, these topologies have diverse advantages that can be relevant for the charging process. This compact topology allows the added weight in the charger and the size of the charger to be smaller, making the design lighter and more compact [82]. In addition, this topology is characterised by being independent of the coupling coefficient and the load value, which makes it an interesting topology for dealing with misalignment situations between coils, as well as for adapting to different charging conditions.

On the other hand, LCC compensation circuit is a multi-resonant alternative equivalent to the SS system in terms of its characteristics and performance. LCC topology consists of the inclusion of four extra components connected in series and parallel to the main coil. Although the number of elements introduced is doubled with respect to the SS topology, it should be mentioned that these elements are smaller, both in terms of characteristic value (inductance and capacitance) and size, so the differences in weight and size are not remarkable. As with SS topology, LCC compensation systems exhibit good performance in misalignment situations, since it has a low sensitivity to the coupling coefficient and the load variation [83]. This compensation has numerous advantages, such as an output current that is independent of the load, ZVS, and the filtering of a large part of the harmonics generated in the inverter and rectifier, as indicated in [40], [48].

As these topologies present numerous advantages, the use of these two compensation systems is also extended to SWPDT chargers. The development of SWPDT solutions have been deeply studied throughout this doctoral thesis and, as stated in [57], paying particular attention to SS and LCC-LCC technologies. Thus, it is interesting to analyse

the performance of SS and LCC-LCC in terms of data transmission, since all the efforts have been focused on power channel analysis [84].

In case of SWPDT systems, it should be noted that the misalignment between coils also directly affects the bandwidth of the data system. As indicated in [85], some studies conclude that vertical misalignment affects the communication capacity of the channel more than horizontal misalignment, as an example. Nevertheless, the bandwidth alteration is not only related to the direction of misalignment, but also to the compensation system used. The authors conclude that a PP compensation system offers the highest communication capacity for misalignment on both the horizontal and vertical axes, while SP compensation offers the lowest channel capacity.

The compensation system also has a relevant impact on the correct demodulation of the information when misalignment occurs. The impedance reflected from the secondary to the primary side depends on the mutual inductance and on the specific topology of the compensation system. Changes in this impedance lead to variations in the amplitude and/or phase of the primary current and, consequently, in the voltage induced on the secondary side. The magnitude of these changes for a particular coil misalignment is related to the topology of the compensation system. Thus, for a specific coil displacement, the variations in amplitude or phase can strongly differ from one compensation to the other. In this way, these variations cannot be considered as data changes for a correct data demodulation. Thus, misalignment conditions of SWPDT systems should be considered to decide if the compensation system and the modulation technique are appropriate for them.

In addition to compensation systems, there are some other elements that are relevant to SWPDT systems. These elements are known as resonant tanks (RTs) [86]. Resonant tanks are mainly used in SL-DC systems, where it is important to avoid the interference between power and data signals, and to prevent the data signal from flowing into the power circuit and interfering with the power electronics.

Resonant tanks consist of an inductor and a capacitor connected to each other in series or parallel. The values of both components must be calculated by following the relation $\omega_d = \frac{1}{\sqrt{LC}}$, considering the angular data transmission working frequency ω_d . According to the type of connection, two different performances can be achieved:

- **Connection in series.** With this configuration, the LC structure behaves as a short circuit at the data frequency, and offers high impedance at the power frequency. Thus, this structure is able to block the power carrier wave in the data circuits.
- **Connection in parallel.** In this case, the LC circuit behaves as an open circuit at the data frequency, and offers low impedance at the power operation frequency. In this way, the power signal can be transmitted through this block, but the data carrier wave is blocked.

In SWPDT systems, series resonant tanks are usually connected in the data injection/extraction point, in order to block the power signal. Parallel resonant tanks are placed in the power channel, so that data signal can be blocked. This basic structure is represented in Fig. 2.15

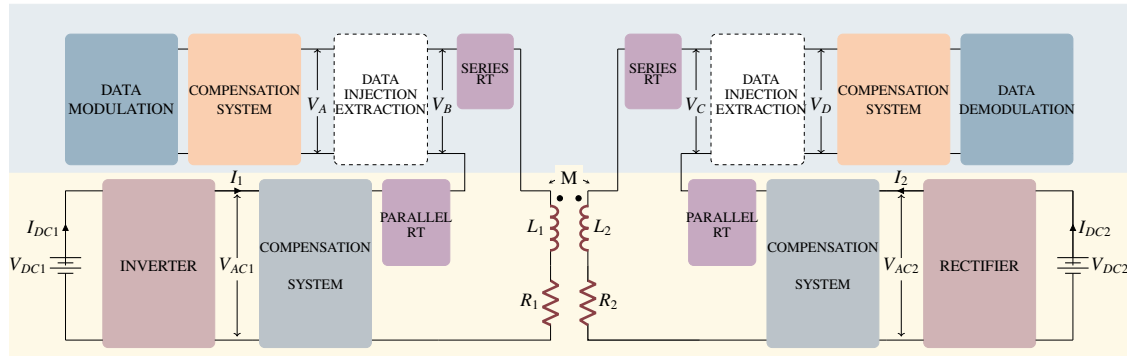


Figure 2.15: Scheme of a SWPDT system with resonant tanks.

2.3 Vehicle-to-grid technology

The growth in electric vehicle sales has resulted in new technological challenges that need to be solved in a short interval of time. One of the most important is the integration of electric vehicles into the electricity grid. According to the International Energy Agency, the global EV stock is estimated at 140 million with a predicted demand of at least 230 TWh in 2030 [87]. Thus, it is necessary to carefully study the way in which electric vehicle charging will be integrated into the grid in order to optimise and reduce its impact significantly. This analysis must be undertaken considering the new electrical paradigm in which renewable energy sources are more frequent. The integration of renewable energy sources, such as solar, wind, and hydropower is studied for reducing carbon emissions and minimizing environmental harm. The benefits of using renewable energy sources are numerous [88]. First, unlike fossil fuels, renewable energy sources such as solar, wind, and hydropower produce little to no greenhouse gas emissions during electricity generation. This helps mitigate climate change and reduce air pollution. In addition, the use of renewable energy helps decrease dependence on fossil fuels, which are the primary contributors to climate change. Shifting to renewable energy is an interesting strategy in global efforts to mitigate the impacts of climate change. With regard to the economic development, renewable energy promotes the growth of the energy sector and its associated industries. For nations whose industries are able to manufacture energy-related gear and equipment based on technological advancements, renewable sources have a major multiplier effect. Finally, the innovation in this sector encourages changes in technology and/or technical aspects of

new market structures. The benefits of the renewable energy sources and electric vehicles can be maximized if they are both considered jointly for the EV charging and discharging in a Vehicle-to-grid (V2G) context.

V2G technology is intended to be one of the solution for the integration of electric vehicles into the power grid. V2G is a technology that enables EVs to not only consume electricity from the grid but also to return excess electricity back to the grid. In a V2G system, electric vehicles serve as both consumers and potential energy storage devices. Its general structure is shown in Fig. 2.16. Since the V2G electric vehicle batteries can be used as a source of energy during periods of high power demand, power grid congestion can be alleviated. Furthermore, these EV batteries can be recharged in accordance with limitations such as the cost of electricity or the state of charge of the batteries. Algorithms for charge planning can handle all these tasks, enabling the best possible energy management at all times in terms of the grid performance and/or to improve the users' satisfaction .

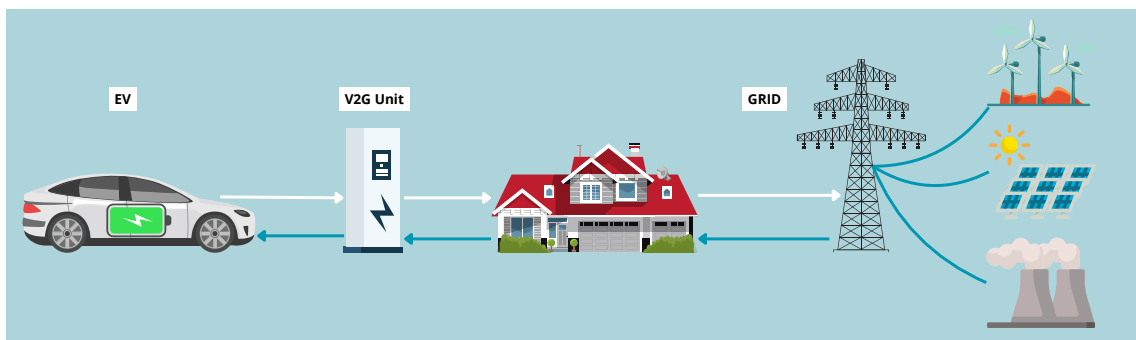


Figure 2.16: V2G generic scheme.

Thus, analysing the advantages of V2G and renewable energy sources, it can be deduced that the use of both technologies together can bring significant benefits. By combining V2G with renewable energy such as solar and wind power, it is possible to create a dynamic energy ecosystem that enhances grid stability and reliability. During peak renewable energy generation, excess power can be transferred to electric vehicle batteries, acting as distributed energy storage [89]. In addition, the EV can participate in ancillary services such as frequency regulation or demand response.

The process of delivering energy to the grid has specific requirements that must be fulfilled. These requirements are related to the signal synchronization and delays. Synchronization ensures that the energy transferred between vehicles and the grid is performed efficiently and at the same phase that the grid keeps. Power converters are expected to be synchronized with the grid to stay actively connected, and they should be able to support grid services [90]. Thus, synchronization with the grid is an important task that should be studied in V2G wireless chargers. On the other hand, delays during the charging process

should be considered. In plug-in EVs, the V2G process requires real-time information related to the grid or to the market, which is transmitted between the control unit and the EVs. This transmission may incur time delays in the control loop, such as processing delay of calculation of V2G gain [91]. In wireless charging, these delays are even more notorious, since the communication takes place wirelessly, so the communication delay of each wireless technology should be analysed.

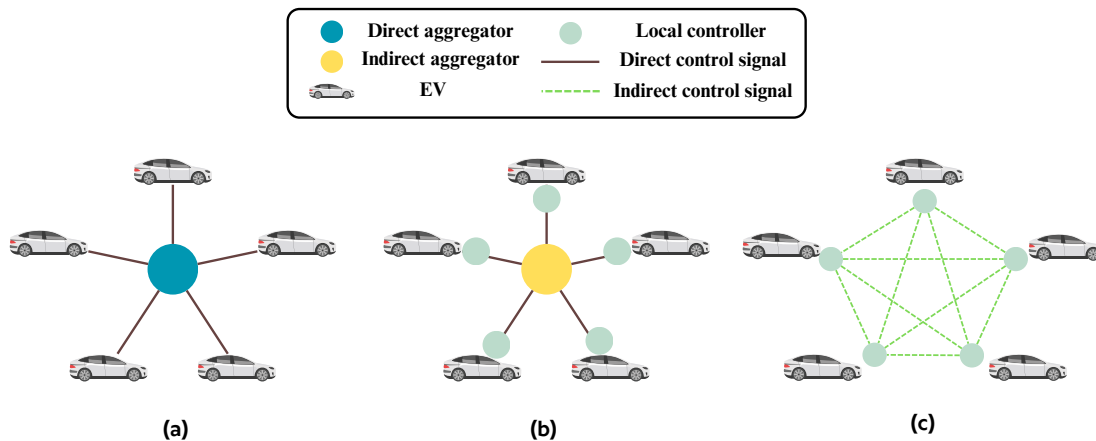


Figure 2.17: Main scheduling strategies for EVs (a) centralized, (b) decentralized, (c) distributed.

Finally, it should be mentioned that V2G technology is related to concepts that study the optimal management of EVs charging and discharging. These concepts are known as dispatching strategies. As can be observed, the convenience of charging and discharging an EV depends on multiple time-varying factors. The dispatching or scheduling strategies refer to the way in which the EVs perform the power exchange with the grid attending to different criteria. Thus, three different main approaches can be distinguished, as shown in Fig. 2.17:

- **Centralized method.** In a centralized method, all decisions regarding charging schedules, resource allocation, and coordination are performed by a central authority or controller, named as aggregator [92], as shown in Fig. 2.17 (a). This central entity has complete knowledge and control over the entire system. It collects information from all EVs and charging stations, analyzes the data, and then determines optimal charging/discharging schedules for each EV based on predefined objectives or constraints. The central authority communicates directly with each EV and charging station to enforce the scheduled charging plans.
- **Decentralized method.** In a decentralized method, decision-making authority is distributed among each EV so that each charging station or EV can make decisions

autonomously, based on local information and optimization criteria [93]. In this case, an indirect aggregator can control indirectly the behaviour of the system by applying cost and incentive strategies that shift the charging/discharging to the time of interest according to the demand curve, as represented in Fig. 2.17 (b). Decisions are typically made independently by each entity, with limited communication and coordination among them. Decentralized methods can offer more flexibility and scalability compared to centralized approaches, as they reduce reliance on a single point of control and allow for adaptation to local conditions.

- **Distributed method.** A distributed method for EV scheduling involves the distribution of decision-making processes across multiple nodes or entities in a network [94]. Distributed methods emphasize a peer-to-peer approach, where entities collaborate and negotiate directly with each other to achieve common goals, as can be seen in Fig. 2.17 (c). Each node in the network has partial knowledge and decision-making capabilities, and they work together through communication and consensus protocols to optimize charging/discharging schedules and resource allocation. Distributed methods can enhance scalability, fault tolerance, and resilience compared to centralized and decentralized approaches.

It should be mentioned that the V2G technology is implemented with a higher degree of maturity in plug-in electric vehicles, which are currently the most popular EV chargers on the vehicle market. There are even some commercial charging stations which implement scheduling algorithms. However, this technology is widely studied to be implemented in wireless charging, as explained in the following section.

2.3.1 State of art of V2G technologies in WPT

As mentioned at the beginning of this chapter, V2G control technology is initially implemented in plug-in electric vehicles, as these are the ones that are currently emerging in the market. However, with the rise of wireless charging and the evolving nature of electric vehicle technology, many of the proposed solutions in the literature point to V2G as one of the most promising control techniques for wireless chargers. In this subsection, an in-depth review of the state of art of V2G technology in WPT is presented, by analysing the control techniques proposed by authors.

In general terms, control techniques can be divided according to the type of power they control. As can be seen throughout this section, some solutions opt to control only the active power (P), while in other cases, authors propose to control both active and reactive power (P and Q , respectively). This dual control can be performed by considering the

different combinations of P and Q , according to the possibilities shown in Fig. 2.18. Thus, a total of eight (from I to VIII) operation modes can be achieved.

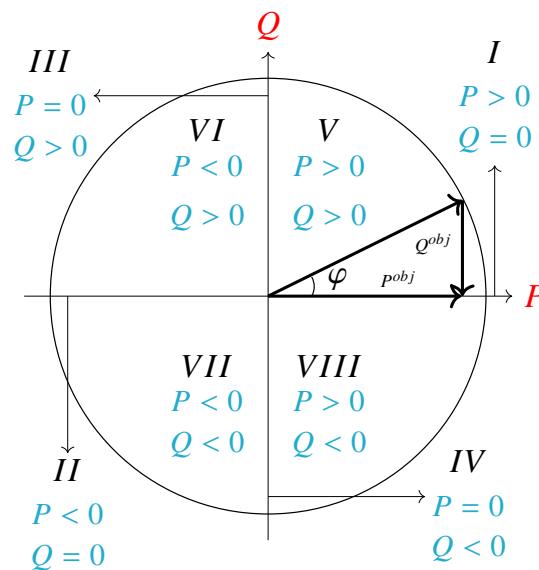


Figure 2.18: Operating modes for all four quadrants for a bidirectional wireless charger.

The control proposed in [95] is based on variable frequency modulation to control the power flow in the wireless power transfer system. This technique allows power transfer to be regulated efficiently and accurately in both grid-to-vehicle (G2V) and V2G operations. The basis of this control is that the deviation of the working frequency with respect to the resonant point leads to the reduction of the power flow. Thus, the transmitted power level through the circuit can be controlled by varying the working frequency to higher or lower operation frequencies, with respect to the resonant point. In addition, soft-switching control is implemented for the devices, independent of the charging current, ensuring safe and reliable system operation. This control approach helps to optimise system efficiency and ensure optimal performance under different operating conditions.

On the other hand, the technique presented in [96] uses information extracted from the input impedance to operate the system at essentially zero phase angle (ZPA) and optimal charging, ensuring that the charging is performed at rated power with optimal efficiency despite misalignments in the coupled coils.

In [97], authors propose a control technique based on fuzzy control. This fuzzy control approach adjusts the operating frequency to compensate the misalignment of the transmit and receive coils. In addition, an improved overcurrent protection system is used which significantly reduces the response time compared to traditional methods. Fuzzy control is based on fuzzy logic and uses fuzzy inference rules to adjust the frequency and phase angle of the current, enabling efficient power and data transfer even in the presence of coil

misalignment.

With these three first proposals, the control of the power flow direction is performed by the activation or deactivation of the power converters. That is, if the primary converter is configured as an inverter, the secondary converter is configured as a rectifier. However, there are some other proposals that allow the control of the power flow by maintaining the power converters as fully controllable, but considering delays between them. Some of these solutions are described below.

In [98], a bidirectional active power control is proposed, with power levels up to 20 kW. In this case, the inductive charger has been designed for a gap of 11 inches and asymmetrical input-output voltage levels. The selected topology for the coupled inductors is double-D (DD), and the employed compensation system is LCC-LCC. Authors highlight that this wireless charger has the largest airgap with the highest efficiency levels and power density.

On the other hand, researchers in [99] discuss the development of a controller for bidirectional wireless power transfer systems for electric vehicles. The controller utilizes measured active and reactive power to synchronize and regulate power flow in both directions without requiring a dedicated communication link. The control is implemented by measuring real-time active power and reactive power using sampled voltage and current, and then deriving the drive signals for the pickup converter based on the power flow and synchronization requirements. This control is validated through 1-kW prototype system, demonstrating the controller effectiveness in achieving high efficiency and performance under various operating conditions.

Authors in [100] discuss the design and validation of a single-stage bidirectional inductive power transfer system with a closed-loop current control strategy for EVs. This strategy can control power bidirectionally with good dynamic performance, achieving unity power factor (UPF) in both grid-to-vehicle (G2V) and V2G modes. The control scheme uses a PI controller to generate modulating signals for the AC/DC converter, maintaining a fixed phase shift angle to control power flow. The system aims to simplify control complexity, reduce component count, increase reliability, and achieve unity power factor.

A bidirectional wireless charger system with dual-side LCC compensation topology is proposed in [101]. In this case, the optimization approach considers the equivalent impedance of the bidirectional power converter (BPC) and focuses on maximizing transmission efficiency while maintaining high system efficiency in both directions. The control is performed using phase-shifting control to adjust the output power of the BWPT system by changing the transmission direction of the converter working mode.

The research in [102] focuses on the design of a single-phase bidirectional AC-DC WPT converter with an integrated power stage that overcomes the drawbacks of existing

topologies. The proposed control scheme generates driving signals for switches based on feedback signals such as AC-side voltage and current, DC-side voltage, and bus voltage. It includes control loops for AC current, DC voltage, and bus voltage to shape the AC current, maintain constant output voltage, and stabilize the bus voltage. The control variables include target peak current, initial values, and proportional-integral parameters for the control loops. Techniques such as soft-switching and zero voltage switching are used in the power semiconductor devices, reducing switching losses and improving overall efficiency.

Finally, in [103] the modeling and assessment of different compensation topologies in bidirectional WPT is discussed. It compares LC-series, LC-parallel, and LCL-topology configurations, highlighting the suitability of LCL topology for bidirectional operation due to its simplicity in design and control requirements. Authors propose phase shifting to control power converters.

In Table 2.4 a summary of the related work is shown to facilitate the comparison between the different proposed controls.

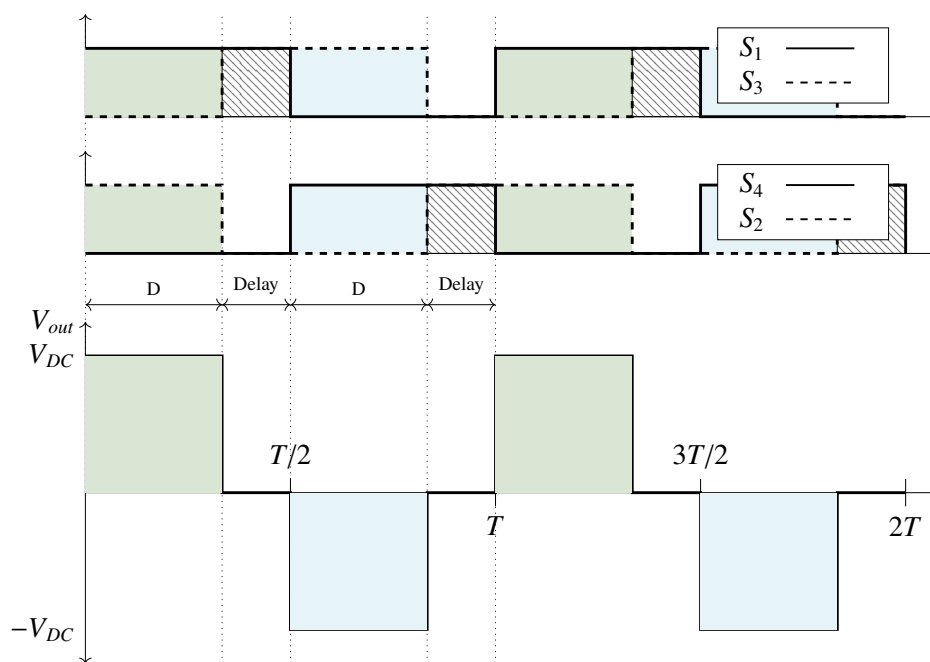


Figure 2.19: Phase shifting output waveform for V_{out} .

Although different control methods have been proposed in literature, special attention must be paid to the phase shifting control technique, since is a common control tool in the reviewed bibliography [104], [105] [106]. With this technique, the charging power level can be controlled by varying the switching sequence of the full-bridge inverter.

In phase shifting control, the achieved final waveform for V_{out} voltage is shown in Fig 2.19, being S_1 , S_2 , S_3 and S_4 the activation signals for the power converter, where the output voltage can be computed as:

Table 2.4: Summary of the most relevant contributions on V2G control for EV wireless chargers.

	Ref.	Power Converters	Comp. topology	Controller Goal	Mode
Activation / Deactivation	[95]	P:Half-bridge (two-switch leg) S:Half-bridge (two-switch leg)	P: C-LC S: LC	Variation of the switching frequency to control the power flow.	I,II
	[96]	P:Full-bridge S:Full-bridge	P:Series S:Series	Sense of the active power flow with ZPA and optimal efficiency under misalignment conditions.	I,II
	[97]	P:Full-bridge S:Full-bridge	P:Series S:Series	Control based on fuzzy algorithms that adjust the operating frequency to compensate misalignment.	I,II
	[98]	P:Full-bridge S:Full-bridge	P:LCC S:LCC	Unity power factor both for G2V and V2G modes with a large air gap and high efficiency results.	I,II
	[99]	P:Full-bridge S:Full-bridge	P:LCL S:LCL	Regulate the amount and sense of the active power on the secondary side without communication with the primary side.	I,II
Delay	[100]	P:Single stage AC/AC S:Full-bridge	P:Series S:Series	The control achieve unity power factor (UPF) with a simplified control.	I,II
	[101]	P:Full-bridge S:Full-bridge	P:LCC S:LCC	It is based on the equivalent impedance of the power converter to achieve high system efficiency.	I,II
	[102]	P: Full bridge with PFC S: Full-bridge	P: Series S: Series	Soft-switching and ZVS techniques are used to improve efficiency.	I,II
	[103]	P:Full-bridge S:Full-bridge	P:LCL S:LCL	Phase-shifting control to select the power flow direction with LCL topology.	I,II, III, IV

$$V_{out}(t) = \sum_{n=1}^{\infty} \frac{4V_{DC}}{n\pi} \sin(n\pi D) \sin(n\omega t) \quad (2.2)$$

being n the harmonic number and ω the angular frequency.

2.3.2 Integration of V2G with SWPDT systems

Simultaneous wireless power and data transfer systems are designed to avoid the use of commercial technologies for communication tasks. Although SWPDT systems is a technology still in its early stages of development, it is true that they can provide a direct solution to instead of the use of other more widespread technologies that can have drawbacks such as loss of connection, pairing problems or cybersecurity issues.

In parallel, V2G wireless charging is a innovative concept that transforms electric vehicles into bidirectional resources, capable of not only consuming electricity from the grid, but also giving energy when needed. Many of the proposals for V2G systems require the transmission of information from the electric vehicle to the charging station.

In this way, it is possible to easily identify the synergy between these two themes in a single solution: V2G systems integrated in SWPDT chargers. Systems with SWPDT technology enable efficient bidirectional communication between the electric vehicle and the grid, which is essential to coordinate the energy flow in both directions, and ensure optimal interaction between the EV and the charging infrastructure.

However, to perform this integration, different operation requirements must be evaluated. First, there is a imperative necessity to carry out synchronisation techniques that allow power converters to work properly. In SWPDT systems, the communication requirements for the implementation of V2G synchronization are as follows:

- During synchronisation tasks, the exchange of information is an important feature to be considered. Thus, communication should be performed in both directions. This bidirectional communication can be performed both to transmit variables values between EV and EVSE, and to inform the other side that the message has been correctly received.
- The data rate is an important feature as the synchronisation must be performed in a short period of time, so that wireless charger is not working for a prolonged period of time in unsuitable conditions.
- Additionally, the system stability is a crucial characteristic of V2G chargers. One of the elements which highly influences in system stability is compensation system. Thus, it is important to select a suitable topology to not compromise the correct performance of the whole system during synchronisation tasks.

In addition to synchronisation, in V2G chargers there is another requirement that should be taken into account: system overall efficiency. As mentioned in Section 2.2, the effi-

ciency control usually implies the use of measurements of the output variables (voltage, current, power, etc.) to act on the primary converters. The communication requirements to perform a correct system efficiency control are:

- The power signal transmission should be carried out without disturbances. For this reason, it is important to avoid communication techniques that modify power signal in amplitude, frequency or phase.
- In this case, it is also necessary to bidirectionally communicate both parts of the inductive charger, so that final measured variables such as output voltage or output power can be computed.
- The modulation technique employed should be carefully studied, since efficiency control is performed by using the variables output values.

Finally, if SWDPT chargers are planned to be integrated in EV market, they must be correctly equipped to participate in grid services, through EV charging strategies. To do so, specific requirements should be considered:

- For EV dispatching strategies, it is important to reduce the power losses, since it is common that the charging scheduling is design to achieve optimal energy management.
- In the same way as the previous features, in this case it is necessary to perform a bidirectional communication between EV and EVSE.
- Communication delays should be reduced to avoid important delays that can affect in the real-time charging scheduling.

Thus, the mentioned features have different requirements that should be considered in the integration of V2G chargers in SWPDT systems. By analysing the different types of SWPDT chargers that can be implemented, some design recommendations have been elaborated during this PhD. In Table 2.5, the selected SWPDT features have been described according to the previously mentioned requirements. As a conclusion, features such as SL-DC topology, half/full duplex communication, SS or LCC compensation system, FDM signal multiplexing technique and ASK and FSK modulation are proposed for V2G integration with SWPDT chargers.

Additionally, in order to better understand the performance of a SWPDT system and, thus, to establish design criteria for the integration with V2G applications, in SWPDT circuits it is interesting to define the relation between different variables that can be found throughout the circuit. This relations are related to both the power channel and the data

Table 2.5: Selected features for the integration of SWPDT systems in V2G chargers

Design parameter	Selected feature	Fulfilled requirements
SWPDT topology	SL-DC	<ul style="list-style-type: none"> - Do not modify the power signal intrinsic characteristics. - According to the reviewed literature, SL-DC offers higher data rates. - Power losses are minimised since the power signal is not modified.
Communication	Half-duplex, Full-duplex	<ul style="list-style-type: none"> - It is possible to transmit information in both directions. - Real-time control of the system is encouraged.
Compensation system	SS, LCC	<ul style="list-style-type: none"> - Both topologies have a good performance in terms of efficiency. - They can offer a good system stability. - They have good performance under misalignment situations.
Signal multiplexing technique	FDM	<ul style="list-style-type: none"> - This technique do not require time synchronisation. - It can minimise latencies, so it is recommended for real-time applications.
Modulation technique	ASK, FSK	<ul style="list-style-type: none"> - ASK modulation is simple and effective, while FSK modulation can give robustness to the system performance.

channel, as shown in Table 2.6. It should be noted that the nomenclature used for these equations is selected according to the variables found in Fig. 2.15.

It should be mentioned that the equations presented in Table 2.6 are included in a generic and simplified form, and the final equations for each variable can be found in an extended version in the contributions of this doctoral thesis.

2.4 Communication protocols

The exchange of data produced during the charging process is not carried out arbitrarily, but there are requirements in terms of format, time and security that must be considered.

Table 2.6: Generic equations to be considered in SWPDT systems

	Forward transmission	Backward transmission
Power channel transfer function	$G_{fw} = \frac{V_{AC2}}{V_{AC1}}$	$G_{bw} = \frac{V_{AC1}}{V_{AC2}}$
Equations of interest for the power channel		
Active AC Efficiency (P)	$\eta_{fw} = \frac{\Re V_{AC2} \vec{I}_2^*}{\Re V_{AC1} \vec{I}_1^*}$	$\eta_{bw} = \frac{\Re V_{AC1} \vec{I}_1^*}{\Re V_{AC2} \vec{I}_2^*}$
Reactive AC Efficiency (Q)	$\eta_{fw} = \frac{\Im V_{AC2} \vec{I}_2^*}{\Im V_{AC1} \vec{I}_1^*}$	$\eta_{bw} = \frac{\Im V_{AC1} \vec{I}_1^*}{\Im V_{AC2} \vec{I}_2^*}$
DC Efficiency	$\eta_{fw} = \frac{V_{DC2} I_{DC2}}{V_{DC1} I_{DC1}}$	$\eta_{bw} = \frac{V_{DC1} I_{DC1}}{V_{DC2} I_{DC2}}$
Data channel transfer function	$G_{datafw} = G_1 G_2 G_3$, being $G_1 = \frac{V_B}{V_A}$, $G_2 = \frac{V_C}{V_B}$, $G_3 = \frac{V_D}{V_C}$	$G_{databw} = G_1 G_2 G_3$, being $G_1 = \frac{V_C}{V_D}$, $G_2 = \frac{V_B}{V_C}$, $G_3 = \frac{V_A}{V_B}$
Equations of interest for the data channel		
SNR	$SNR_{dB} = 20 \log_{10} \frac{V_{data}}{V_{power}}$	$SNR_{dB} = 20 \log_{10} \frac{V_{data}}{V_{power}}$
Capacity	$C = B \log_2 \left(1 + \frac{V_{data}}{V_{power}} \right)$	$C = B \log_2 \left(1 + \frac{V_{data}}{V_{power}} \right)$

These requirements are usually established by communication protocols regulated by official organisations. Each protocol plays a key role in defining the rules and regulations governing the interaction between vehicles and charging stations, thus ensuring efficient, secure and standardised data exchange. These protocols can be manufacturer-independent protocols, such as OCPP or ISO 15118, or specific protocols, such as CHAdeMO, CCS (Combined Charging System), Tesla Supercharger Protocol or GB/T (Guobiao/T). These protocols comprise the definition of the procedures related to several layers in the OSI (Open Systems Interconnection model) model. Knowing their features, we could determine if SWPDT provides the physical layer necessary to support other protocols in upper layers (e.g. application) defined in the previous EV charging protocols.

OCPP (Open Charge Point Protocol) is an open communication protocol widely used in electric vehicle charging. This protocol establishes the guidelines for communication between charging stations and central management systems enabling efficient interoperability between different charging equipment and vehicle manufacturers. OCPP stands

out as the de facto protocol used in 148 countries across 6 continents, and more than 65,000 operational charging stations support this protocol. In addition, more than 40 electric charger vendors are integrating OCPP into their products. OCPP is supported by the Open Charge Alliance (OCA), with more than 220 members and companies active in the area of electromobility.

The OCPP protocol has evolved over the years, as described bellow:

- OCPP 1.5, published in 2012. This version of the protocol focuses on basic charging and communication functions. It establishes an initial set of standards for basic interaction between chargers and management devices. This version is based on Simple Object Access Protocol (SOAP), encoding its messages in XML.
- OCPP 1.6, published in 2015. This version represents an evolution of the previous version, introducing improvements in security and communication stability. It provides a broader set of commands and functions for more advanced charging station management. This version supports both SOAP and JavaScript Object Notation (JSON).
- OCPP 2.0, released in 2018. Version 2.0 is a significant step forward in the evolution of the protocol, incorporating more advanced features such as bi-directional charging management (V2G) and enhanced authentication. It also improves flexibility and interoperability between charging systems from different manufacturers. This protocol, version 2.0, is based on JSON and its operability is based on a set of messages in "Request" and "Response" format that allows basic actions to be carried out. This scheme could also generate more complex actions.
- OCPP 2.0.1, published in 2020. This is the most recent version of the protocol. Its main objective is to make corrections to the OCPP 2.0 version, while clarifying more specific aspects of the protocol.

On the other hand, the ISO 15118 standard defines a communication protocol for charging electric vehicles. This standard establishes the communication requirements between the electric vehicle and the charging station. Like the OCPP protocol, it allows bidirectional communication. ISO 15118 is structured in layers or levels, encompassing the physical, data link, network, transport and application layers. Commonly, the ISO 15118 standard is used together with the OCPP protocol, each of them taking care of a part of the communication, as shown in Figure 3.1.

The generic structure of the communication process by using OCPP and ISO 15118 protocols is shown in Fig. 2.21. As can be seen, the communication takes place by a "Request" and "Response" format, both between EV and EVSE, and between EVSE and

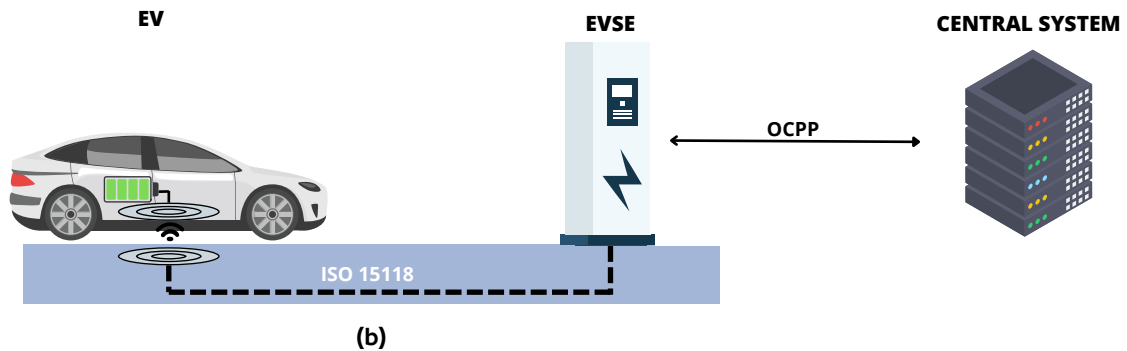


Figure 2.20: OCPP and ISO 15118 communication protocols application.

Central system. It should be mentioned that all actions have the same message structure. In Request and Response messages, variables of different types are sent containing information about the action to be carried out.

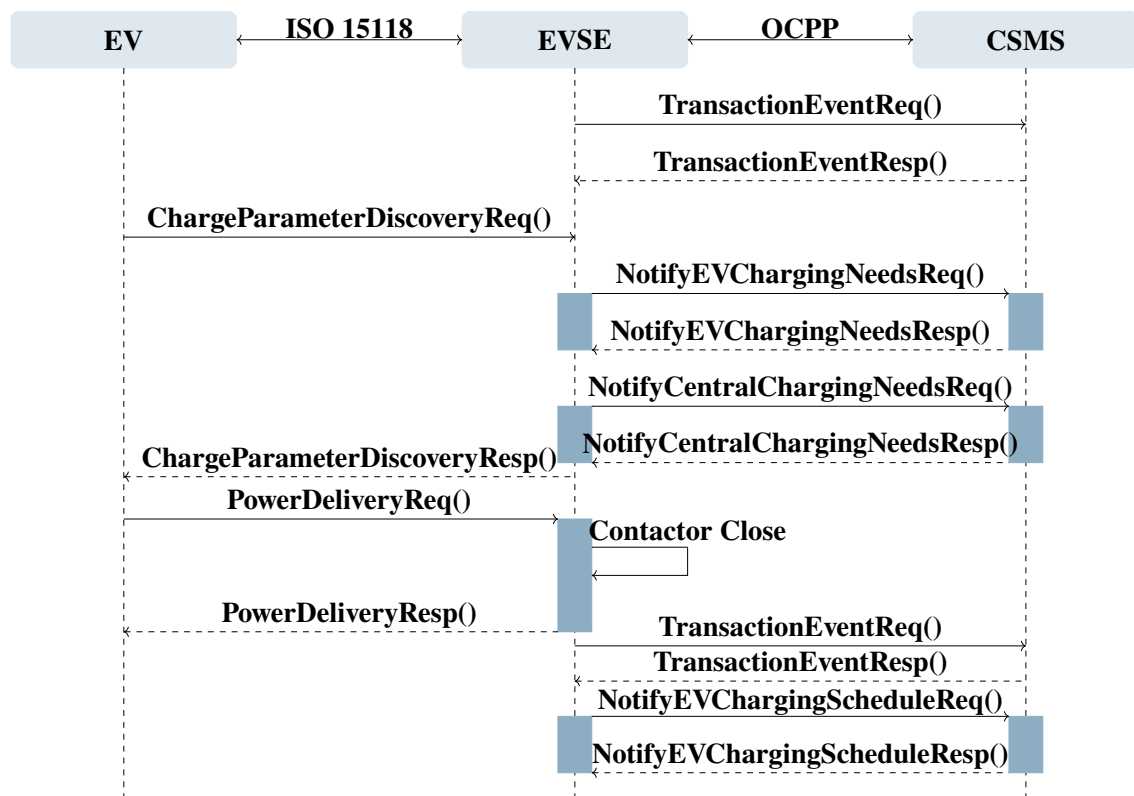


Figure 2.21: OCPP and ISO 15118 communication sequence example.

On the other hand, there are several specific protocols as stated as follows:

- **CHAdEMO.** It is an electric vehicle charging protocol initially developed in Japan. CHAdEMO has gained international recognition and is used by several vehicle man-

ufacturers. Its design enables fast charging speeds, facilitating an efficient experience for electric vehicle users. Its DC charging mode is a highlight of this protocol.

- **Combined Charging System (CCS).** The Combined Charging System represents a standard that combines direct current and alternating current charging, providing a versatile solution for charging electric vehicles. CCS uses dedicated connectors and enables fast charging, contributing to the expansion of the charging infrastructure worldwide.
- **Tesla Supercharger Protocol.** Tesla's fast charging protocol, being used exclusively in the network of Supercharger stations, is a specific solution for Tesla vehicles. This protocol, designed to optimise charging of Tesla vehicles, enables significantly faster speeds and offers an efficient charging experience for Tesla vehicle users.
- **GB/T.** The GB/T protocol, also known as Guobiao/T, is a national standard in China for electric vehicles charging. GB/T defines a set of rules for communication between vehicles and charging stations, thus contributing to the development of electric mobility in the Chinese market. This protocol is designed to promote the mass adoption of electric vehicles in the country.

Although the variety of existing protocols is wide, the use of the OCPP protocol is noteworthy for the following reasons:

- **Open standard.** OCPP is an open standard, so it is publicly available and accessible to any interested party. As an open standard, this protocol encourages interoperability between different suppliers and manufacturers of electric vehicle charging equipment.
- **Flexibility and adaptability.** The OCPP protocol is designed to be flexible and easily adaptable. It has a modular architecture that allows its implementation in different situations and environments, which facilitates its integration in a variety of systems and devices.
- **Bidirectional communication.** Bidirectional communication is an essential feature in systems with advanced functions such as charging management, remote authorisation and real-time data collection. This protocol enables two-way communication between charging stations and charging management systems. This feature makes it compatible with the ISO 15118 standard, which allows bi-directional communication between the electric vehicle and the charging station.

These communication protocols are used in conductive EV chargers. However, in order to favour the implementation and adoption of wireless chargers, it is important to study if an existing protocol can be used on top of the physical layer provided by SWPDT systems, or, otherwise, there is a necessity of creating new protocols. As stated before, OCPP is one of the most widely used communication protocols in EVs, so in this PhD thesis we have focused on analysing whether the characteristics of the OCPP protocol fit with wireless charging. One of the main criteria that should be considered is required data rate, since there are time limits that must be fulfilled.

In order to analyse the data rate requirements of OCPP protocol, based on ISO 15118, it can be useful to understand the structure of the communication sequence. To do so, in Table 2.7 messages with different sizes and time requirements are shown.

Table 2.7: Representative example of ISO 15118 messages data rates.

MESSAGE	Bytes	Bits	Time (s)	Minimum data rate (bps)
ServiceDiscoveryReq	70	560	2	280
PaymentsDetailsReq	1616	12928	5	2586
CurrentDemandReq	207	1658	0.25	6632
CertificateInstallationRes	3289	26312	4.5	5848
ChargingStatusRes	260	2084	1.5	1390

Table 2.8: Example of message parameters

Message	Parameter	Element name (type)	Bytes	Bits	Time (s)	Data rate (bps)
CurrentDemandReq	DC_EVStatusType	EVReady (boolean)		2	0.25	6632
		EVErrorCode (string)	72	576		
		EVRESSSOC (byte)	100	800		
		Multiplier (byte)	7	56		
		PhysicalValueTypex7	Unit (string)	14		
		Value (short)	14	112		

The calculation of the number of bytes needed for the message transmission has been performed according to the required parameters for each of them. As an example, the case of *CurrentDemandReq* is shown in Table 2.8. As can be observed, a message is divided into different parameters, which are composed of a number of elements. These elements do not have the same data type, that is, several types can be found, such as boolean, string, bit, byte, unsigned long, short, etc. Additionally, the time requirement for each message is indicated in ISO 15118-2, so it is considered for this analysis. The procedure to compute the minimum data rate calculation is as follows: (i) identification of the selected message,

(ii) identification of the parameters included in each message, (iii) analysis of the elements that contains each parameter, considering the type, (iv) according to each data type, the number of bytes and bits is counted, (v) for each message, the time requirements are considered following the ISO 15118-2 specifications, (vi) the minimum data rate is calculated through the relation between number of bits and time requirements, following the equation

$$DR = \frac{\text{Numberofbytes}}{\text{Time}}.$$

Thus, it is possible to deduce that there are messages whose data rate requirements are higher than 6 kbps, according to the results obtained in Table 2.7. This leads to the conclusion that SWPDT proposals with data rates lower that 6 kbps are not suitable for the integration of OCPP and ISO 15118 in wireless charging.

Chapter 3

Contributions

Contribution 1 I. Casaucao, A. Triviño and Z. Lin, "Simultaneous Wireless Power and Data Transfer for Electric Vehicle Charging: A Review," in IEEE Transactions on Transportation Electrification, doi: 10.1109/TTE.2023.3309505 **JCR Impact Factor (2022): 7 (Q1)**.

Contribution 2 I. Casaucao, A. Triviño, F. Corti and A. Reatti, "SS and LCC-LCC in Simultaneous Wireless Power and Data Transfer: a Comparative Analysis for SAE J2954-compliant EVs" in IEEE Transactions on Industrial Informatics, doi: 10.1109/TII.2024.3360510 **JCR Impact Factor (2022): 12.3 (Q1)**.

Contribution 3 A. Triviño, I. Casaucao and M. Castilla, "Flexible Regulation of Active and Reactive Power for a Fully-controllable V2G Wireless Charger" in IEEE Transactions on Transportation Electrification, doi:10.1109/TTE.2023.3265189 **JCR Impact Factor (2022): 7 (Q1)**.

Contribution 4 A. Triviño, I. Casaucao and J.A. Aguado (2023). "Distributed Operation of an Electric Vehicle Fleet in a Residential Area". In Energy Smart Appliances (eds A. Moreno-Munoz and N. Giacomini). <https://doi.org/10.1002/9781119899457> **Book chapter**.

3.1 Simultaneous Wireless Power and Data Transfer for Electric Vehicle Charging: A Review

There are several reviews found in literature related to the simultaneous transmission of power and data focusing on biomedical [25], [26] and general [27] applications. However, there is a lack of studies analysing the SWPDT systems in electric vehicles. This work aims to provide the scientific community an in-depth review of the SWPDT technologies proposed by the researchers, analysing their advantages and disadvantages for electric vehicle applications.



Figure 3.1: Review papers found in related work about SWPDT systems.

The basis of this paper is the classification of SWPDT solutions into six categories: number of signals and links, data communication, signal combination, signal modulation, compensation system and data injector/extractor method. These categories, represented in Figure 3.2, have been deduced from the in-depth review of the EV SWPDT systems found in literature.

For each category, an exhaustive analysis have been performed studying the different configurations, highlighting the strengths and weaknesses of each solution.

The proposed classification of SWPDT systems can be useful to perform a comparative analysis of the analysed technologies. The conclusions extracted from this comparative study are significant:

- According to the number of links and signals, it can be seen that SL-DC configuration is the most used topology as it is the solution that generates most interest among authors.

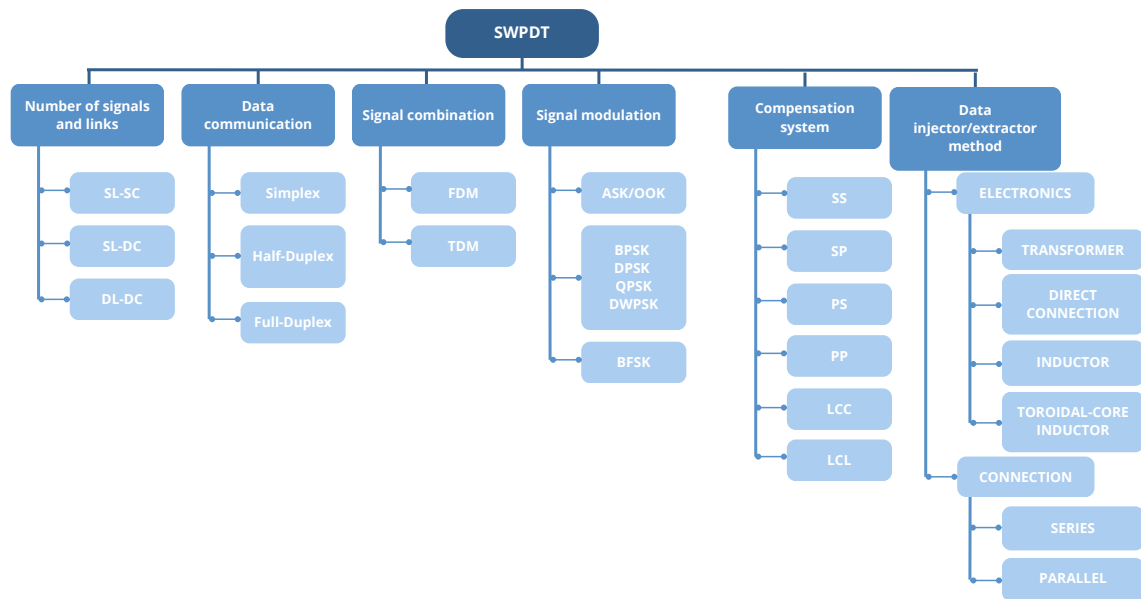


Figure 3.2: Classification scheme for SWPDT chargers in EVs

- The frequency of the data signal (f_d) used is usually chosen with a value an order of magnitude higher than the power carrier frequency (f_p). That is, if the power frequency is selected to be in the order of kHz, the data frequency should be in the order of MHz.
- With regard to the communication type, half-duplex technology is found more frequently than simplex and full-duplex.
- The most commonly used compensation systems in wireless charging systems are SS and LCC. SS compensation is more common in SL-SC systems, while LCC compensation is more relevant in SL-DC systems. LCC compensation is particularly advantageous in SL-DC systems, as it allows for the transmission of a data signal through a signal higher than the power carrier signal.
- The modulation techniques used in these systems are diverse, with FSK and its variants being the most common in SL-SC systems, and ASK/OOK in SL-DC and DL-DC topologies.
- The geometry of the coils used in these systems is typically circular, but some cases use rectangular and DD coils.

Similarly, the second objective of this work is to explore the possibility of using OCPP protocol in EV wireless communication. OCPP and ISO 15118 are considered as the communication standard used in EV plug-in charging, so it is interesting to study the feasibility

of using these protocols with the physical layer provided by the SWPDT system. The analysis performed in this paper shows that there are time requirements that must be fulfilled. These time requirements are related to the message structure and maximum transmission time associated to each instruction. The conclusions extracted from this analysis is that the solutions with data rate lower than 6 kbps are not appropriate to use OCPP and ISO 15115 protocols.

Finally, one of the most interesting contents of this work is the case studies proposals. With case studies, the real applications of SWPDT are highlighted, which can be of interest to researchers and practitioners. The proposed case studies are:

- **Maximum efficiency control.** Wireless charging solutions for EVs aim for maximum efficiency control, using communication systems to exchange parameters like load voltage, current, or battery status. SWPDT systems could be beneficial for these controls, as they operate through power coils without added wireless data technologies, which could be manipulated maliciously. Communication parameters like data rate or bandwidth must be studied and designed to meet all requirements.
- **Synchronisation.** The use of data transmission between the primary and secondary power converters is proposed in a specific case study for V2G operations. Synchronization of power converter signals is crucial for controlling power flows. Commercial communication platforms can be used for this, but the communication delay is variable due to the uncertain number of phases required. SWPDT could avoid this by setting the sequence of communication phases precisely, allowing for accurate communication latency estimation on the secondary side.
- **Dynamic charging.** In dynamic wireless charging systems, data transmission is crucial for robust and fast communication. However, data acquisition is usually done at the beginning of the charging line, which can lead to connection losses, data loss, delays, or inaccuracies. SWPDT systems with simple communication protocols can provide a clear alternative to commercial communication systems.
- **EV dispatching strategies.** EV dispatching strategies are gaining relevance due to increasing power consumption and peak demand in limited time slots. Bidirectional charging technologies like V2G and V2H can decongest power grids by using EV batteries as energy sources during high-power demand. Charging planning algorithms can optimize energy management at any given moment, allowing EV users to recharge their batteries according to electricity prices or battery state.

For each case study, a discussion of the most important characteristics has been made according to the established classification criteria, obtaining a comparison that can be seen

in Figure 3.3.

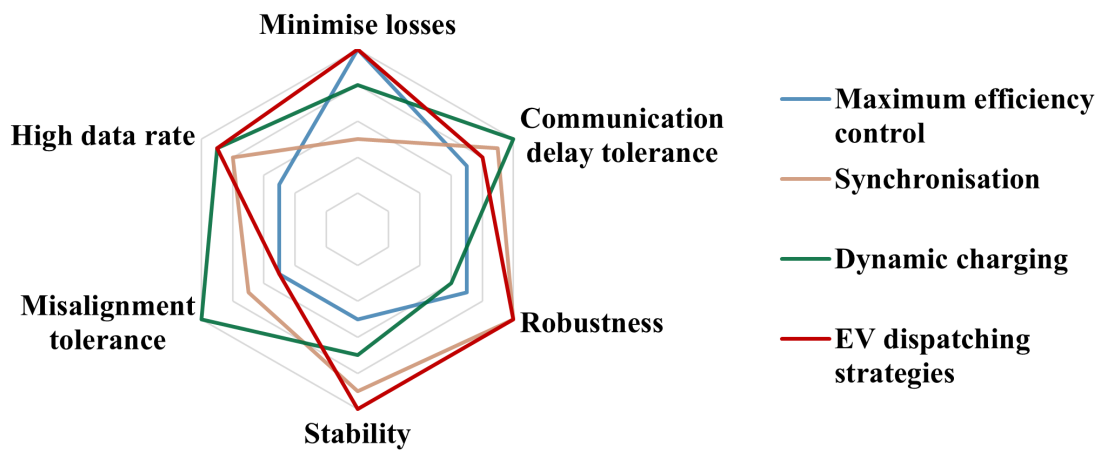


Figure 3.3: Case studies critical parameters.

This study has been useful to determine the most common features of SWPDT systems, as well as identifying design criteria that are suitable for the required application.

As a summary, the main contributions of this paper are:

- Classification and analysis of SWPDT systems according to 6 different criteria: analysis of the number of signals and links, data communication, signal combination, data modulation, data injection/extraction method and compensation system. The study has been performed considering the particularities of the EV applications. Specifically, the analysis has been performed taking into account the communication requirements of EV services and the particular misalignment and gap conditions expected in these vehicles, which are not so severe in other scenarios as medical implants.
- Analysis of design criteria within the main classification, based on the number of channels and signals. The design criteria are: operating frequency, data rate, electronics, crosstalk minimisation and coil geometry. The criteria have been evaluated considering the operational power frequencies imposed by the international standards for EVs, which is notably different to those used in wireless chargers for other areas as in medical applications.
- Study of different use cases of potential interest for EVs. The case studies are: (i) maximum efficiency control to cope with EV misalignment, (ii) synchronisation between power converters for bidirectional EV chargers, (iii) dynamic charging to control the power flow for EVs on move and (iv) EV dispatching strategies. The suit-

ability and configuration of the SWPDT technology have been analysed to provide an adequate performance.

- Study of the feasibility of using the OCPP protocol, widely deployed in EV charging stations, with SWPDT.
- Comparative analysis of the different current SWPDT solutions proposed in the literature in terms, mainly, of the frequency used, the bit rate achieved and the misalignment conditions tested.
- Discussion of possible future works related to SWPDT systems for EV wireless charging.

I. Casaucao, A. Triviño and Z. Lin, "Simultaneous Wireless Power and Data Transfer for Electric Vehicle Charging: A Review," in IEEE Transactions on Transportation Electrification, doi: 10.1109/TTE.2023.3309505 **JCR Impact Factor (2022): 7 (Q1)**.

3.2 SS and LCC-LCC in Simultaneous Wireless Power and Data Transfer: a Comparative Analysis for SAE J2954-compliant EVs

SS and LCC compensation topologies are widely used in literature both for WPT systems and SWPDT systems. The reason is that both solutions have a good performance under misalignment situations, as well as good efficiency values. In fact, their performance is similar in terms of power transmission.

However, although there are several studies that analyse the performance of SS and double-sided LCC compensation systems in power transmission, there is a lack of studies that compare their behaviour in SWPDT solutions. This comparison can be helpful to decide which is the appropriate solution according to the application and to their intrinsic characteristics.

This contribution aims to perform an in-depth mathematical study of SS and LCC-LCC compensation topologies in a SWPDT system considering the analysis of variables related to data transmission, providing the literature with a clear comparative focus on SWPDT systems.

The first analysed variable is the transfer function of power and data channel, as shown in 3.4. With this study, the performance of SS and LCC-LCC topologies can be understood, by analysing terms such as voltage gain, bandwidth, and phase. In order to perform the transfer function analysis, it should be considered that the components that constitute the system are not ideal, so their parasitic resistances must be taken into account throughout the complete analysis. Additionally, the value of the parasitic resistance strongly depends on the operation frequency at which the component is working. Thus, it is important to perform this study by differentiating the operation frequency of the power channel from the frequency governing the data channel. This analysis has been performed both for forward data transmission and for backward data transmission, so that it is possible to identify the requirements for bidirectional communication. Experimental verification was performed to validate the mathematical models.

Based on the analytical model, we have derived other important parameters related to the communication: bandwidth and signal-to-noise ratio. Another of the significant advances achieved in this paper is the comparative study of how the misalignment between coils affect on the data transmission for both topologies. In this case, three different distances for each axis have been selected to verify the performance of both topologies in data transmission terms. It should be noted that the distances have been selected by following the limits indicated by SAE J2954. During this study, the channel bandwidth have been

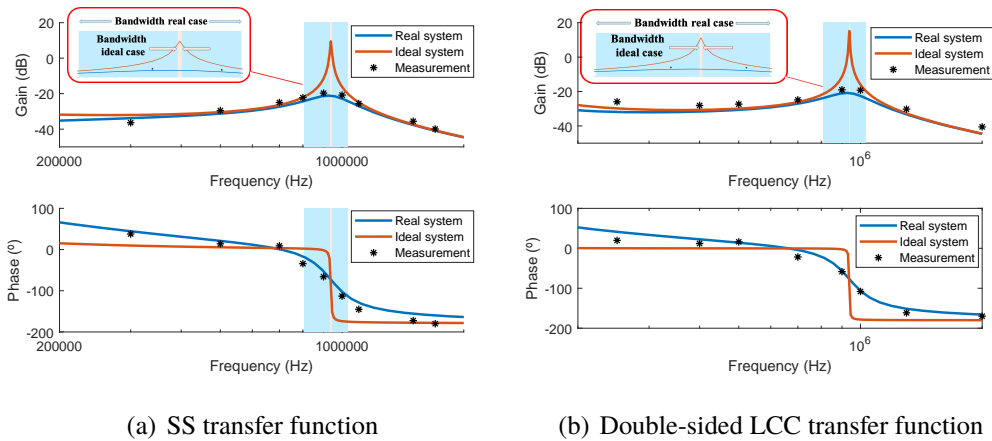


Figure 3.4: Transfer functions

used as a variable to measure the modifications in data channel during coil misalignment.

Finally, one of the most important variables that should be analysed in this type of systems is the interference between the power and data channel. To study this variable, two approaches have been proposed. First, it is important to understand the effect of the simultaneity of power and data channel in the transfer function of the complete system. This simultaneity, which can be calculated by considering the superposition principle, leads to changes in the final equation of the output voltage with respect to the input voltage. Second, the interference analysis can be measured by using the SNR variable, which has been defined in Chapter II of this document. With this variable, it is possible to determine the relation between the voltage of the data signal with respect the voltage level of the power signal. Finally, channel capacity is also analysed by following Shannon-Hartley theorem. SNR and capacity have been computed for different input voltages and for different misalignment conditions.

It should be mentioned that all these analyses have been experimentally validated in order to verify the accuracy of each approach, achieving satisfactory results for each case.

The conclusions achieved through this contributions highlight the similarities between SS and double-sided LCC compensation systems. In terms of efficiency, both technologies reach values higher than 90 %, so they are appropriate solutions for SWPDT systems. However, in term of data transmissions differences can be found. Although the trend in the curves of transfer function, SNR and capacity is similar for the two cases, double-sided LCC topology has a very significant advantage that makes it the optimal solution in this type of system. This advantage is that, in bidirectional communication, the transfer function of forward and backward data transmission are the same in the range of MHz, which is the frequency for information transmission. Thus, it is possible to deduce that, with the aim of constitute a symmetrical system, which simplifies the implementation of

a SWPDT system, double-sided LCC is the most convenient option.

As a summary, the main contributions of this paper are:

- the definition of the transfer function (in terms of gain and phase) for the data and power channels in a SWPDT EV charger. The formulation includes the parasitic resistances of reactive components, which have a significant impact on the system performance as we have demonstrated for SS and a LCC compensation systems. To validate the transfer functions under realistic conditions, the variation of the parasitic resistance with the working frequency has been considered, as two frequencies are involved in these EV applications.
- the theoretical analysis of the bandwidth offered by the data channel for both compensation systems to understand the effects of typical coil misalignment conditions identified by SAE J2954.
- the study of the impact of the data channel on the power channel and vice versa for the conditions set in SAE J2954. For this purpose, it has been analysed the Signal-to-noise ratio (SNR) between the power and data signals and the capacity (bits/s) for each misalignment distance and at different power levels, studying the trend of the curves under variations of the input voltage.
- the study of the backward data transmission, with a comparative between forward and backward performance for both topologies. The study of backward transmission is of interest for the integration of wireless electric vehicle chargers with Vehicle-to-grid (V2G) control systems. In this context, communication occurs in both directions, and the performance for each compensation topology is different.
- the design and experimental tests of SS and LCC prototypes to validate the theoretical approach.

I. Casaucao, A. Triviño, F. Corti and A. Reatti, "SS and LCC-LCC in Simultaneous Wireless Power and Data Transfer: a Comparative Analysis for SAE J2954-compliant EVs" in IEEE Transactions on Industrial Informatics, doi: 10.1109/TII.2024.3360510 **JCR Impact Factor (2022): 12.3 (Q1)**.

3.3 Flexible Regulation of Active and Reactive Power for a Fully-controllable V2G Wireless Charger

With the rise of electric vehicles in recent years, energy demand is expected to increase to 230 TWh by 2030. In order to alleviate the potential problems that may be caused by this increase in demand, Vehicle-to-grid (V2G) technology has gained popularity in the charging process of electric vehicles. In this technology, energy flows bidirectionally between the electric vehicle and the grid, so that the battery is charged or discharged depending on the overall needs of the installation. In the case of conductive chargers, there are already commercial solutions that rely on this technology. However, in wireless inductive charging, this technology is still in the research and development phase.

The aim of this work is to develop a V2G control algorithm for a bidirectional wireless electric vehicle charger. In this control, the charger is intended to operate in all four quadrants, addressing eight different operating modes. The operating modes are shown in Figure 3.5. With the control of the four quadrants, it is possible to define any combination of active and reactive power value to be transmitted by the wireless charger, as well as the direction of the power flow.

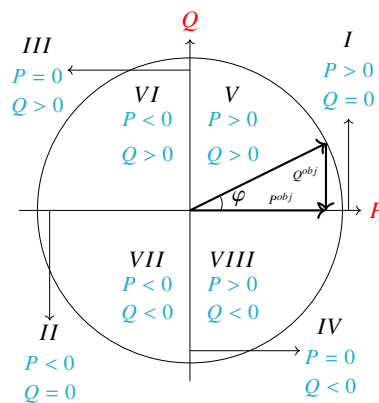


Figure 3.5: Operating modes for all four quadrants for a bidirectional wireless charger.

The control has been designed for an SAE J2954 wireless charger with an SS compensation system, and with a communication system between the primary circuit and the secondary circuit for the control of the power converters.

In general terms, this designed control is based on the calculation of three angles, α , β and δ , which define the phase shift between the activation signals of each power converter (α and β), as well as the phase shift between the two converters (δ). A schematic of the

proposed solution is shown in Figure 3.6. With α and β the amount of power transmitted is controlled, while δ sets the direction of power flow. This algorithm can be developed by using the the equations defining the active and reactive power of the primary and secondary circuit (equations (3.1)-(3.4)).

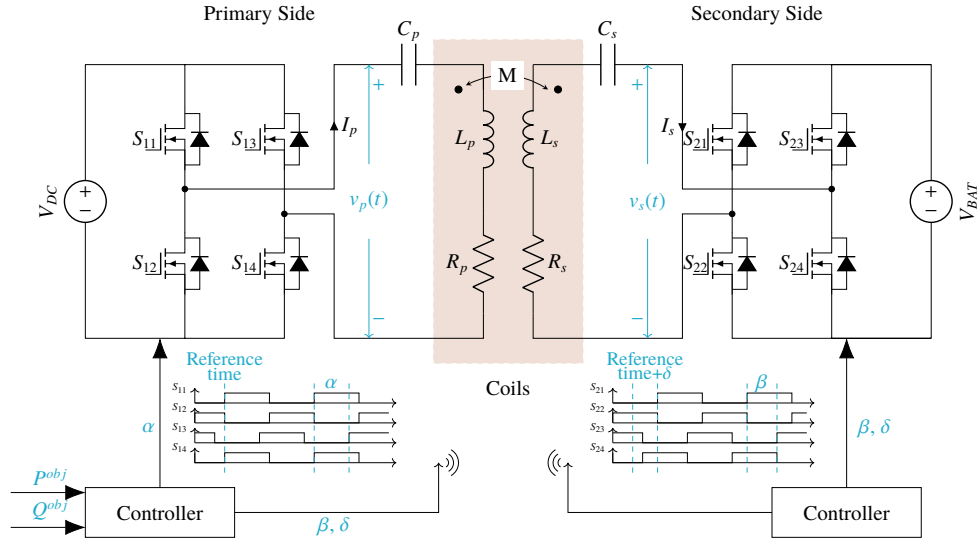


Figure 3.6: Complete bidirectional charger circuit with a Series-Series topology.

$$P_p = V_p \sin\left(\frac{\alpha}{2}\right) \frac{V_p \sin\left(\frac{\alpha}{2}\right) R_s - M \omega_o V_s \sin\left(\frac{\beta}{2}\right) \sin(\delta)}{R_p R_s + M^2 \omega_o^2} \quad (3.1)$$

$$Q_p = V_p \left(\frac{M \omega_o V_s}{R_p R_s + M^2 \omega_o^2} \right) \sin\left(\frac{\alpha}{2}\right) \sin\left(\frac{\beta}{2}\right) \cos(\delta) \quad (3.2)$$

$$P_s = V_s \sin\left(\frac{\beta}{2}\right) \left(\frac{-V_s R_p \sin\left(\frac{\beta}{2}\right) - M \omega_o V_p \sin\left(\frac{\alpha}{2}\right) \sin(\delta)}{R_p R_s + M^2 \omega_o^2} \right) \quad (3.3)$$

$$Q_s = V_s \left(\frac{-M \omega_o V_p}{R_p R_s + M^2 \omega_o^2} \right) \sin\left(\frac{\alpha}{2}\right) \sin\left(\frac{\beta}{2}\right) \cos(\delta) \quad (3.4)$$

As these equations present nonlinearities, it is necessary to simplify the expressions in order to obtain a simple relation between α , β , δ and the objective active and reactive power (P^{obj} and Q^{obj} , respectively). To simplify these expressions is necessary to consider that the numerator term found in eq. 3.1 and 3.3 can be reduced, so that:

$$V_p \sin\left(\frac{\alpha}{2}\right) R_s \ll M \omega_o V_s \sin\left(\frac{\beta}{2}\right) \sin(\delta) \quad (3.5)$$

Furthermore, it is also possible to neglect the term $R_p R_s$, since the value of the primary and secondary resistance is very low. Thus, it is possible to find the simplified expression of the primary and secondary active power as follows:

$$P_p^{simp} = V_p \left(\frac{-V_s}{M\omega_o} \right) \sin\left(\frac{\alpha}{2}\right) \sin\left(\frac{\beta}{2}\right) \sin(\delta) \quad (3.6)$$

$$P_s^{simp} = V_s \left(\frac{-V_p}{M\omega_o} \right) \sin\left(\frac{\alpha}{2}\right) \sin\left(\frac{\beta}{2}\right) \sin(\delta) \quad (3.7)$$

With these simplified equations, the calculation of δ , α and β angles is simple. It should be noted that $\alpha = \beta$ to simplify the control. The final expressions relating these angles to the objective power values are found in eqs. 3.8 and 3.9. The complete formulation of this algorithm can be found in the paper.

$$\delta = \arctan \frac{P^{obj}}{Q^{obj}} \quad (3.8)$$

$$\alpha = 2 \arcsin \left(\sqrt{\frac{P_s M \omega_o}{-V_p V_s \sin \delta}} \right) \quad (3.9)$$

This control topology through phase shift angles has been addressed in other solutions proposed in the literature implementing, in most cases, operating modes I and II. However, in any previous case, the control of a V2G system in wireless charging with 8 different operating modes has been studied and implemented. This is the main contribution of this paper.

Algorithm 1 Control of primary power converter

1. **Input** data: $M, L_1, L_2, C_1, C_2, R_1, R_2, \omega_o, P^{obj}, Q^{obj}$
 2. Compute δ (Eq.18)
 3. Compute α (Eq.19)
 4. Timer configuration: α, δ phase shift
 5. **while** (1)
 6. Signal generation: (S11, S13)
 7. **end while**
-

Algorithm 2 Control and synchronization of secondary power converter

1. **Input** data: $M, L_1, L_2, C_1, C_2, R_1, R_2, \omega_o, \alpha, \delta$
 2. Reference signal generation
 3. Measure initial phase delay
 4. Timer configuration: α, δ phase shift
 5. **while** (1)
 6. Phase delay measurement
 7. Compute PI+I control
 8. Compute synchronized δ
 9. Signal generation: (S21, S23)
 10. **end while**
-

Figure 3.7: Pseudo-code of algorithms for primary and secondary converters

It should be noted that for the implementation of this control with two different controllers, it is necessary to define a synchronisation algorithm. In this way, at the beginning

of the charging process, it is ensured that the offset between the converters is adequate. This issue has also been studied and implemented in this paper, ensuring accurate power regulation within a range of 0.2 to 0.3 seconds. For the implementation of this synchronisation control, two different algorithms have been developed, as shown in Fig. 3.7. The first algorithm is implemented for primary controller, while the second algorithm is for secondary controller. In the first algorithm, δ , α and β angles are computed. In the second algorithm, the controller receives the previous computed δ , α and β , and through a PI+I controller generates the phase shifting according to these angles.

The proposed control algorithm has been validated through experimental results. The charger has been tested for eight different operation modes, with charging power up to 1 kW. The results demonstrate the effectiveness of the algorithm in achieving the desired power configurations.

As a summary, the main contributions of this paper are:

- It presents the design and implementation of a V2G wireless charger with a typical configuration of two full-bridges and a Series-Series compensation topology. The topologies of the power converters are common in EV wireless charger so the proposed controller can be easily adapted for a wide set of systems.
- The controller functions by delaying the activation of the power converters on the primary and secondary sides. Based on an analytical study, we derive the equations to configure a controller that can effectively work in any position of the four-quadrant diagram with any relation between the active and reactive powers (P^{obj} and Q^{obj} respectively). With this control, the EV gains flexibility to participate in diverse ancillary grid services not only for frequency control - as most of the previous works - but for voltage regulation. As shown in the related work some previous proposals are restricted to operate in some specific conditions (e.g. maximum active power transfer, unity power factor) so they do not contemplate any combination of P and Q, that is, they cannot participate in all the potential services provided for EV conductive chargers.
- The control has been implemented with a synchronisation algorithm and tested for the eight operation modes. From the results, it is concluded that the efficiency is not equivalent for similar power demands with opposite sense of the power flows. Previous works included results for some operation modes (mainly Mode I and II) only as they cannot work in the complete P-Q four-quadrants.

A. Triviño, I. Casaucao and M. Castilla, "Flexible Regulation of Active and Reactive Power for a Fully-controllable V2G Wireless Charger" in IEEE Transactions on Transportation Electrification, doi:10.1109/TTE.2023.3265189 **JCR Impact Factor (2022): 7 (Q1)**.

3.4 Distributed Operation of an Electric Vehicle Fleet in a Residential Area

The rise of renewable energy poses challenges to power grids, compounded by increased urban consumption and electric vehicle adoption. EVs, projected to reach 145 million by 2030, will strain electricity demand and infrastructure. Unmanaged EV charging could lead to grid issues such as overloading and power quality deterioration.

EVs offer flexibility as controllable loads, aiding grid stability. Optimized charging schedules taking advantage of this flexibility can mitigate these challenges if they are aligned with grid demand. EVs can also transition from controllable loads to grid energy providers, with technologies like Vehicle-to-Grid (V2G) and Vehicle-to-Home (V2H) interactions, enabling energy exchange.

The charging strategies are varied, including Plug-in and Charging, Delayed Charging, Smart Charging, and V2X Charging. Dispatching strategies play a fundamental role in managing EV charge and discharge processes.

Home Energy Management Systems (HEMS) are governed by algorithms that prioritize objectives such as reducing electricity bills, utilizing renewable energy sources, and achieving self-sufficiency. Various algorithms, including deep reinforcement learning and multi-objective optimization, have been proposed to enhance HEMS performance [107–109].

This chapter presents a review of different types of EV dispatching strategies that can be installed at residential areas, providing an overview of the services they offer to the distribution grid and home energy services provided by electric vehicles. Three main topologies are analysed: centralised, distributed and decentralised. Centralized dispatching strategies involve a central controller that manages the charging and discharging of electric vehicles (EVs) in a residential area. The central controller aggregates information and charging requirements from each EV and determines the parameters for charging and discharging at each instant of time. The objective is to achieve the best global operation from a centralized position. However, this approach has some disadvantages, such as the potential failure of the system in the event of an optimization problem without a global solution. It also lacks scalability as the difficulty of solving the problem increases with the number of vehicles in the system.

On the other hand, decentralized dispatching strategies offer benefits such as increased flexibility, scalability, and potential cost reductions. They also enable EVs to serve as a source of electricity during power outages. However, challenges include the need for coordination among multiple stakeholders and the potential failure of the system without

a global solution.

The main contribution of this chapter is the proposal of two distributed EV dispatching algorithms for a residential area. Figures 3.8 shows the scenario for unidirectional chargers and in Figure 3.9, this scenario is adapted to V2G chargers. Due to the subject addressed by this doctoral thesis, the interest of this second algorithm is highlighted. The full theoretical development can be found in the chapter.

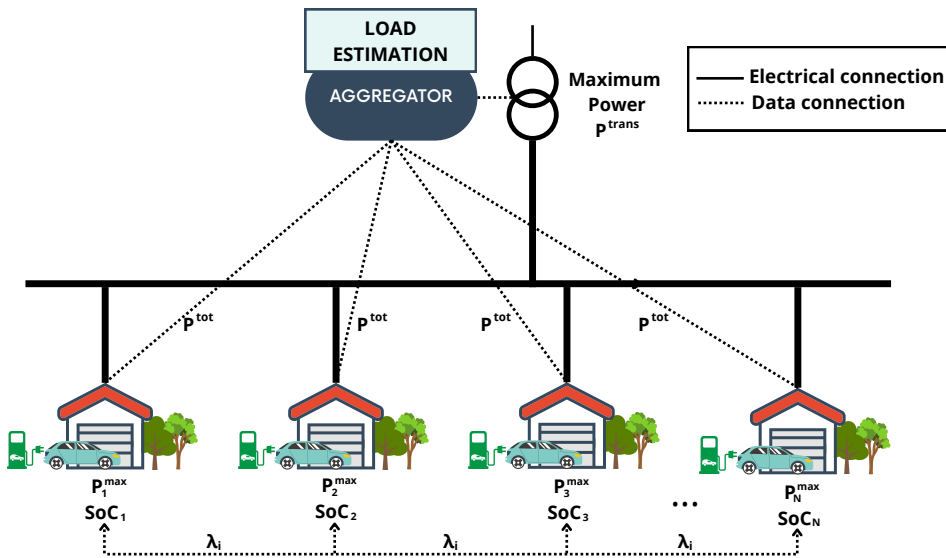


Figure 3.8: Basic scenario tested for the distributed management of EV charging.

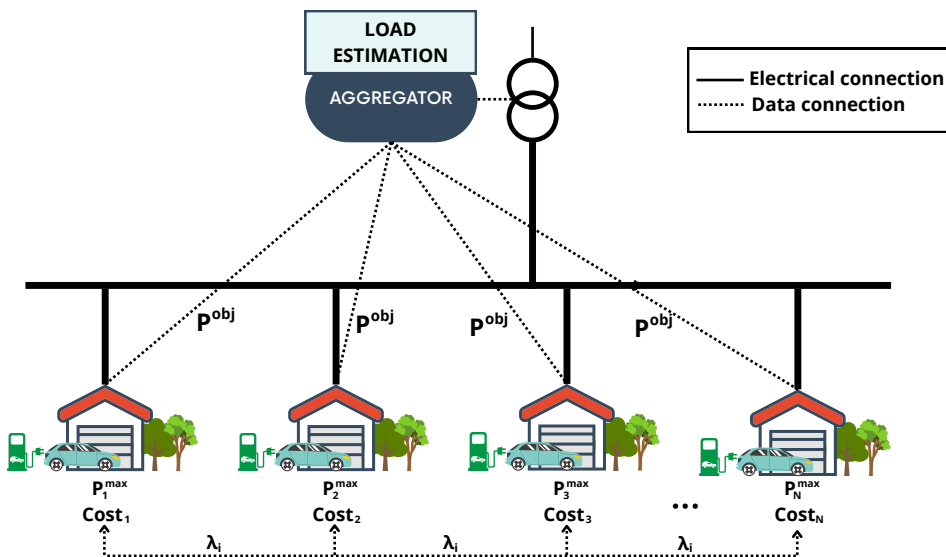


Figure 3.9: Scenario with home PV and storage tested for the distributed management of V2G operation.

The main goal of both algorithms is to reach the maximum optimal energy management

of the EVs controlled by an aggregator. The SoC and electrical aspects of home chargers are taken into account for unidirectional charging in order to maximize power while optimizing the schedule for each EV. As an alternative, the V2G operation determines how convenient it will be to contribute to the goal power based on anticipated home demands, the capacity to collect renewable energy, or by the SoC. As final results, the simulation analysis confirm that both proposed strategies are computationally efficient and converge to the global optimum.

A. Triviño, I. Casaucao and J.A. Aguado (2023). "Distributed Operation of an Electric Vehicle Fleet in a Residential Area". In Energy Smart Appliances (eds A. Moreno-Munoz and N. Giacomini). <https://doi.org/10.1002/9781119899457> **Book chapter.**

Chapter 4

Conclusions and future works

Chapter 4 of this document ends with the description of conclusions and future works that have been identified throughout this Thesis.

4.1 Conclusions

The development of this doctoral thesis has allowed the achievement of all the initial objectives proposed, as well as the contribution to the scientific community of numerous advances related to SWPDT systems and V2G technology. Specifically, the following conclusions have been drawn:

- Through a first review of the state of the art, it has been identified that there was a lack of studies in the literature that compiled all the proposed solutions for SWPDT systems in EVs. According to the current trend of proposed solutions, SWPDT systems are presented as a feasible alternative to commercial technologies for the simultaneous transmission of power and information. In addition, the proposed solutions are not unique, and specific design criteria for the specific application of EV were not found. This was the main motivation of the proposed review. Based on the review, we could conclude that the preferred system topology by researchers is SL-DC, with SS or LCC-LCC compensation systems, due to the advantages they provide. With regard to the communication type, bidirectional technologies as half-duplex or full-duplex are selected. In relation to the data signal, the most adopted signal division multiplexing technique is FDM, and communication is preferable performed with ASK modulation, and injected/extracted from the power circuit with transformers, according to the reviewed literature. Additionally, it can be concluded that SWPDT systems can be an advantageous solution for different case studies, such as dynamic charging, maximum efficiency control, synchronisation algorithms and EV dispatching strategies. Finally, it has been analysed the feasibility of using SWPDT systems in protocols such as OCPP and ISO 15118 addressing physical layer requirements.
- SWPDT systems are still under development, since it is a new technology that intends to substitute the commercial wireless communication devices. For this reason, studies related to the performance of the compensation system, which is an important element in inductive-resonant chargers, are not oriented to analyse the performance of data channel. In this Thesis, a comparative study of SS and double-sided LCC compensation topologies is proposed in order to give researchers a detailed description of the behaviour of these systems during data transmission. Specifically, we have developed a mathematical model to characterise the transfer functions and the capacity of the communication channels offered by these two topologies in SWPDT systems. According to this formulation, we could conclude that it is of crucial importance the consideration of the parasitic resistances of the system components,

since they have a significant effect on the gain magnitude of the system. In addition, it is important to consider that the behaviour of the components is different according to the operation frequency, so different values should be selected in the analysis of power and data channels. From this first analysis, it is possible to determine that the double-sided LCC compensation system has a symmetrical behaviour in the frequencies in the range of the data frequency. The performance under misalignment conditions could be also studied with the proposed formulation. Particularly, it can be determined that the misalignment distance has a direct effect on the voltage gain of the system for all cases, being more significant in Y-axis. The analyses have been verified with experimental validations which confirm the accuracy of the developed approximations.

- V2G technology has been extensively studied in conductive chargers. However, in wireless charging systems for EVs, this technology is still under development. Proposals for wireless chargers with V2G should consider the possibility for the vehicle to participate in the grid ancillary services. One of the main requirements favouring the participation of EVs in V2G applications is the control of transmitted active and reactive power. This work proposes a control algorithm that allows working in the four quadrants of P and Q, allowing up to 8 operating modes without any restriction about the active and the reactive power and their relation. The design has been calculated theoretically, accompanied by a simulation study and validated through experimental tests with charging powers up to 1 kW. The results of this proposal have been satisfactory, achieving full operation of the charger with efficiency values above 90 %.
- The V2G technology allows the EV to participate in dispatching strategies that schedule the charging process in an optimal, economical and efficient way. Throughout this Thesis, a distributed EV dispatching algorithm is proposed to reach the maximum optimal energy management of the EVs. Simulations validate the proposal, concluding that the solution is computationally efficient and converges to the global optimum point.
- Considering these two main areas, SWPDT systems and V2G control algorithms, it is possible to identify a synergy between the two fields. In V2G chargers, it is necessary to transmit information on, for example, voltage, current and power output values, so that the charging of the vehicle can be regulated by means of control techniques without compromising its safety. On the other hand, SWPDT is considered as an efficient method to perform the data transmission via the power circuit. It is, therefore, interesting to design a SWPDT system whose specific application is the

transmission of information related to the V2G control algorithm. Furthermore, in order to design the complete system, the results obtained in the comparative study between SS and double-sided LCC can be considered. In addition, it should be mentioned that this validations of the SWPDT system have been performed by using a SAE J2954-compliant charger, which was not present in the literature until the proposal carried out in this doctoral thesis. With this final system, a fully functional system is achieved that allows the control parameters of the V2G system to be communicated in a reliable way.

4.2 Future lines

Based on the conclusions drawn in Section 4.1, different future lines have been identified:

- Although this doctoral thesis briefly describes the possibility of integrating SWPDT systems with widely used communication protocols such as OCPP or ISO 15118, it is important to extend this analysis to other criteria different from data rate, such as delay tolerance. Additionally, it is also interesting to perform experimental validations by using messages with the structure proposed in OCPP and ISO 15118.
- SWPDT are presented as an alternative to the use of commercial communication technologies, such as Bluetooth, Wi-Fi or ZigBee. However, there is a lack of studies that focus their research on analysing the vulnerabilities of SWPDT systems. This could provide literature with a realistic comparative about the security of both alternatives.
- As briefly mention in this document, in order to minimise the effect of misalignment in WPT chargers and, therefore, in SWPDT systems, active inductors can be used. The PhD student initiated her study on this topic during her pre-doctoral stay at the University of Florence, so it is expected that an analysis of this effect will be carried out in the near future.
- Dynamic charging is attracting interest from the scientific community due to its direct application in electric vehicles following a pre-established route. Thus, it could be interesting to study the integration of SWPDT systems in dynamic wireless chargers.
- In order to increase the data rate, it is of interest to study the relation between the modulation technique used and the final data rate achieved. As inductive-resonant chargers for EVs use to work at high power levels (higher than 1 kW), the effect of the

power transmission in data channel could be alleviated by using different modulation techniques that remain unchanged under external disturbances.

- As misalignment is an intrinsic issue in EV wireless charging, there should be methods to ensure that communication in a SWPDT system occurs correctly regardless of the position between the coils. Thus, it is proposed to study the possibility of creating a control algorithms that allows to adapt the data rate with respect to the misalignment situation.
- In the last years, there is a growing trend in the study of wireless charging in autonomous underwater vehicles (AUV). In this way, it is proposed to extend the analyses presented in this doctoral thesis to other environments, such as freshwater or seawater. Thus, it could be possible to perform a comparative analysis between environments, from which new conclusions can be extracted.
- Finally, an interesting field of study is the analysis of the electromagnetic interference (EMI) under non-ideal conditions. Thus, it can be useful to perform experimental validations near devices that can emit unwanted noise in the order of kHz and MHz, in order to validate the performance of power and data channel, respectively.

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