Wireless charging systems for electric vehicles – a critical review of the dynamic charging feasibility

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ABSTRACT

In recent years, the transport system has been transforming through the introduction of new sustainable technologies, leading auto vehicles to be increasingly automated and independent. The promising technological innovation in the transportation field treated in this paper is the dynamic wireless power transfer (WPT) of electric vehicles (EVs). The purpose of the paper is to evaluate if the WPT-based solution is advantageous in economic, logistical, and environmental terms, comparing to competing solutions based on conductive vehicle charging. Concretely, the paper provides a comprehensive review of the disruptive innovations that stand influencing the way of producing auto vehicles in developed economies. It discusses the parameters that can lead to the construction of the WPT system and presents an examination of the main advantages and main limitations of the application of the model.

INTRODUCTION

The increased interest in environmental sustainability has allowed a rapid evolution of electric vehicle propulsion systems. Charging the battery pack of an electric car typically takes place via a wired connection between the power source, i.e., the charging column or the standard domestic socket, and the load of the car's battery itself. In recent years, however, there has been the development of a new type of electric charging, more complex but at the same time more advantageous in many respects, called wireless power transfer (WPT). The two most popular methods of WPT are inductive power transfer (IPT) and capacitive power transfer (CPT). In particular, this paper focuses on IPT technology, which, in the case of charging EVs, is the most common and applies to many power levels and spatial distances. Instead, CPT is applicable only for power transfer applications with inherently short distances due to constraints on the developed voltage (Panchal et al., 2018).
The first real application of the IPT technology was built in 1943 by the electrical engineer George Iljitch Babat, who tested the wireless charging system on the prototype of an electric car. But the realization of a complete IPT system for an electric vehicle in motion happened only in the 1980s, with the creation of the PATH (Partners for Advanced Transit and Highways) project in California, relating to a small electric bus

(Machura and Li, 2019). However, due to financial and technical impediments, the studies remained unfinished for several years until the improvement of finer microelectronics which allowed the use of reliable technologies for controlling the transfer of energy effectively while moving. Afterwards, several companies, universities, and research centres have begun to develop systems and prototypes to improve electric mobility through WPT technology.

The idea of using WPT technology for charging EVs is becoming increasingly popular, together with many other sustainable ideas and projects to reduce pollution and CO2 emissions. But unfortunately, there have been just as many obstacles and resistances. For instance, there has been a constant evolution of economic and political systems, which have neglected serious consequences of climate change. Our ecosystem is struggling every day against global warming, pollution, and the exploitation of primary resources. These problems affect our planet and require immediate solutions. Therefore, experts and auto vehicles industries felt the need both for concrete and timely intervention to implement policies in favour of sustainable transports' development at an economic and ecological level.

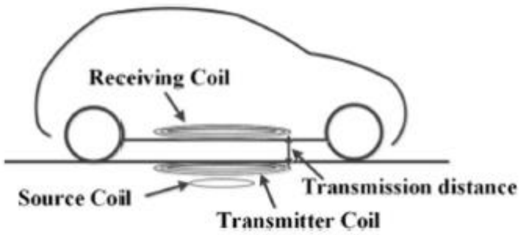
However, dynamic wireless charging still requires more evolution before it could be effectively implemented, as it requests more complex infrastructures. When developing EV inductive charging systems, it is essential to accurately predict and measure efficiency, determining the power entering the ground system and that sent to the vehicle. That is a necessary requirement for automotive industries to develop solutions for reliable energy performance of charging systems. This paper stands precisely on this thesis, which has its primary goal to make innovations in e-mobility and possible feasibility during the charging session known, estimating its current potential and future horizons.

METHODOLOGY

To conduct this research, the main keywords used were: "wireless charging system", "wireless power transfer for electric vehicles", and "inductive power transfer". Subsequently, several articles from online journals, technical reports, and projects about the existing WPT systems in motorway networks have been examined. The analysis is carried out not only at the European level but is also extended to other developed countries. Nonetheless, this study has repeatedly been confronted with the difficulty of finding specific information relating to the new plans of recharge placed on the market. The assessment examines some technical aspects and also the economic-environmental ones. The latter represents one of the cornerstones of this work: to conduct a benefit analysis of this technology. In this respect, the investigation is carried out regarding externalities concerning environmental impacts. The average efficiencies of the WPT system are shown focusing on the state-of-the-art and the progress made by the bodies and organizations that deal with its implementation, as well as on the most important projects in the matter. Finally, the main pros and cons of the aforementioned technology are summarized.

RESULTS AND DISCUSSION

In order to understand how WPT charging works, it is first necessary to explain how such a system is based: namely, on magnetic coupling between the transmitter coil fixed at ground level and the receiver coil under the vehicle. The transmitting coil is powered by an electronic power converter, which supplies a time-varying current in the frequency range from 20 to 100 kHz (Torchio et al., 2020). In general, to determine the efficiency of the WPT technology, Sun et al. (2018) revealed that four main criteria have to be taken into consideration: transmitted power, the geometry of the coils, coupling parameters, and frequency.
One of the most investigated compensation of the WPT system is shown in the picture below and involves the following steps: The coil placed in the charging base transmits a signal. This signal searches for a receiving coil, such as that of a compatible smartphone. Once the coupling is found, the electromagnetic induction starts. The electrons (electricity) inside the transmitting coil start moving inside the coil. That generates a magnetic field, which is detected by the electrons in the receiving coil. The electrons trapped inside the receiving coil start moving due to the magnetic field. This flow of electrons in the receiving coil is practically the electricity that powers the battery in the EV. (Machura and Li, 2019)



Studies in this field - from Asia to Northern America to the Polytechnic of Turin - are numerous. From a comprehensive study conducted by Panchal et al. (2018), three specifical types of WPT systems have been identified: static (SWC), dynamic (DWC) and quasi-dynamic (QWC). Static WPT charging represents a valid alternative to standard electric charging; even in this case, however, the vehicle needs to be parked during the entire charging phase. From a similar investigation conducted by Machura and Li (2019), it emerged that the DWC recharging for electric cars has numerous advantages compared to the classic recharging method. This last, showing various problems related to public and private columns, times and wiring it struggles to spread adequately on the market. The dynamic WPT recharge, opposed to the static one, allows the transport to recharge on the go, eliminating the need to stop even for several hours in the recharging areas.
Moreover, the DWC leads to a reduction in the capacity of the battery pack, thus, in its volume and weight. Lower electricity consumption, due to the reduced weight, reduces charging times and maintenance costs. Other advantages could be greater autonomy with the same battery capacity, less vulnerability to adverse climatic conditions, and less

damage and risks associated with vandalism. Furthermore, thanks to a notable development of the WPT technology, it has been possible to increase the power transfer distances, going from a few millimetres to several centimetres. (Machura and Li, 2019)
Another positive result revealed from a study conducted by Nishimura et al. (2012) is related to human health and safety: it resulted that with WPT technology, there is no risk of electrocution or hazard, as there are no exposed live elements. The cons related to health and safety problems of magnetic fields that transfer energy are very low. A parallel study conducted by Shimamoto et al. (2015) ensures that in-situ electric fields do not directly damage the human body. There is no immediate threat to the health of the persons operating or using a WPT system based on electromagnetic emission; however, scientific studies on the long-term effects of the WPT system on human organs have been still limited.
The first companies that made possible the development and growth of WPT technology of electric vehicles are Bombardier and Conductix-Wampfler. Conductix-Wampfler first developed and marketed the WPT system for inductive non-contact power transfer on a large scale. Instead, Bombardier has developed various WPT solutions for different types of means of electric transports. Indeed, the Bombardier PRIMOVE project concerns not only buses and tramways but also light commercial vehicles, trucks, and private cars. (Jang, 2018)
Among the institutions and universities most involved in this sector, we find the KAIST (Korea Advanced Institute of Science and Technology), which developed a wireless charging technologies project for buses called OLEV in 2009. Tests performed by OLEV confirmed the innovative advantages, particularly in terms of infrastructure, electricity, manufacturing costs, and safety (Suh et al. 2011). Also, the Oak Ridge National Laboratory (ORNL) in the United States carried out a technological feasibility study regarding static and dynamic wireless charging, specifically in a highway. Equally, it highlighted the pros of efficiency and resistance of the design (Miller et al., 2015).
The first study project funded by the European Union, called FABRIC (Feasibility analysis and development of on-road charging solutions for future electric vehicles), was developed between January 2014 and December 2017 by 25 different partner organizations from 9 European countries. It was conducted with test sites in Sweden, France and Italy. FABRIC focused on the technological and economic feasibility, as well as on the socio-environmental sustainability of the technology in question. Besides demonstrating the economic benefits of the technology, it also served as a guideline for several international scientific and technical communities. It provided policymakers and regulators with state-of-the-art information about wireless charging EVs, as developed among experts in the academic community. (Bi et al. 2016)
Furthermore, from September 2012 to May 2015, the eCo-FEV (efficient Cooperative infrastructure for Fully Electric Vehicles) research project of the European Green Vehicles Initiative, was implemented. It had as its primary purpose the creation of a platform for cooperative electric mobility. This platform would have made it possible to foster the spread of electric vehicles thanks to real-time communication between the different infrastructures, such as roads, parking and rest stops, public and private transports, and charging systems (Jang, 2018). In this respect, a study conducted by Deflorio (2018) affirmed that the sharing and connection between infrastructures would have made it

easier and more complete to drive an electric vehicle, assisting the user through optimal management services of the charging system, effectively increasing the range of the cars themselves. However, it is still an ongoing project.

Another European project worthy to mention is UNPLUGGED, carried out by 17 partners, including the main companies in the energy (Enel, Endesa), automotive (Volvo, Continental) and transport sector (Transport for London), as well as several companies and research centres. It was initiated to create a fast and flexible infrastructure capable of recharging the batteries of electric vehicles using a high-power IPT system. Specifically, it designed and built a fast wireless charging system of up to 50 kW, which allowed completing 80% of the charge in less than 30 minutes. UNPLUGGED also investigated the socio-economic pros, technological feasibility, detail regarding the actual impact, interoperability and safety of different solutions for customer acceptance. (Unplugged Final Report, 2015)

Despite these series of projects which proved the practical and economic advantages provided by the DWC system, there are limits and perplexities regarding the development and commercialization of this technology. The main problem of the DWC concerns its distribution due to high investment for its installation. Indeed, Sun et al. (2018) observed that implementation problems are mainly due to the very high infrastructure investment costs. In this context, it could be said that the economic savings resulting from the reduction in the size of the batteries of dynamically charged electric vehicles are offset by the increase in costs that would be shifted to the electrical network buried in the pavement.

According to Machura and Li (2019), additional disadvantages concern the achievement of satisfying power transfer efficiencies, the achievement of wider tolerances related to the misalignment between transmitter and receiver, the resolution of problems associated with more high-frequency electromagnetic fields, potentially harmful to the safety and health of people, greater technological complexities, difficulties associated with the construction and installation of infrastructures, and last but not least the lack of sector-specific laws and regulations. Furthermore, it may be impractical to instal charging-in-motion facilities everywhere.

Despite the abovementioned limitations, from an energy-environmental point of view, the effective reduction of the concentration of pollutants is certain, following a partial replacement of vehicles with internal combustion engines in favour of electric cars equipped with a WPT charging system. In conclusion, downstream of this assessment, the costs related to the construction, installation and use of the charging infrastructure can be considered justifiable.

CONCLUSION

The most important concept highlighted within this paper is the indispensability of the electric mobility sector and renewable sources. For the full affirmation of electric vehicles to be justifiable from the point of view of environmental benefits, it is necessary that, in parallel, there is an important increase in the field of renewable energy, thus reducing dependence on fossil fuels and the consequent polluting emissions. Within this context, in the future, a decisive factor could be the rapid evolution and commercialization of the WPT dynamic charging system, capable of contributing to the large-scale adoption of electric cars both in the transport and private sector. Although this is a relatively recent technology and therefore not yet fully mature, its potential is huge, especially in terms of reducing the weight of batteries and increasing the limited range of electric vehicles. Despite the positive outcomes in several developed countries, it can be deduced that the internal energy policy of an economy determines the feasibility of WPT projects. For example, for what it concerns Italy, since 2002, only two separate projects have been launched in the cities of Genoa and Turin, inherent static wireless charging of electric buses. Indeed, in Italy, the lack of a general and unified vision in policies and strategies has led to a slowdown in technological initiatives linked to sustainable mobility (Jang, 2018). For instance, economic, political, and social factors in Italy hinder the spread of the technological paradigm of electric mobility. Even though it is a country with enormous potential, Italy has serious delays in terms of sustainable mobility. Only in recent years, the topic has been gaining ground, and citizens are becoming aware of the importance that hybrid and electric cars have for improving the quality of the environment and life. Paradoxically, Italian society has reached the knowledge and awareness of what is necessary for a sustainable future but at the same time struggles to put into practice those actions that allow this to be achieved. Homogeneous measures should be implemented throughout the national territory, perhaps simplifying the bureaucracy and providing concessions for the purchase of EVs. Also, an adequate infrastructure present in the area would theoretically allow electric vehicles able to take advantage of this technology.

It follows that the environmental and economic feasibility of a potential application of the WPT charging system for EVs within the highway infrastructure of a country is extremely connected to how and to what extent the sharing of electricity production gets implemented. This led to reflect on the importance that must be given to the dissemination and sharing of knowledge so that WPT can become widespread; because, if on the one hand innovations must start from researchers, on the other, it is also true that to be effective it must be supported by policies. But when will wireless charging become marketable and accessible to everyone? It cannot be said with certainty, but a more structured development is near.

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