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An overview of bidirectional electric vehicles charging system as a Vehicle to Anything (V2X) under Cyber–Physical Power System (CPPS)

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Abstract

Nowadays, EVs are rapidly increasing in popularity, and are accepted as the vehicles of the future all over the world. The most important components are their battery and charging systems. The energy capacity of EVs' batteries has a significant potential to supply different energy requirements. Therefore, EVs must be designed in accordance with bidirectional power flow, and Electric Vehicle Supply Equipment (EVSE) should be upgraded as Electric Vehicle Power Exchange Equipment (EVPE). This power exchange infrastructure can be called Vehicle-to-Anything (V2X). V2X will also be the key solution for energy grids of the future that will turn into a much larger and smarter system with the help of emerging digitalization technologies, such as Artificial Intelligence (AI), Distributed Ledger Technology (DLT), and the Internet of Things (IoT). This study introduces a multi-layer Cyber–Physical Power Systems (CPPS) framework to explore the potential of V2X technologies allowing bidirectional charging. In addition, the impact of e-mobility is discussed from the V2X perspective. V2X has the potential to provide more practical use of electric vehicles and to bring advantages to the user in terms of both economy and comfort, thus accelerating the transformation of e-mobility and making it easier to accept.

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Keywords: Electric vehicles; V2X; Bidirectional charging systems; e-mobility; Cyber–physical systems

1. Introduction

Due to the effects of global warming on our lives, it is necessary to take important actions to reduce emissions. This situation has made the transformation of the transportation sector more inevitable. Thus, electrification of transportation has emerged and introduced the concept of e-mobility [1]. E-mobility, a component of the concept of

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digitalization, takes place in creating a holistic system together with a Cyber–Physical System (CPS) environment. The most important unit of e-mobility is electric vehicles (EVs). They are the next-generation mobility solution for human beings. However, the first examples of EVs date back to the internal combustion engines in the 19th century. Unfortunately, the lack of sufficient facilities in battery technology created a severe problem in terms of usage range, and it succumbed to internal combustion engines [2]. Nowadays, developing storage and semiconductor technologies have provided practical solutions to range limits, which are the most important disadvantages of EVs [3]. Although EVs appear as a new solution for transportation, it is expected that they will affect many areas of our lives besides transportation. EV is one of the CPS layers that can be used much more functionally rather than just an electrical tool, a load for the grid, or a vehicle for transportation. In addition, the need for energy in our digitalized world is constantly increasing and becoming much more important. For this reason, more diverse usage areas and solutions can be created by using EVs' existing energy capacities and technological systems. This concept can be called vehicle-to-anything (V2X), the broader term used to describe the energy storage within an EV and its ability to supply power for particular end users. V2X is a next-level power exchange system that can provide more flexible energy mobility and benefits. The system should be designed with cyber–physical infrastructure. Using the cyber–physical system's relationship makes it possible to use the energy potential of electric vehicles with smart algorithms in different fields for different needs and economic gains. For this to happen, electric vehicle and EVSE manufacturers need to consider this concept and prepare the appropriate hardware infrastructure. In particular, different studies are carried out for bidirectional power flow [4–6]. These studies mainly prioritize power flow from the vehicle to the grid. One of these studies analyzed the use of electric vehicles to calculate the grid frequency balance [7]. In another study, the power flow from electric vehicles to the grid was optimized and used to minimize load variance [8].

Although V2X is more prominent as a power exchange the Vehicle-to-Grid (V2G), it can also be used in different usages, such as Vehicle to Vehicle (V2V), Vehicle to Load (V2L), Vehicle to Home (V2H), Vehicle-to-Building (V2B), Vehicle to Emergency (V2E), etc. V2X can be used to reduce peak demand in the grid, feed critical loads, and balance the grid stability, as well as for emergency assistance to living things, a mobile power source in an off-grid location, or a charger for another electric vehicle that needs charging. V2B and V2H can be implemented with a building/home energy management system that can control battery SOC conditions of EVs and manage the energy needs for better performance and benefits [9]. Another V2H application has been implemented and analyzed by Denso and Toyota collaboration [10]. The Energy Management System (EMS) has been proposed for V2L operation with a Li-Ion battery degradation model and realistic weather conditions during standard driving cycles. The proposed EMS estimates and increases the battery life by controlling V2L operation [11]. In the other study, V2V is presented with an off-board DC V2V charger with a bidirectional DC–DC converter. The proposed V2V charger reduces the power conversion stages and benefits from mitigating the range anxiety issue [12].

It is also stated that the technology of V2X will have significant economic benefits. According to the Electric Power Research Institution (EPRI), it has been revealed that around 1 billion dollars of economic benefit can be obtained with the application of V2G with 5 million EVs in the state of California, USA [13]. Considering this situation, it can be assumed that it will provide a great economic benefit throughout the country and the world, and this benefit will dramatically increase when V2X is included. It is obvious that V2X will be an important denominator of the future energy system.

On the other hand, CPS is the combination of the physical components, digital and communications, and cyber systems [14]. The typical application of CPS in power systems is called Cyber–Physical Power Systems (CPPS) under the smart grid. The CPS integration is the state-of-art area to implement the internet of things (IoT), energy management, and bidirectional power-flowing in the power systems. Thus, V2X can be categorized under the CPPS to analyze and enforce bi-directional energy-flowing opportunities. The interaction between the EV and anything under CPPS can be used to manage these mobile energy sources to supply any energy needs. One of the studies has proposed a secure and efficient V2X energy trading framework by exploring blockchain, contract theory, and edge computing in CPS [15]. That is the critical part of the V2X operation with secure and safe trading. In this study, the V2X concept has been analyzed depending on the cyber–physical power system perspective. Versions of the V2X have been studied in the literature with some specific applications. An overview of these studies has been given for researchers and readers to get the advantages and challenges of V2X applications. In addition, it is emerging that cyber–physical infrastructures are needed, defined as EVPE and on-board power exchange (OBPE), for the spread of V2X applications.

The remainder of the study is organized as follows: In the second part, the Cyber–Physical System is introduced with a V2X perspective. In the third part, the power and transportation structure under the Physical Space is widely described. In the fourth part, Cyber Space is described with data and communication layers. In the fifth part, the applications of V2X are provided in detail, and the feasibility of V2X is discussed. The last part includes the concluding remarks.

2. Cyber–Physical systems

Modern power systems are rapidly evolving in parallel to the recent advancements and trends in Industry 4.0. Deep digitalization technologies such as Artificial Intelligence (AI), Distributed Ledger Technology (DLT), and emerging information communication technologies (e.g., 5G) are shaping the boundaries of next-generation smart grids. In addition, EVs are increasing their market shares, which requires fundamental challenges for the power systems operations with increased power demand. CPPS has also emerged with the digitalization of energy systems and a new hardware and software relationship. Hence, modern and highly digitalized power systems are the largest cyber–physical systems. The need to consider systemic considerations more fully can be addressed in part through the multilevel perspective.

EVs as emerging components of the next-generation power systems can be handled within the scope of CPPS. Fig. 1 demonstrates the CPPS structures of the V2X that consists of three sub-spaces: (i) Physical Space, (ii) Cyber Space, and (iii) Other Spaces. CPPS framework is proposed to systematically demystify the fundamental inter-operations, which enables EV Charging and other V2X functions such as Authorization, Authentication, Payment Settlement, Billing, EV Charging/Discharging, Handling of EVPE/OBPE Information, Routing, managing the price and tariff signals and other related features.

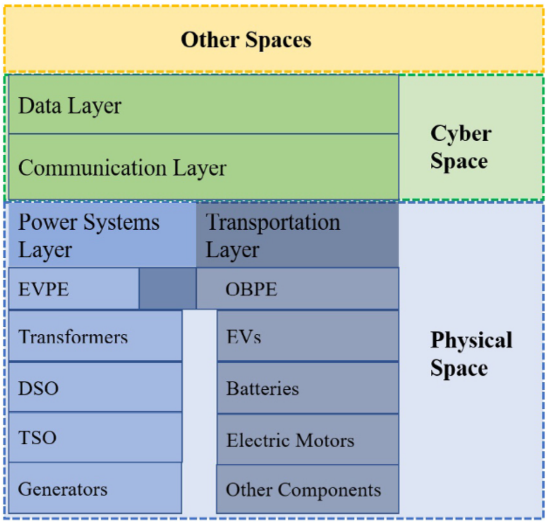

Fig. 1. Cyber–Physical Power Systems structure of V2X.

Physical Space accommodates the physical components of the CPPS, such as power systems and transportation layers. Power systems layers consist of the entire value chain of the electrical power systems landscape, including bulk power generators, renewable energy resources, energy storage systems, transmission lines, distribution systems, prosumers, and consumers. EVPE refers to dedicated grid-edge equipment that allows bidirectional power exchange for EVs. In addition, OBPE is an interface between power systems and transportation layers designed to charge and discharge EVs. The transportation layer hosts EVs, EV batteries, electric motors, and other components. In a broader perspective, transportation infrastructure, such as roads and highways, can also be considered under this layer.

Cyber Space has two primary layers: (i) Communication Layer and (ii) Data Layer. Sensors and measurement devices like electric meters are responsible for digitizing the analog values, such as AC power, to digital information where the boundaries of Cyber Space start. The communication layer transmits digitalized information via various wired and wireless communications technologies. The data layer employs emerging digitalization technologies, including AI, DLT, and IoT. This layer also accommodates systematic data collection, processing, and visualization of datasets that are obtained from the CPPS ecosystem. Other Spaces provides broader perspectives, including power markets, business interactions, and energy policy aspects. The following sections provide more information about relevant details about corresponding extensions.

3. Physical space: Power and transportation structure

Electric vehicles need the energy to charge their batteries, and most of the energy is supplied from outside in plug-in electric vehicles. The primary source of electrical energy is the electricity grid. Therefore, EVSE is connected to the grid mostly. A power system connection is required according to the standards determined by the grid. EVSE is classified according to specific standards about charge levels. The most common charging levels in the standards are given in Table 1 [16,17].

Table 1. EV charging power levels.

Levels	Maximum power [kW]	Maximum current [A]
IEC Standard		
AC charge		
Level 1	3.3–7.5	16
Level 2	8–15	32
Level 3	60–120	250
DC charge	100–200	400
SAE Standard		
AC charge		
Level 1	2	16
Level 2	30	80
Level 3	20 and up	80 and up
DC charge		
Level 1	40	80
Level 2	90	200
Level 3	240 and up	400
CHAdeMO		
e-PTW	1–10	80
ChadeMO	100–400	400
ChaoJi	1000	400 and up
GB/T Standard		
AC charge		
Level 1	2–4	8
Level 2	4-7.5	16
Level 3	8–120	32–63
DC charge	250	250

Also, the idea of bidirectional energy transfer with electric vehicles brings the need for a new design and standard for EVSE and On-board Charging (OBS). For bidirectional power flow, EVSE should be updated as EVPE. However, for the broader use of V2X, the OBS system should also be updated as an OBPE, which is designed in accordance with bidirectional power transmission. Therefore, EV manufacturers also need to take steps besides the charge station manufacturers for the V2X. Existing technology has the capability to design OBS in line with bidirectional energy flow. The overall physical layers of the V2X are given in Fig. 2.

In addition, standards related to V2G have been defined to emerge because of its applicability and potential. Applicable standards for V2G are listed in Table 2.

These studies about standardization will also form a basis for V2X and contribute to its dissemination. With the widespread use of electric vehicles in commercial and domestic use, battery energy capacities are increasing rapidly. According to the future projections, it is predicted that the number of EVs will increase significantly in the

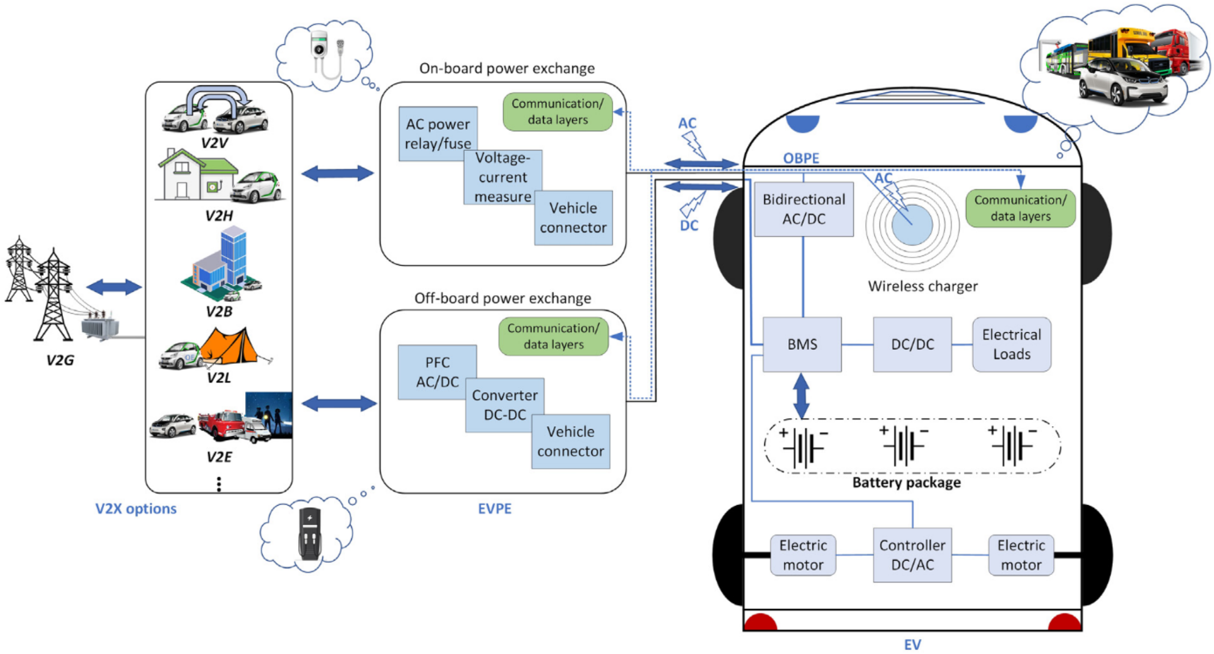

Fig. 2. V2X physical power layer with EV charging.

Table 2. Applicable standards and protocols for V2G.

Standard/Protocol code	Title	Scope
UL 1741 UL 9741	Inverters, Converters, Controllers, and Interconnection System Equipment for use with Distributed Energy Resources (DER) Outline of Investigation for Electric Vehicle Power Export Equipment (EVPE)	Safety and Functionality for EVSE
SAE J3072 SAE J2836/3	Interconnection Requirements for On-board, Grid Support Inverter Systems Use Cases for Plug-In vehicle Communication as a DER	EV Functions
IEEE 1547-2018 IEEE 1547-2020	IEEE Standard for Interconnection and Interoperability of DER with Associated Electric Power Systems (EPS) Interfaces IEEE Standard Conformance Test Procedures for Equipment Interconnecting DER with EPS and Associated Interfaces	Interconnection
SAE J2847/3 IEEE 2030.5 OpenADR OCPP ISO/DIS 15188	Communication for Plug-In Vehicles as a DER IEEE Standard for Smart Energy Profile Application Protocol Open Automated Demand Response Open Charge Point Protocol 2.0.1 Road vehicles: vehicle to grid communication interface	Communication

near future [18]. The V2X concept has considerable potential to solve the problems caused by the high demand for electric vehicles in the grid. However, the adverse effects of the non-driving use of battery energies of EVs on battery life are also highlighted [19]. Although there are different implications in studies on this subject, some studies stated that the negative impact on battery life will be much less than expected with appropriate battery energy management [20,21]. Thanks to new technology developments, more durable and cheaper batteries will be commercialized. Therefore, the reservations in V2X applications will disappear. Also, advances in power electronics can help more efficient AC/DC and DC/DC conversion designs, and power quality problems caused by EV charging stations in the grid can be minimized. V2X requires a much more functional connection between the electricity grid and the transportation system. There is the necessary technology infrastructure for this. Thanks to the digitalization of the energy systems and the cyber–physical relations with multi-spaces, V2X will be more widespread and an indispensable part of EVs.

4. Cyber space

The Cyber Space in the CPPS structure of Vehicle to Anything Communication (V2X-com) consists of two main layers: communication and data. The communication layer provides all the interconnection and interoperability between the electric vehicle and the operations management system. The data layer is responsible for data collection from EVs and related devices/sensors for data storage, visualization, and future analytics. The communication layer, i.e., vehicular communication technologies and infrastructure, is crucial to meet requirements for V2X applications in terms of safety, energy efficiency, and comfort. It is expected that the characteristics of the communication layer should be flexible and scalable vehicular networking supporting the high-bandwidth and high-reliability transmitting links. The communication layer allows communication between electric vehicles and infrastructure and sharing data such as each vehicle's battery status. The communication layer can significantly contribute to achieving the expected requirements, especially for safety.

With advanced communication and power electronic technologies, V2X applications have become more available, and EVs have started to act as generators or storage units. However, it needs more improvement to make V2X applications fully functional in terms of communication technologies. Wireless communication technologies are typically preferable for these purposes. The Cellular V2X (C-V2X) among them is the most popular one, as an alternative to 802.11p selected as the technology for V2X communications. Cellular V2X provides real-time, highly reliable, and actionable information flows to enable safety, mobility, and environmental applications [22].

The data layer supports the communication layer, where the data-driven functions are based on big data analytics, AI, DLT, and data visualization techniques. Once the data is collected from the CPPS ecosystem, it is handled using various data preprocessing methods, such as data cleansing, feature engineering, and plausibility check. The data should be used to extract meaningful features and outcomes, which can be used as an added value in the CPPS ecosystem using tailored AI, optimization, and control algorithms. For instance, collected EV charging data can be used to develop advanced AI-based EV Charging and Forecasting system. The use of blockchain technology to enable more effective operation of EV charging use cases can also increase the cyber resilience of the system at the same time [21]. Human–machine interfaces (HMIs) are useful visualization tools, which help the end-users and system operators with EV and V2X-related tasks. Such HMIs can be integrated into smartphones, which can accommodate the location of EVPEs, availability, pricing information, and many other features. Advanced optimization algorithms can be used to maximize the economic viability of the EVPE and V2X commercial operations

5. Vehicle-to-anything applications

The V2X concept can cover all bi-directional power flows and relations, cyber–physical environments, and more. The massive number of cars driving around on earth is used only 5% a day, which means an average trip distance of up to 30 km [23,24]. Therefore, more than 90% of cars are parked at any given time, which is a lot of energy just sitting inside but doing nothing. This energy can be used for balancing frequency, controlling peak demand in the grid, or supplying home, building, or other loads so that there is enough electricity on the grid when we all need it.

V2X is an important CPPS application for personal, commercial, and public electric vehicles. For example, electric school buses that are actively used only at certain times of the day can hybrid work with a local solar energy system in the school building as energy storage during long-term parking processes and provide a smoother power output. It can also supply schools' energy demand with minimum need for the grid. Public buses, construction, and agriculture machines can form an important ESS resource in fleet charging lots, and the peak demand in the evening can also supply the grid.

Thanks to V2X, direct energy transfer between electric vehicles can be achieved with OBPE. In this way, the EV owners can transfer the energy from their EVs to an EV stuck on the road with V2V to help them go to the nearest charging station. EV users can contribute to the building's energy needs in coordination with the building's solar energy system while their vehicles are parked in office buildings. Thus, with V2B, both charging and economic gain can be achieved. In another case, when the grid is unavailable, our electric vehicle can provide significant comfort in using our electrical appliances by providing energy with V2L. In addition, in the event of an emergency such as an accident or disaster, energy can be supplied with V2E instead of a generator for emergency energy needs. All these V2X application examples are given in Table 3 in a summary form.

Table 3. Overview of V2X applications.

Direction type	Charging type	Benefits	Applications
V2G	Off-board	Peak demand reduction, frequency/voltage balance, DSM, energy source	Refs. [6,7,25]
V2V	On-board/Off-board	Energy trading P2P, power exchange, off-grid	Refs. [12,26]
V2L	On-board	Energy source, off-grid, battery management	Refs. [11]
V2H	On-board	Demand control, energy source, energy trading	Refs. [9,10]
V2B	On-board/Off-board	Demand control, energy source, electricity price	Refs. [27,28]

For the widespread use of V2X, not only an EVSE but also an OBPE is needed under the CPPS environment. V2X applications show that the advantages of V2X outweigh the disadvantages.

6. Conclusions

EVs will affect our lives in different ways, and one of them is described in this study, i.e., V2X. This concept can be used differently to improve energy mobility and benefit EV owners more. As the same example of these effects, smartphones are used not only for phone calls but also for finance, photo, appointment, game, social networks, advertisements, etc. As with this, EVs will give different application perspectives in our lives.

The share of EVs is rapidly increasing in parallel to the digitalization process of power systems and many other businesses. Flexibility in terms of power flow is an integral part of modern power systems where bidirectional power flow is allowed. Next-generation EV charging infrastructure and V2X operations are expected to support such bidirectional power flow, which can be built on a complex cyber–physical systems ecosystem. This work aims to systematically explore the new boundaries of next-generation V2X technologies using the CPPS framework. Also, the CPPS can give a better environment for implementing V2X applications. Thus, EV owners, utilities, and other energy stakeholders stand to gain by going for a bidirectional charger. The bidirectional power flow comes with clear economic benefits, such as making extra income by selling energy back to the grid. It also becomes energy self-sufficient and improves decentralized energy systems. However, one of the initial hurdles for the decision-makers is to determine how to safely and cost-efficiently interconnect V2X technologies, such as mobile inverters and power transfer between vehicles and the grid. Many interconnection rules have not been updated to reflect the unique attributes of energy storage. Barriers and concerns of V2X include the high cost of V2X-enabled equipment, battery degradation and charging management, customer awareness, and value streams for grid services. Potential grid impacts will be investigated and discussed for future studies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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