VEHICLE ELECTRIFICATION IN MODERN POWER GRIDS:

INNOVATIVE PERSPECTIVES ON POWER ELECTRONICS TECHNOLOGIES AND CONTROL CHALLENGES

01. Introduction

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Abstract

This book chapter seeks to present a concise introduction and contextualization affecting the topics correlated to the disruptive perspectives of vehicle electrification in modern power grids, welcoming innovative power electronics technologies, and control challenges in support of the power grid interface. As demonstrated in this book chapter, the main objective is to combine in a single book, power electronics technologies and control strategies for vehicle electrification in modern power grids in a future viewpoint, indicating that vehicle electrification is facing challenges, but it is also of added value for the power grid. In terms of power electronics technologies covered aspects such as power charging and traction systems; the interface of the vehicle electrification with renewables and energy storage systems; vehicle electrification operating as power quality conditioners for the power grid; vehicle electrification framed with solid-state transformers and within AC, DC, and hybrid power grids; vehicle electrification in smart homes, smart cities, and smart grids; advanced topologies of power electronics converters. To deal with the increasing penetration of vehicle electrification, control strategies are also retained: for the power electronics converters; for interfacing renewable energy sources and energy storage systems as support of electric mobility; for operation modes, e.g., innovative modes in addition of vehicle-to-grid; for ensuring power quality and reliability in smart grids; for demand response strategies; and forecasting strategies.

Index Terms— Vehicle electrification; Smart grids; EV charging; EV traction systems; Power quality; Power electronics; Operation modes.

I. INTRODUCTION

Nowadays, the prompt expansion of vehicle electrification has persuaded a significant, positive, and necessary shift in the transportation sector and, in counterpart, it contributed to a huge amount of energy that is demanded and, most importantly, it is predictable to continue in such path [1][2]. This is a new reality, specifically in what concerns to private level, where the substitution of conventional vehicles is running faster than in other sectors, where various models and technologies are available. Nevertheless, the shift of paradigm for vehicle electrification is not acting alone and such shift has spawned a set of challenges and opportunities in other associated sectors, where the power grid and the automotive industry are included and, at a certain point, leading such route due to different, but both with very relevant reasons [3]. Issues, opportunities, and surveys are always appearing since the transition is always ongoing [4][5]. The new and revolutionary paradigm imposed by vehicle electrification, in particular, caused by the adoption of battery electric vehicles and hybrid vehicles, characterizes a noteworthy transformation in the automotive sector and, inherently, in the energy sector, which, combined with a set of other innovative technologies, is continuously facing the transition for smart grids [6]. The largely illustrative vehicles are the pure and hybrid plug-in battery electric vehicles, where the principal distinction is about the storage capacity, therefore, influencing the necessitated charging time. In the scope of this chapter, the terminology “electric vehicle” is used for mentioning both types. Affecting the power interface, the commercially electric vehicles are designed only for the unidirectional possibility [7][8], and it is generic for both on-board and off-board systems. In a particular analysis from the point of view of the automotive sector, it can be highlighted, e.g., new and/or adapted factories with the necessary machinery targeting vehicle electrification, new suppliers of components and materials, new sources of rare materials, new qualified employees and, when applicable, additional training for current employees.

Generally, in all sectors, as the world looks for natural and sustainable solutions targeting to significantly cut the carbon emissions linked to the transportation sector and aiming definitively stop climate change, the appearance of vehicle electrification with more prominence, demonstrates that it is a viable alternative to traditional internal combustion engine vehicles. It seems that vehicle electrification reaches a point without return: future mobility will be electrified. This assumes even more relevance since it is feasible to verify a clear correlation between the resultant environmental benefits of vehicle electrification adoption and the acceleration of its proliferation and the reduction of sustainable issues. Such topics are correlated, and they are walking together. Such correlation contributes to the advancement of several technologies framed with vehicle electrification, including the advancements: in the charging systems to accommodate the necessities of the users in terms of power and schedules; in the traction systems, e.g., with one or more motors, and regenerative operation; and in the battery technologies for storing more energy for the same volume and mass, with more reduced charging times, and with higher guaranteed lifetime [9][10]. These points are strategic and are primordial topics of research for mutual synergetic cooperation between academia and industry. Nevertheless, such an indispensable transition is not performed softly, since it is also accompanied by a series of challenges and opportunities for all intervenient, notably in the contextualization with modern power grids with more and more connected power devices, where status and issues of the vehicle electrification are well documented [11][12].

From a global perspective around the world, year-by-year, the number of sales demonstrates that vehicle electrification is gaining more expression, proving its competitiveness with traditional vehicles based on internal combustion engines. This is a reality for several countries and, most important, it is predictable that the sales of electric vehicles will surpass conventional ones with internal combustion engines. Fig. 1 demonstrates the number of electric vehicle sales (including both battery electric vehicles and plug-in hybrids), showing that it reached a total of 10.5 million in 2022 [13].

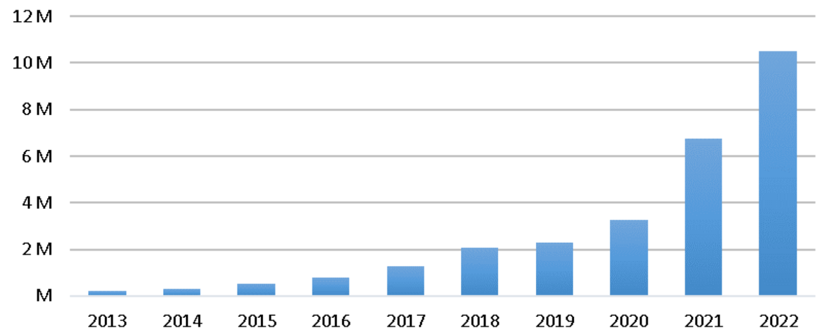

Fig. 1 Number of electric vehicle sales, including both battery electric vehicles and plug-in hybrids.

II. Power Electronics for the Vehicle Electrification

The paradigm of vehicle electrification has been growing progressively and mainly over the past two decades it is incontestable the tremendous increase, where, in the first perspective, it was forced by factors such as government incentives and consumer awareness about environmental issues, and, in a second perspective it was forced by the improved skills and the advances in the storage technologies (e.g., permitting the storage of more energy for the same volume and weight and faster charging times). Both perspectives were decisive in catapulting the rapid growth of vehicle electrification, which is not only related to road vehicles (e.g., full battery vehicles and hybrid vehicles) but also to a much wider range, which includes maritime and aircraft [14][15].

Independently of the perspective, the incursion of vehicle electrification requires the power grid to provide the necessary energy, which is the fundamental perspective of the vehicle electrification connected to the power grid but provokes both opportunities and challenges. However, once connected to the power grid, vehicle electrification can serve as a distributed energy resource, offering grid support, dedicated energy demand strategies, and peak load management, all of them through advanced power electronics and control technologies. For that purpose, it is indispensable to the formation of a robust infrastructure of power grid and smart charging strategies to accommodate the tremendous growth of vehicle electrification. In a first step, vehicle electrification started with small EVs, but rapidly, converge to commercial vehicles as an expected progression. Thus, numerous commercial vehicle manufacturers have moved the attention to vehicle electrification. Therefore, commercial vehicle charging complements such convergence and two approaches are possible, explicitly the return-to-base and the on-route charging strategies [16].

Power electronics technologies are decisive for vehicle electrification for several on-board and off-board purposes, facilitating the conversion and control of electrical energy [17]. In the first point of view, when looking for vehicle electrification, two key elements are distinguished, which include the fundamental principles of power inverters for the motor drivers, and power converters for battery charging [18]. However, inside these two parts power electronics are also indispensable for other purposes, e.g., such as the battery management system, which is a complement of the heart of vehicle electrification: the battery. Battery management systems are crucial for managing the battery, and consequently for ensuring that the maximum battery lifetime is reached, but also for guaranteeing safety and enhanced performance.

In this context, appearing power electronics technologies are decisive for the continuous improvement of vehicle electrification and for new contextualization in modern power grids, which includes emerging technologies such as semiconductors, cooling solutions, and mixing with renewables. Concerning control challenges in power electronics, real-time strategies are needed to guarantee safe and optimal operations since, as vehicle electrification becomes more prominent, the answers linked to grid integration should attend to it. Moreover, the integration of vehicle electrification in power grids requires additional care concerning voltage and frequency stability, harmonics, and grid upgrades, which do not happen with traditional loads. On the other hand, with the increasing integration of vehicle electrification, establishing communication with the power grids, as well as with the connectivity among vehicles, cybersecurity, and data privacy become significant concerns, where the data privacy of the users, vulnerabilities and safeguard solutions against cyber threats cannot be neglected.

In terms of innovative perspectives on power electronics technologies, it is indisputable that wide bandgap semiconductors offer enhanced performance and efficiency. This is also reflected in vehicle electrification and the future perspective of wireless technologies, which includes charging methods and bidirectional operation, as well as dynamic charging targeting to minimize the charging time and driver range anxiety [19]. In terms of energy storage technologies, solid-state batteries represent a groundbreaking development, offering a new potential for vehicle electrification, including safety, energy density, and fast-charging capabilities [20]. It is important to highlight that lithium has contributed decisively to the shift to the vehicle electrification paradigm [21]. The development of technologies for the powertrain [22], and for the electric motors is also a pivotal point in vehicle electrification, where various possibilities are established [23][24].

Regarding the power grid management with support of vehicle electrification, it can be highlighted: grid stability accommodating the charging/discharging from vehicle electrification with specific and cooperative strategies; demand response programs allowing operators to manage peak loads, incentivizing the energy consumption with supportive adjustments targeting the accommodation of all charging requirements while guaranteeing reliability; operation in microgrid scenarios and with direct context of renewables, offering a complementary solution to deal with the intermittent production of renewables.

Real-world projects of different stakeholders show the challenges and solutions engaged in realizing the large-scale integration of vehicle electrification in modern power grids and the obtained results offer valuable insights into best practices [25].

III. The Vehicle Electrification: Key Contributions for a Full Transition

This book aims to explore the landscape of vehicle electrification within modern power grids, concentrating on two correlated technological looks: the necessity of more and more innovative power electronics technologies; and associated control challenges for interfacing with the power grid and achieving high-efficiency vehicles. Starting from such perspective, the book encompasses diverse aspects, including the impact on the power grid caused by vehicle electrification, the arisen advantages of vehicle electrification in modern power grids, the emerging power electronics solutions to support the continuous development of the vehicle electrification, as well as the strategic plans for efficient integration of the vehicle electrification. The book seeks to support an in-depth presentation and investigation concerning the correlation involving the vehicle electrification paradigm and the modern power grids, by examining the key factors involved and comprehensively understanding the dynamics surrounding such correlation. More specifically, the book focuses on the innovative perspectives about on-board and off-board power electronics technologies and on the control challenges that must be addressed, both viewed as key drivers for the evolution of vehicle electrification in modern power grids. Fig. 2 shows a contextualization of the key technological contributions for a full transition to vehicle electrification, noting a specific framework of the distinct book chapters and how they are related.

The book covers a wide range of technological areas connected to vehicle electrification, both internally and externally within the context of interfacing modern power grids, investigating the impact, discussing the power electronics technologies, exploring the associated control challenges, presenting future innovative perspectives, and giving power grid forecasting and management strategies. Aiming to mitigate and anticipate problems in the interface of vehicle electrification into power grids is indispensable for the adoption of customized legislation and grid codes. Such consideration is not generic for the world, and it can be very specific according to a given country, which contributes to advancing sustainable transportation in the different countries and harmonizing the collaboration between electric vehicles and existing power grid infrastructures, guaranteeing continuous incorporation while preserving stability. Legislations and grid codes address vast and complex topics, covering subjects about charging infrastructure, power balancing and management, and motivation models for satisfying both consumers and industry participants, targeting optimizing the benefits of all due to vehicle electrification adoption.

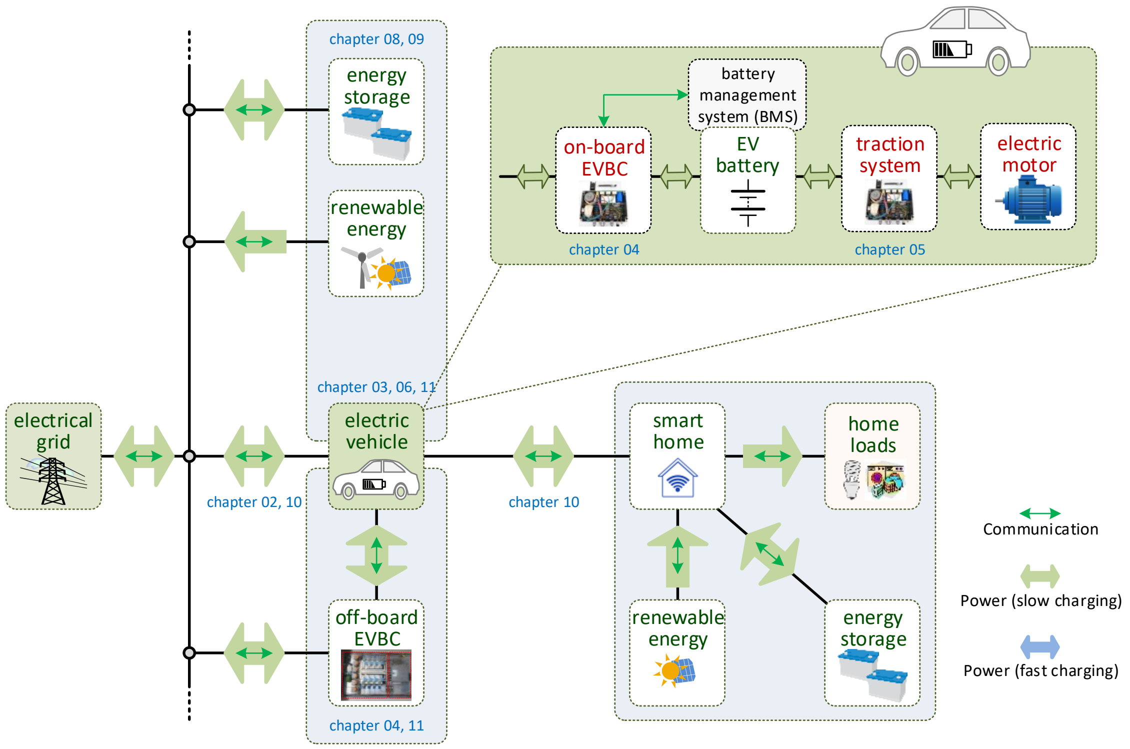

Fig. 2 Contextualization of the key technological contributions for a full transition to vehicle electrification.

Vehicle electrification acceleration is ongoing and mainly proved by battery electric vehicles, but in the perspective of modern power grids and knowing that it is a dynamic load in the power grid (i.e., with specific power demand and almost randomly placed and with random schedules for charging), accurate forecasting of vehicle electrification is pivotal for strategic power planning. Such forecasting is not a trivial task, and it can imply several conditions, e.g., calculating the growth trajectory of electric vehicles and the direct impact of the charging in the power grid. Hence, topics of machine learning and predictive modeling are positioned as strategic to estimate the charging patterns and overall power demand. In addition, the forecasting must ensure the optimization of the power grid infrastructure without compromising it in terms of stability.

The modeling, analysis, and implementation of more innovative and multifunctional charging systems is an important vector for the huge adoption of vehicle electrification from the perspective of the power grid and the user and constitutes a multidimensional approach targeting a sustainable and massive integration of vehicle electrification in modern power grids. Thus, based on sophisticated approaches it is possible to consider various related scenarios, such as the power grid capacity in diverse schedules, the charging station locations and nominal power, the required power for charging, and the dynamic user behavior. Moreover, supported by an in-depth analysis and correlation of these points, it is possible to optimize strategies of interaction between vehicle electrification and the power grid, as well as the involvement of diverse charging possibilities (e.g., including charging interactions between vehicles), from home to public stations, targeting widespread accessibility. This holistic approach aims for a seamless and continuous evolution and integration of vehicle electrification while ensuring a more resilient and inclusive power grid.

In addition to charging systems, the modeling, analysis, and implementation of traction systems are pivotal topics in the realm of vehicle electrification in modern power grids. The main aim is to design efficient, robust, and reliable electric traction systems, factoring in variables such as the on-board power distribution and management based on the dynamic driving of the user. Throughout the analysis of such parameters, it is expected the optimization of key traction components is expected to guarantee the peak performance and the maximum possible range of the vehicle. The synergy of modeling, analysis, and implementation propels the evolution of robust traction systems, contributing significantly to the advancement and widespread adoption of vehicle electrification.

As previously mentioned, it is unquestionable that technologies of power electronics play a pivotal role in the seamless integration of vehicle electrification into modern power grids, and it will be more pertinent as vehicle electrification gains the leading of mobility. Technologies of power electronics encompass two vital features, all the power converters for different purposes and the electronic control systems for managing the power flow between the power grid and electric vehicles, as well as internally in the vehicle. In terms of charging systems, which is the most important in the power grid perspective, advanced technologies of power electronics are also fundamental for ensuring that the charging becomes efficient, while the power grid stability is maintained independently of the charging power and the unidirectional or bidirectional power operation. In addition, through off-board systems, technologies of power electronics can also facilitate the incorporation of renewable energy sources contextualized with vehicle electrification, contributing in this way to sustainability. Thus, the continual evolution of technologies of power electronics is influential and indispensable in shaping a resilient and adaptive infrastructure for the electrified transportation landscape in modern power grids.

The concerns of control challenges regarding vehicle electrification within modern power grids are multifaceted, including, e.g., the management of diverse charging patterns in terms of power and schedules, the adoption of fluctuating power demand scenarios, real-time monitoring for decision-making control systems, as well as balancing power to prevent overloads during peak charging periods. Considering these points, it is obvious that they are also associated with the development of technologies targeting to make power grids smarter. In such context, it is also pertinent to underline other topics of relevant pertinence, like cybersecurity concerns and interconnected systems, which, effectively, are essential for ensuring a robust and resilient power grid with the capability of accommodating the growing demands of vehicle electrification.

Vehicle electrification is, for that reason alone, of utmost importance, but from the power grid point of view, such a scenario can be enriched, where the smart control synergy with renewables is a fundamental vector in modern power grids. The integration of electric vehicles, it is offers an excellent opportunity for power management from the power grid point of view, since if well-coordinated in terms of required power and charging periods, it can act as a controlled load, also contributing to a dynamic load balancing and optimizing the power grid utilization. In addition, since the vehicle can operate in bidirectional mode, it becomes a mobile energy storage solution, offering the possibility of supporting power grid stability through vehicle-to-grid technology. Harnessing the collective potential of vehicle electrification and renewables paves the way for a more sustainable energy future and resilient power grid.

The association of the previously mentioned technologies with vehicle electrification is a viable path, but other scenarios are also possible, where the mutual integration of vehicle electrification and energy storage systems is also possible and contributes to the development of sustainable solutions in modern power grids. In such a scenario, the charging power required by the vehicle electrification can be provided by the power grid or by the energy storage system, with a controlled power to balance both sources, but considering the double purpose of vehicle electrification with bidirectional systems, the reverse scenario is also possible for all the interfaces. Moreover, supported by bidirectional systems, vehicle electrification can be seen as dynamic mobile energy storage units, aiding power grid stability functions. Such possibility does not include the perspective of a complete battery discharge, but the possibility of each vehicle contributing only a very small percentage of the stored energy, and only when it is necessary by the power management system. In addition, both can be managed by targeting to optimize the power production from renewables, also contributing to enriching the benefits of introducing small-scale renewables (e.g., in smart home scenarios). From the power grid perspective, such kind of coupling technologies improve the power grid resilience by balancing power supply and demand, independently of fluctuations in production. As the adoption of vehicle electrification rises, the shared storage capacity strengthens, fostering a more sustainable, dynamic, and efficient power grid.

The control, optimization, and management of vehicle electrification are central aspects in shaping modern power grids: it is an unquestionable point. Advanced control systems with an emphasis on smart grids and controlled in cooperation between the power grid and the vehicle electrification technologies, ensure efficient charging, accomplish the user expectations in terms of availability, charging power and time, power stability, and balance in the power grid side, and, therefore, contribute to the seamless integration of more and more electric vehicles. Successful management of all interventions involves demand forecasting, real-time monitoring, and adaptive profiles to efficiently handle power grid congestions. By harmonizing such possibilities, the interaction concerning vehicle electrification and power grid management becomes a key player in creating a smart managed power infrastructure.

When the interaction of vehicle electrification with the power grid, in addition to the previously mentioned, it cannot be omitted that vehicle electrification demands an effort on power quality optimization in modern power grids, and it is more relevant as vehicle electrification proliferates. The impact on power quality is caused by the charging systems and it is influenced by its dynamic operation, therefore, sophisticated technologies in power electronics are required, both hardware and software. Ensuring the minimization of power quality disorders throughout any condition of power operation is fundamental for minimizing power grid disturbances, unbalances, harmonics, and voltage fluctuations during the power exchange with the power grid, i.e., independently of the bidirectional operation. This can be critical since the power quality problems caused by one charging system can indirectly (i.e., by disturbing the power grid) affect other charging systems in the same electrical installation. Applying a smart charging infrastructure, coupled with proper control protocols, guarantees symbiotic cooperation between the vehicle electrification and the power grids, contributing to confirming that the power quality will remain robust, independent of the operation mode and power level. In addition, it is also possible to consider advanced control technologies to make vehicle electrification an interesting and controllable solution to compensate for power quality issues produced by other equipment in the same electrical installation. Such possibility can be performed only by controlling the AC of the charging system, e.g., for producing reactive power respecting the nominal current of the charging system. Therefore, considering such additional control possibilities for vehicle electrification, it represents a contribution to modern power grids absent from power quality issues.

IV. Conclusions

This book chapter offered a summarized introduction about elemental topics that are indispensable to support vehicle electrification in modern power grids, concerning the support offered by power electronics technologies. In addition, it is indicated that the sales of battery electric vehicles and hybrid electric vehicles are continuously increasing, revealing that the transition from the conventional transportation sector to vehicle electrification is on a path without return. This introductory contextualization seeks to familiarize each topic that is covered in much more detail inside the individual book chapters since the main idea behind this introductory chapter is just to present to the reader a global vision and a mutual contextualization between the different chapters, regarding the innovative perspectives on power electronics technologies and control challenges for the vehicle electrification in modern power grids. With such an approach is easier to understand the main objective of the whole book. It was demonstrated that vehicle electrification is confronting inevitable challenges, but at the same time, it can be extremely important to the power grid, since it can actively contribute to support the power grid since, from the moment that it is plugged in, it can offer much more than the simple power control in unidirectional mode (e.g., supporting the grid for ancillary services, for flexible energy storage framed with renewables, and for demand response strategies).

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