UNIVERSITY „**POLITEHNICA**” OF BUCHAREST

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Ph.D. THESIS SUMMARY

INTEGRATION OF ELECTRIC VEHICLES IN THE NETWORKS OF FUTURE SMART CITIES

INTEGRAREA VEHICULELOR ELECTRICE ÎN REȚELELE VIITOARELOR ORAȘE INTELIGENTE

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Contents

List of abbreviations

ADR	–	Automated Demand Response
BESS	–	Battery Energy Storage Systems
B2G	–	Building-to-Grid
BEV	–	Battery Electric Vehicle
CHAdeMO	–	Charge-de-Move (standard for direct current charging of EV)
CCS	–	Combined Charging System (standard for direct current charging of EV)
CAMC	–	Central Autonomous Management Controller
CVC	–	Cluster of Vehicle Controller
DMS	–	Distribution Management System
DSO	–	Distribution System Operator
DER	–	Distributed Energy Resources
DSM	–	Demand Side Management
EMS	–	Energy Management System
ETSI	–	European Telecommunications Standards Institute
EVSE	–	Electric Vehicle Supply Energy
EVS/A	–	Electric Vehicle Supplier/ Aggregator
FCV	–	Fuel Cell Vehicle
GES	–	Greenhouse gases
G2V	–	Grid-to-Vehicle
GD	–	Distributed Generation
H2G	–	Home-to-Grid
ICT	–	Information and Communication Technology
IEC	–	International Electrotechnical Commission
I2G	–	Industry-to-Grid
ITS	–	Intelligent Transport Systems
IoT	–	Internet-of-Things
IEA	–	International Energy Agency
ISO	–	International Organization for Standardization
ITU-T	–	International Telecommunication Union
ICCB	–	In Cable Control Box
LPWA	–	Low Power Wide Area
LTE	–	Long Term Evolution
LC	–	Load Controller
LAC	–	Load Area Controller
MES	–	Multi Energy Systems

MMG	–	Multi-MicroGrid
MC	–	Micro-source Controller
MGCC	–	MicroGrid Central Controller
MGAU	–	MicroGrid Aggregation Unit
MSP	–	Mobility Service Provider
NIST	–	National Institute of Standards and Technology
OMS	–	Outage Management System
OPCOM	–	The operator of the Romanian Electricity Market
OPE	–	Balancing Market Operator
OPEE	–	Electricity Market Operator
PHEV	–	Plug-in Hybrid Electric Vehicle
PV	–	Photovoltaic panels
PCCB	–	Centralized Market of Bilateral Contracts
PZU	–	Day ahead market
PI	–	Intraday market
PE	–	Balancing market
PSTS	–	System Technological Services Market
SEE	–	Electric power system
SRE	–	Renewable energy sources
SEN	–	National Energy System
STS	–	System Technological Services
SoC	–	State of Charge
t.a.	–	Alternative voltage
t.c.	–	Direct voltage
ToU	–	Time of Use
TSO	–	Transmission System Operator
VE	–	Electric Vehicle
V2G	–	Vehicle-to-Grid
VPP	–	Virtual Power Plant

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Keywords

Chapter 1: electric vehicle, pollution, decarbonization, greenhouse gas emissions;;
Chapter 2: Smart Grid, Smart City, smart mobility, interoperability, Internet of Things (IoT);
Chapter 3: standardization, charging mode, connector, battery swapping, wireless charging;
Chapter 4: integration, Vehicle-to-Grid, aggregation, control strategies, battery storage systems, renewable energy sources, linear programming;
Chapter 5: distributed generation, power grid, virtual power plant, demand response, model predictive control;
Chapter 6: energy market, balancing market, flexibility services, smart charging, regulation band.

Summary

The planet's population is facing many changes and challenges including the environment, energy, food, water, transportation, infrastructure, health, education, administration and the economy. Although cities occupy only 2% of the planet's surface, they consume 75% of the total energy produced and are responsible for 80% of total CO2 emissions.

The cities of the future need to adapt to mitigate the effects of: climate change; population growth and human mobility (including migration); social tensions and inequality; globalization of the economy; technological developments; insecurity regarding food, water, energy; geo-political changes, etc.

As the planet becomes more "urban", future cities need to become smarter in the way they manage infrastructure and resources to provide what they need today and tomorrow.

Taking into account the aspects presented above, mobility is at the heart of modern civilization. In this regard, significant changes will take place over the next 20 years, as electrification, shared mobility, vehicle connectivity and, finally, autonomous vehicles are reshaping automotive markets and the transport sector around the world.

This transition is underpinned by technological change and other factors that play an important role, such as policy factors directing these two sectors towards low-carbon options and improved fuel efficiency.

Car manufacturers and large fleet operators are taking the decarbonisation targets more and more seriously in the medium and long term. More than 7 million passenger electric vehicles (EVs) currently run on roads around the world, and electrification extends to other segments of road transport, such as the freight transport sector.

The electric car is not a recent innovation, but appeared at the same time as cars with internal combustion engines. Between 1890 and 1900, electric vehicles outperformed all other types of cars. They gained significant popularity in the early twentieth century because they were not as noisy and polluting as vehicles with internal combustion engines. Instead, the disadvantage of electric cars was the low battery life, and the owners could not cover long distances.

At that time, as now, not everyone could afford an electric car, it was bought by people with financial means.

In recent years, technological advances and concerns about climate change have gradually stimulated the rebirth of electric vehicles.

The automotive industry is currently undergoing the most important change in its history: the transition from the internal combustion engine to the electric motor. Car companies invest huge sums of money and make unexpected alliances to adapt to new market conditions.

Electric vehicles have gained more and more popularity in recent years due to their ability to offer multiple benefits which include:

Energy efficiency: electric vehicles are more energy efficient than conventional vehicles with an internal combustion engine (ICE).

Energy security: electric mobility increases energy security, as the road transport sector is heavily dependent on oil-based fuels. In addition, electricity can be produced with a variety of resources and fuels and is often generated domestically.

Air pollution: Due to zero emissions, electric vehicles are suitable in relation to air pollution problems, especially in urban areas and along roads, where a large number of people are exposed to harmful pollutants in road transport vehicles.

Greenhouse gas emissions: Increased electric mobility in combination with a gradual increase in low-carbon electricity production can lead to significant reductions in GHG emissions from road transport compared to conventional vehicles. In addition, electric vehicles can provide flexibility services for power systems (EEA) and can act in accordance with the integration of variable renewable energy sources for electricity generation.

Noise reduction: electric vehicles are quieter than ICE vehicles, especially those in the two/ three wheel category.

Industrial development: electric vehicles are essentially positioned as a potential facilitator of major cost reduction in battery technology, which is one of the key chains for industrial competitiveness, given its relevance for the transition to "clean" energy through the possibility of storing electricity .

These and other benefits of electric vehicles have led to growing global development and a greater understanding of the challenges and opportunities of electric mobility over the last decade.

Statistically, if in 2010, globally there were only 17,000 electric cars and only five countries could count over 1000 DEVE on their roads (China, Japan, Norway, UK and USA), in 2020 there are approximately 7.2 million electric cars, the global stock remaining concentrated in China, Europe and the United States.

In Europe, electric car sales in 2019 increased by 50% compared to 2018, the countries with the highest share of electric cars in total car sales being Norway by 56% and Iceland by 22%. Germany surpassed Norway in 2019 for the highest sales volume of 109,000 electric cars (an increase of 61% compared to 2018) [4].

Electric vehicles have become a daily presence in many cities around the world, in the form of personal cars, taxis, car sharing services, municipal car parks, city buses, two / three-wheeled vehicles (especially electric scooters) and more and more more on commercial and freight vehicle segments.

Governments have introduced a number of ambitious policies to support the electric vehicle industry. These include approaches to reduce adoption barriers and to promote the development of the necessary charging infrastructure.

Achievements in technological progress and market development combine with the objectives of a number of policy makers, industry companies and civil society, anticipating further acceleration of electric vehicle deployment in the coming years, which will significantly transform the road transport sector but at the same time, that of the electric power systems that will have to provide the energy necessary to charge the EV batteries.

In the context of the above, the chosen research theme is in line with current trends in the decarbonisation of the transport sector and the reduction of pollution in cities. It is also in line with the recent goal of the European Union to become neutral in terms of greenhouse gas emissions (Green Deal Directive). Thus, the authorities want a Euro 7 pollution standard to be introduced starting with 2025, and after 2040, only zero-emission cars will be sold in the European Union.

The doctoral thesis consists of seven chapters, an appendix and has 121 bibliographical references.

The aim of the study is (*i*) to analyze the impact and possible effects of the integration of large numbers of electric vehicles in power systems, as the need to charge all these vehicles can generate both negative effects on the operation of electricity networks and positive effects through flexibility services generated. of these, but also (*ii*) to propose a series of strategies and measures for their integration.

Electric vehicles along with energy storage systems will be the main component of smart mobility within the Smart City concept. An important branch of smart mobility is electric mobility that uses electric vehicles with various technologies such as fixed electric batteries, replaceable batteries or wireless charging.

Chapter 1, entitled *Introduction*, gives a brief description of the general context of the topic, a brief history of the evolution of the electric vehicle over time and the main arguments for the transition to electric mobility.

Also in this chapter are presented the motivation and purpose of the study, along with the description of the thesis structure.

Chapter 2, *The general context on the integration of electric vehicles in the new concepts of Smart Grid and Smart City*, presents the main aspects of the two concepts and the links between them through new technologies, such as the Internet of Things (IoT) and 5G technology.

The concept of smart city considers a number of key elements, such as: economy, citizens (people), government, living conditions (quality of life), environment and last but not least mobility (transport).

Electric vehicles, like energy storage systems along with active management of electricity networks and intelligent automation systems, are parts of what are currently considered future smart electricity networks. The integration of these elements will imply the existence together with the infrastructure of the electricity network and of a communication network.

Regarding the integration of EVs in electricity networks, the electricity consumption due to EV charging is still negligible today. With a widespread adoption of EV, the additional electricity consumption can reach values that will affect the operation of the power system, in a positive or negative way. In fact, if EV charging is performed without restrictions, the additional consumption of electricity during peak hours can pose problems for the safe operation of the energy system.

As a consequence, unrestricted charging of EVs may involve additional investments in electricity generation and transmission capacity, increased wear of components in distribution networks and problems with electricity quality. On the other hand, if EV charging is supported by differentiated tariff systems that take into account the actual production of electricity from renewable energy sources, it can bring many benefits for the operation of energy systems, as well as benefits for reducing pollution and for environment.

In this chapter, a number of issues regarding the integration of electric mobility were analyzed, taking into account elements such as sustainability and environmental awareness, political and economic issues, user acceptance, the evolution of technologies.

Chapter 3, entitled *Electric Vehicle Power Supply Solutions*, presents a number of aspects, such as: standardization of electric vehicle recharging technologies and equipment, alternative EV charging solutions and technologies compared to conventional conductive charging.

Standardization plays a key role in the development and implementation of technology in society, providing an indispensable basis for large-scale market penetration and user acceptance / awareness.

According to the IEC 61851-1 standard, four EV charging modes are defined: mode 1, charging at a normal outlet without the use of any protection or control device (use of this charging mode is not recommended); mode 2, charging at a normal outlet but using a cable equipped with a protection and control device; mode 3, charging to equipment dedicated to EV charging (charging station) provided with protection and control functions, also the charging power (at alternative voltage) is determined by the communication between the charging station and the vehicle; mode 4, allows accelerated charging with special charging technology, such as direct voltage charging. All necessary control and protection functions are included in the installed infrastructure. The conversion from alternating voltage to direct voltage takes place in the charging station.

The solutions and alternative technologies for EV charging presented in this chapter are: the concept of battery swapping, wireless charging, pantograph charging systems for freight and passenger vehicles.

Also in this chapter are described the main communication protocols on the entire ecosystem of electric vehicle recharging infrastructure: electric vehicle users, recharging infrastructure operators, electricity transmission and distribution system operators, electricity suppliers, electric mobility service providers.

Taking into account the framework context of the doctoral thesis, that of the smart city and based on the bibliographic study conducted in chapters 2 and 3, this chapter presents an analysis of the typologies of charging stations and proposes a series of factors regarding the optimal location of stations. charging inside future smart cities.

Chapters 2 and 3 of the thesis contain complex theoretical aspects processed based on the literature.

Chapter 4, *The impact of the integration of electric vehicles on electricity distribution networks*, presents the analysis from a technical point of view of the impact of electric vehicles on urban electricity distribution networks, on changing electricity consumption, generating harmonics, voltage variations, voltage regulation and reactive power, the provision of ancillary system services, the integration of renewable energy sources. In this sense, a series of control strategies (usual, of medium complexity and advanced) of the charging of electric vehicles are described.

Given that large fleets of electric vehicles are expected to be integrated into electricity networks in the near future, one aspect is related to demand management, as this impact can be mitigated if EV charging is done outside load peak hours. From the point of view of electrical networks, EVs can be considered either as simple loads (with constant consumption), or as flexible loads by scheduling recharging periods, or as storage devices that through the Vehicle-to-Grid (V2G) concept can coordinate the charging procedure or inject energy from their batteries back to the grid.

In the event of a massive penetration of EVs, it is necessary to coordinate their operation not only as a business opportunity, but also as a new aggregating agent that would have an impact on the electricity network by controlling demand. If EVs are grouped / aggregated, then by coordinating the load, they can participate in the balancing process by adjusting the grid consumption or injecting power to the grid when necessary. Thus, V2G systems can provide services to network operators such as ancillary services, active power support, reactive power compensation and voltage regulation.

In the case study, two strategies for optimizing EV charging are proposed, taking into account battery energy storage systems (BESS) and the integration of renewable energy sources. The formulated mathematical model aims to find the best strategy for EV charging in the urban electricity distribution network, using both unidirectional mode (Grid-to-Vehicle - G2V) and bidirectional mode (Vehicle-to-Grid - V2G).

The optimization and coordination of EV charging within charging stations is based on the variation of the electricity price, the electricity price profile being taken from the OPCOM platform.

The results obtained for the one-way charging mode of the EV illustrate that they are programmed to be charged mainly at night and during the day when the load is lower, respectively the price of electricity is lower. During peak loads when the energy price is higher, the EV charge is limited or even stopped where possible.

In the case of the bidirectional charging mode scenario, the EVs are programmed to charge / discharge the batteries so as to minimize the total electricity costs. Thus, during power outages or when there is a surplus of power in the production of renewable energy sources, EVs consume energy from the grid at a lower price, and during peak loads they inject energy back into the grid at a higher price.

Battery power storage systems, within the tested electrical network, function as a "buffer" installation, which dampens the power variations introduced in the electrical network both by the consumption caused by the charging of EV batteries and by the fluctuating nature of the production of the two photovoltaic plants.

The software programs used in the case study are IBM ILOG CPLEX Optimization Studio in order to determine the optimal EV charging strategy and NEPLAN for simulating the optimal strategy scenarios on the tested distribution network.

Chapter 5, entitled *The role of electromobility in the integration of renewable energy sources and distributed generation*, describes the current situation regarding distributed generation and integration of electric vehicles. At the same time, aspects regarding the aggregation of electric vehicles and the coordination of their charging within the micro-grids and virtual power plants are presented and the relations between the “response to demand” type services and the intelligent charging of the EV are described.

Large urban agglomerations face increasing challenges in terms of security of electricity supply, so that urban energy systems are in a period of transition from a centralized model to a distributed one. This is largely due to the development of Smart Grid technologies and the integration of a growing number of distributed energy sources.

In the case study, a methodology for coordinating EV charge according to the production of electricity from renewable energy sources is described, using a model predictive control, MPC. The objectives of the study are to minimize the difference between the production and consumption of electricity within the microgrid and use only the available power from the production of renewable energy sources for EV charging.

The case study in this chapter examines two scenarios for coordinating EV charging in a microgrid, in the context of a high degree of penetration of distributed generation sources: (*i*) coordinating EV charging to minimize the gap between production and consumption within (*ii*) the coordination of the EV load according to the production of renewable energy sources connected to the test microgrid.

For both scenarios the coordination of the EV load uses a predictive control model. This strategy allows EV users to participate in Demand Response programs, in this sense proposing to carry out interactions between the local dispatching of distributed generation units and the distribution system operator (DSO) for a microgrid interconnected with the public network. The proposed control strategy always takes into account compliance with the requirements of EV users who choose to participate in such programs that provide flexibility services to network operators.

The numerical simulations performed in this study could be validated based on the tests performed within the company Enel X Italia, having available cars and charging stations.

Chapter 6, *Integration of electric vehicles in the electricity networks of power system under the conditions of participation in the energy market*, presents the general framework and structure of the electricity market in Romania. It also describes a number of issues regarding the adaptation of the electricity market and the requirements of the next generation of markets from the perspective of massive EV integration and influence on the energy market.

Given the possibility of EV participation in different types of market through aggregating agents, this chapter proposed an algorithm for optimizing the EV charging to participate in the balancing market by offering adjustment services, in the form of a dispatchable unit.

The developed algorithm proposes to follow an aggregate power profile, calculated by the Transport and System Operator (TSO) based on the consumption / production forecasts the day before, and to respect the preferences of EV users regarding the degree of battery charge.

The case study analyzes the potential of EV for participation in the balancing market and that of system technology services, with the aim of adjusting to reduce imbalances between the forecasted power profile and the realized power profile. This presents the participation on the balancing market of an aggregating agent that has in its portfolio four groups of EVs with distinct characteristics (Home, Work - slow charging, long charging sessions (8-9 hours); Shopping, Public - fast charging, charging sessions with a shorter duration (10 min - max. 2 hours)).

Taking into account the forecasted and realized consumption curve, the regulation bands that the aggregating agent can offer are established, behaving as in the case of dispatchable unit /

consumption holders, in order to compensate for deviations from the programmed values of production and consumption of electricity. Thus, during the period of excess power, energy will be consumed from the grid, and in case of power deficit, energy will be injected into the grid from the EV batteries.

The results of the numerical simulations confirm that EVs have an increased potential to participate in energy markets, as their batteries have a very short response time and can accurately track the signals given by the market operator, DSO or TSO, as appropriate.

Chapter 7, of *General Conclusions and Perspectives*, presents the general conclusions and personal contributions regarding the methodologies, algorithms and calculation programs developed within the doctoral thesis. The prospects for further research are also listed.

Following the research activity that was the basis for the elaboration of this doctoral thesis, the following conclusions can be distinguished:

- In the conditions of the phenomenon of "global urbanization", cities are at the confluence of major challenges in several sectors: economy, energy, transport, buildings, water supply, environmental protection and basic services. In order to respond to the aforementioned issues, cities are motivated to use smart solutions and experiment with various smart infrastructure applications, thus becoming the future smart cities.
- In the Smart City concept, a significant role they have transport problems of cities, where electrification of the transport sector constitutes indisputable future mobility, confirmed by the more than 7.2 million electric vehicles on passenger and freight transport.
- Contributing to this rapid increase in the number of EVs were: (*a*) the tightening of regulations on the use of conventional fuels (petrol, diesel) in Europe and China, which led the car industry to rapidly reorient to various EV models (PHEV and BEV), with over 442 new models currently available; (*b*) decrease in prices of Lithium-Ion batteries, per kWh, by 87% between 2010 and 2019.
- In view of the issues presented, electric vehicles have become one of the main answers in terms of decarbonising the transport sector and renewable energy sources in the field of electricity generation. However, their impact on electricity networks cannot be neglected.
- The main influences on the operation of medium and low voltage electrical distribution networks, due to the integration of EV charging stations and distributed generation are: overloading of network elements (power lines, substations); lowering the voltage level and adjusting the voltage; changing the direction of power flow; increased power losses; energy quality issues.
- The electrification of road transport is projected to gain significant momentum in the coming decades, driven by the global desire to move towards low-emission mobility. The growing number of electric vehicles can change the volume of global

electricity demand and pose significant challenges for electricity generation, transmission and distribution infrastructure.

- The impact of the integration of a large number of electric vehicles on power systems depends largely on their charging strategies; by coordinating the charging process of electric vehicles, flexibility services can be obtained in the electric power system, and the necessary investments in the modernization of the infrastructure could be reduced.
- Numerical simulations related to the methodologies, algorithms and calculation programs developed in this paper have shown that intelligent charging of EV batteries could help smooth the charge curve (which in turn can lead to lower electricity prices compared to with uncoordinated charging), can provide ancillary system services and facilitate the integration of renewable energy sources, resulting in a much safer and more economical operation of electricity networks.
- In order to "benefit" from the full advantages of the additional flexibility brought to the electric power system by electric vehicles and to ensure a fully compatible integration with the system, it was necessary to bring aggregating agents to market, which can group the controllable load of all flexible consumers to trade in the profile markets this flexibility.
- The use of EV batteries for system services through V2G technology requires dedicated IT-based communication and management solutions, as well as the access of electric vehicle owners or intermediaries to the respective markets for system services.

The main contributions of this paper include:

i) Carrying out a documentary study on the general framework for integrating electric mobility within the Smart Grid and Smart City concepts. This study highlighted the key factors in the integration of electric vehicles.

ii) Given the novelty of the field, the main standardization organizations and standards regarding the charging infrastructure of electric vehicles were identified and the solutions and technologies for charging EVs were presented. Also, based on the information gathered, issues related to the optimal location of charging stations within urban electricity networks were presented..

iii) Optimizing the charging of electric vehicles to improve the operating conditions of electric distribution networks, which aimed to identify the effects of different charging modes (G2V and V2G) of VE on an urban distribution network in terms of the degree of charging of the electricity network, voltage level in the nodes of the network, losses of active power in the conditions of integration of two photovoltaic plants and electricity storage systems in batteries.

For this purpose, an algorithm and calculation program was developed that uses the linear programming method; the results obtained from the simulations illustrate a better operation of the electricity network, respectively the reduction of operational costs and the maximum use of the production of photovoltaic power plants.

iv) An original methodology for coordinating the charging of electric vehicles according to production from renewable energy sources has been developed. The EV load management strategy is a "predictive control model" that allows EV users to participate in Demand Response programs. In this sense, it is proposed to create interactions between the local dispatching of GD and DSO units for a micro-network interconnected with the public network.

The objectives of this interaction are (*a*) to minimize the difference between production and consumption within the microgrid and (*b*) to use only the available power from the production of renewable energy sources for EV charging.

v) Carrying out for the first time experiments with electric cars and real charging stations, within the E-Mobility Solutions Development Department of the company Enel X Italia, from Rome. These experiments were used to validate the results obtained by numerical simulations.

vi) Strategies for coordinating the charging of electric vehicles to participate in the electricity market. The control strategy aims to follow an aggregate power profile, calculated by the TSO on the basis of consumption / production forecasts the day before, and to comply with the preferences of EV users regarding the degree of battery charge.

Following the simulations performed, the degree of satisfaction of the users participating in this type of services was 98%, and the EVs participating in the control services demonstrated that they can provide a fast and faithful response to the signals from the system operator.

vii) Valorization and dissemination of research through participation and publication of papers in national and international conferences:

2014 IEEE International Conference on Renewable Energy Research and Application (ICRERA), Milwaukee, WI, USA; 2017 IEEE Electric Vehicles International Conference (EV), Bucharest; International Conference on Condition Monitoring, Diagnosis and Maintenance - CMDM 2017, Bucharest; Scientific Bulletin of the Petru Maior University, Targu Mures, 2017; Days of the Romanian Academy of Technical Sciences, Energy and Environment. Major challenges of the 21st century - ZASTR 2018, Ploiesti; 2019 IEEE Milan PowerTech, Milan; 2019 IEEE Electric Vehicles International Conference (EV), Bucharest; Scientific Bulletin of the Politehnica Bucharest, Series C: Electrical Engineering and Computer Science, 2020.

In order to continue the studies presented in this doctoral thesis, the following research directions are proposed:

- Participation of electric vehicles in reactive power regulation services through converters, which use power electronics, with which EVs or charging stations are equipped;
- Study of EV battery degradation in terms of providing system ancillary services, especially from the point of view of EV users;
- Providing ancillary services that use the coordination of EV charging connected to low voltage power grids. The EV fleet is equivalent either to electrical charges during the charging process or to photovoltaic power plants when injecting energy into the grid, thus leading to variations in the voltage level;
- Analysis of solutions for the integration of ultra-fast charging stations with powers up to 350 kW in urban power grids, which are already required, through hybrid solutions with battery energy storage systems.

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