POLITECNICO DI TORINO

Master's Degree in Automotive Engineering

Master's Degree Thesis

IMPLEMENTATION OF V2H IN THE TWO-WHEELER MARKET

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Summary

In recent years, and especially after the European Union decided to ban the sale of new gasoline and diesel cars from 2035, the interest in the future of e-mobility has grown steeply.

The greater market share of electric vehicles will lead to problems concerning energy distribution on the public grid, which will be increasingly subjected to outages due to the peak request during charging periods of electric vehicles. In fact, during the evening hours, when the greatest part of the electric vehicles will be connected to the grid and charging, the overall power request will be higher than that for which the cities have been designed.

To solve this problem, research centers and in general the automotive industry started thinking about the development of alternative charging methods. The first solution has been Smart Charging, which allows scheduling of electric vehicle charging. Then, Vehicle-to-Home and Vehicle-to-Grid were developed, the basis of this technology stands in the concept of bidirectional charging, which is the capability to manage the charging and discharging cycles of the vehicle while plugged in. The Vehicle-to-Grid technology is used to feed energy back to the grid, while Vehicle-to-Home is based on supplying a household or managing better peak power request periods.

This thesis work, which has been conducted in collaboration with KTM F&E, aimed at the early phase development of a new system, following the innovative idea of implementing Vehicle-to-Home technology in the motorcycle market.

Starting from the first step of the work, it consisted of a deep literature review, and this has been of fundamental importance to put down the basis of the work, defining which is the starting point and which are the boundaries in which it is possible to act and make decisions. Furthermore, also the state-of-the-art technology had to be assessed to allow a conscious development of the project.

The second and third steps, are concerned with the modelling, simulation, and analysis of two different models that can be perceived as two sides of the same coin. The first model has the objective of analysing in depth the detailed system and component physical modelling, based on a short-time horizon since the aspects to inspect can be observed during the transient phase, clearly observable in the first few seconds of simulation. Through these results, it has been possible to define the architecture that gave the best behaviour under each loading condition, and this layout has been the basis for further developments. Instead, the second model had the aim of analyzing the energy transfers in the entire system, to have an overall view of how the system would behave during an entire year of usage, from the cycling behaviour to the capability of the house to power itself through the supply from the electric motorbike battery.

In the end, the results are presented and discussed, with observations regarding the feasibility of the project, giving particular importance to the balance of costs and benefits from customers and company point of view.

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Chapter 1

Introduction

In recent years, and especially after the European Union decided to ban the sale of new gasoline and diesel cars from 2035, the interest in e-mobility has grown steeply. Until now the focus has always been on cars, but also motorbike industry will certainly face stricter regulations about emissions and probably in the future a ban on gasoline engine-powered bikes will also come, since some politicians already proposed to extend the 2035 ban for cars to motorbikes.

With an increase in the share of electric vehicles, one problem will come out, and this will be the peak power demand when many electric vehicles will be under charge at the same time. This led researchers to find a solution, and this resulted in the smart charging technology. It is based on a system that allows for controlling the charging process of the vehicle, delaying it, or interrupting it when needed, making it possible to avoid overloading the grid during peak power demand and charging the vehicle during off-peak hours. In this way, two advantages can be exploited, the first is that for the customer it will be possible to charge during off-peak hours when the energy price is the lowest. The second is that the grid will be more evenly loaded along the day, leading to fewer problems on the distribution side.

It is with the evolution of smart charging that the Vehicle-to-Home (V2H) concept came out. V2H capability enables a vehicle to take energy from its battery to feed the house grid to satisfy household energy needs as well as take energy from the grid to power the vehicle, making possible a process that is inverse to the traditional one. This is possible through the implementation of bidirectional charging on the electric vehicle, allowing the owner to use the battery as a backup battery system. This technology gives the chance to exploit the electric vehicle potentialities when used for moving as a conventional vehicle, but also when parked and plugged into the house grid. It can be used to power the house in case of grid outage but also to save money by optimizing the energy consumption of the household. A simplified scheme is provided in Figure 1.1.

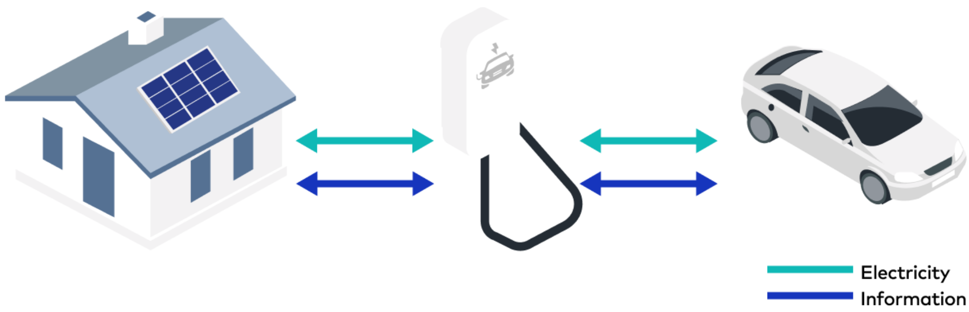

Figure 1.1: V2H simplified scheme as in [1]

All these considerations have been made only with cars until now, based on distinct reasons:

- The large and growing share of electric cars.
- The great quantity of energy that can be stored in the battery pack.
- The 95% parking time, also if the car is not parked at home for part of this time.
- Near no constraints on component weight and volume.

All the points can be modified to be applied also for motorcycles:

- The low but growing share of electric motorbikes.
- The quantity of energy that can be stored in the battery pack could even be one order of magnitude lower than the one of cars.
- A great part of motorcycles remain parked for all the winter months, significantly reducing the active usage time (depending on the geographic area).
- There are stringent constraints on component weight and volume.

This could allow optimal utilization of the motorbike bidirectional charging, especially during winter months, without any problems regarding the minimum range needed for the next day since the charger could know the motorcycle will not be used for the next months. This is the field in which KTM is interested and where the company decided to deepen its knowledge through this project.

KTM is the largest European motorcycle manufacturer for either the on-road and off-road industry. Since 2014, on the catalogue, it has been possible to find the KTM Freeride E-XC, an electric homologated off-road motorbike. Year by year, improvements have been made, from a performance perspective, but now other parallel paths for the motorcycle development are coming out.

Figure 1.2: KTM Freeride E-XC 2023 with charger

Currently, there are no motorcycle manufacturers on the market that are commercializing electric motorbikes with bidirectional charging capability, so this would lead to a Unique Selling Proposition (USP) for the company that, from a knowledge and marketing point of view, would make KTM stand out from competitors. A motorbike equipped with this innovative technology could lead customers to buy it for several reasons apart from the typical riding feeling, such as the economic advantage that should come from the energy storage capability during the entire year when it is plugged into the house grid.

As said before, the concept of having battery energy storage in the house is already diffused and some homes have already been implemented with backup battery systems or energy buffer systems in their houses. The reasons for that are to have a backup energy source during an outage or also to store energy produced from renewable sources to use it when needed. The innovation comes when the energy storage system used is the battery of an electric vehicle. In this way, the vehicle could be perceived as a house battery energy storage on wheels, exploiting V2H capabilities as a primary function, depending on the customers' intentions. Research projects have already been conducted for existing electric cars. Still, the challenge of this thesis project is to prove if this technology could be successfully implemented on a motorbike, which benefits will come out, and which will be the limits or compromises to face.

In the case of integration with PV power, the study will have to consider all the power flows from and to the battery, to the appliances and from the PV. The PV power flow has dependencies on the hour of the day and on the day of the year so, consequently, V2H effectiveness along the year will change accordingly. Another dependence will be on motorbike plugged periods, which will be higher in winter and lower during summer.

Chapter 2

Literature Review

The literature review is the first step to start the project, and this is because it is needed a strong knowledge background on the topics to be discussed to make sure the project development will lead to meaningful and reliable results. This chapter will be subdivided into macro sections, to make it more organized and easier to consult.

2.1 V2H

In [2], the main features of V2H have been depicted, and these will be the core requirements that the final project shall comply with. In the following, the list of the features is provided:

- Generally, it involves one GEV per house.
- Simple configuration and easy to accomplish.
- Ability to smooth household daily load profile (DLP).
- Ability to provide reactive power to the home grid (also without GEV, simply using the charger).
- High efficiency during operation.
- No substantial changes are required to the existing home grid.
- Improve the effectiveness of renewable energy production.
- Smart home more attractive.
- Improvement of smart grid.

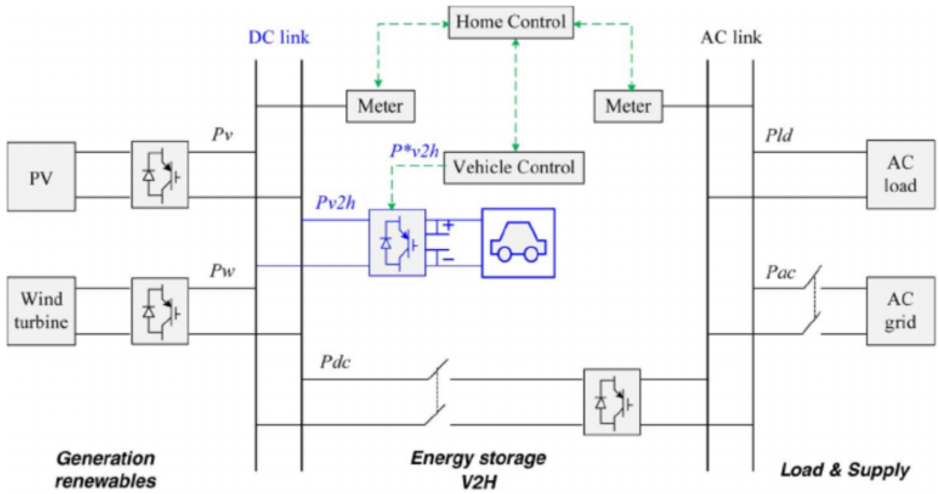

Figure 2.1: V2H network proposed in [2]

In Figure 2.1 it is also possible to see the proposed converter network for a V2H system, consisting of the AC link, the DC link, the bidirectional converter for the charging of the electric vehicle, unidirectional converters for renewable energy sources, the bidirectional converter for the AC link and the DC link, and the control circuit. The charger in the figure is of DC/DC type, but it is worth mentioning that it could also be of AC/DC type and connected to the AC link.

In [3], the authors propose a Home Centralized Photovoltaic (HOCP) System, which includes the V2H technology, a Photovoltaic (PV) system, and a Green Electric Vehicle (GEV), aimed at reducing energy demand from the household. This objective is reached by providing optimal automation of the appliances and gaining control of the time scheduling of appliances' working hours. With an optimized design, the HOCP system should be able to cover the household power demand in all meteorological conditions (e.g., sun and rain) through PV and V2H. Starting from these assumptions, this paper aims at the development of a Home Energy Management System (HEMS) able to satisfy the energy demand of a household. In the end, results show that V2H combined with PV can help reduce energy consumption coming from the public grid.

In another case study, the authors of [4] work on a proposal and subsequent implementation of a V2H system feasible to be applied to commercialized EVs, able to support islanded AC/DC load and power grid. Simulations and implementation have been performed and results show that the system can support critical islanded DC/AC loads. In this application, a grid-tied inverter has been used, synchronized with the power grid. After the first proof of concept, other explanations regarding the software architecture and the various communication protocols have been given. For the aim of this thesis work, the focus has been put on the hardware layout, also concerning the one proposed in [2], it is noticeable that this configuration came out from an adaptation of an already existing system. This kind of adaptation leads to a higher number of power conversions, as it is possible to see in Figure 2.2, which leads to lower efficiency. A further analysis of this layout could make it possible to assume as V2H the system comprised between the vehicle and the AC load, assuming an approximation of the household appliances in that AC load.

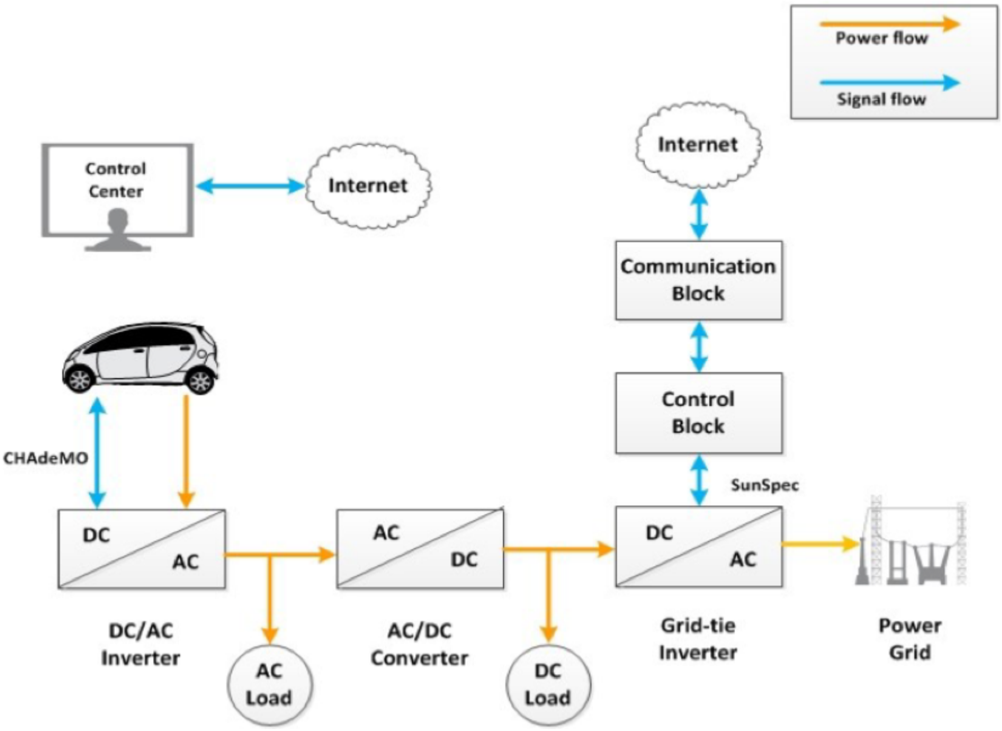

Figure 2.2: V2H system according to [4]

Studies have also been conducted in the field of V2H optimization. As with every optimization problem, the solution must be defined through the minimization (or maximization) of a variable. This objective can be maximizing energy efficiency as in [5] and [6], minimising costs as in [7], minimising costs and environmental impact as in [8], or increasing backup duration under a grid outage [9]. This kind of research study has been a useful proof of concept about the feasibility and the advantages drawn from this new technology. It will not be the aim of this thesis to define and develop an optimization algorithm, but this literature is useful for understanding various load cases and working conditions of the system that need to be considered.

2.2 Challenges

As stated in [10], it is needed to outline the challenges that the project will lead to, going through Political, Economic, Social, Technological, Legal, and Environment (PESTEL) and above. Here will be reported the main points treated that can be of interest in a Vehicle-to-Home (V2H) application instead of a Vehicle-to-Grid (V2G) one. The first considered section is one of the technical challenges:

- Accuracy of the EV response to loads power demand, current EVs tested by the authors did not show issues regarding the speed of response since batteries have usually been found to respond in about 1-10s and it is compliant also with the most stringent requisites.
- Low efficiency of power electronics during the discharging phase and in partial loading, so the components responsible for the discharging process must be optimized to reduce as much as possible the gap of efficiency between charging and discharging.

Then, economic challenges have been studied:

- Cost of the equipment, with the introduction of new functionalities that must be compliant with requisites from the safety and regulations point of view, the components will become more costly than the current ones.
- Cost of metering equipment, useful to manage power flows from and to the battery, considering power from the PV and power required from load appliances.
- Uncertainty regarding revenue generation, which is an important variable for market positioning among competitors.

Then, challenges regarding the market's current state, which is a problem for the V2G, instead, in this V2H case study, this would not be a problem because every owner will benefit from his investment, directly generating revenues from it in the optimal case.

From the procurement point of view, it is not clear which are the manufacturers that already produce and sell off-shelf solutions for V2H applications. A study needs to be performed to evaluate possible already developed solutions or if it will be needed to design and develop a new component.

Regarding product quality assurance, the impact of V2H on the vehicle battery must be evaluated, and it must be defined how it affects the lifetime and consequently warranty of the vehicle. A certain number of charge and discharge cycles must be guaranteed under warranty, and this will be higher than the number considered for traditional use only.

Among all the challenges and requisites mentioned above, the technical ones will be the focus of this project, also considering the product quality, which is strictly linked to the technical topics that will be discussed. In the next chapter, an analysis of each key component on the motorbike will be performed, after a brief technical description of the element, the focus will be put on the impact of the innovative technology to be implemented on the component itself.

2.3 Battery

The authors of [11], propose a battery pack optimization through a Simulink model to simulate charge and discharge cycles. A list of ways in which it is possible to increase battery life is presented:

- Active balancing and cell switching.
- Optimized partial charging.
- Avoid charging to 100%.
- Limit battery temperature.
- Avoid high charge and discharge rates.
- Avoid deep discharging.
- Select the proper charge termination method.

Also, two methods to model battery degradation are presented:

- Theoretical, in which the focus is the loss of Li-ions, explanation of degradation mechanisms and correlation with battery conditions. It is difficult to correlate charging and discharging with molecular processes because of a lack of knowledge.
- Empirical, convenient for storage planning and operational study with good accuracy. Limitations come from experimental data, in this way, a model designed for one application could not work for another.

Two types of battery ageing are introduced: calendar ageing and cycle ageing, the first is the degradation caused by the effective age of the battery, while the second is the degradation caused by the utilization and the cycling, which can be different based on working and loading conditions. To slow down battery ageing, the author made four observations that can be assumed as good practices in battery usage:

- Do not use batteries in hot environments and avoid exposure to sunlight.
- Do not keep the battery inactive and discharged for too long.
- Do not charge too frequently (only when SOC<25%).
- Replace the battery when the state of health drops below 90-50% based on the type of application.

After that part of the paper, a step-by-step explanation of how to build the Simulink model is provided, which can simulate charging and discharging cycles, with the analysis of the results.

The author of [12] proposes an innovative ageing model for Lithium Ion batteries based on a theoretical model of crack propagation.

In general, there are two types of models. Detailed models regarding the chemistry of the cell or empirical models fitting test data to equivalent circuits. The first type requires an important computational effort and does not approximate well the entire cycle life, the second requires testing of each type of cell to be analyzed, in this case, it is not possible to simulate complex cycles of charge and discharge.

Crack propagation gives an estimation of the damage parameter based on the history of the cell, applying structural materials crack propagation theory to battery electrodes. During the simulations, the parameters that have been varied are SOC swing, average SOC, and battery temperature, comparing the results and evaluating the best and worst conditions for battery life. As a result, it is needed to:

- avoid very deep cycles (<60%DOD).
- keep temperatures low (<35°C).
- maintain a low average state of charge (<60%).

Other authors worked on research papers about battery degradation in electrified vehicles, such as in [13], in which in different chapters modelling and analysis is carried out. In the first part, modelling of a battery through equivalent circuits has been performed. In the second part, cell degradation modelling has been performed, and cycling and calendar ageing have been tested for the single cell. In the third part the cell model is used to perform simulations at the pack level, evaluating differences between different layouts for the pack cells connection, pack state of health is strictly dependent on the single cell state of health and on the connection. In the fourth part, the model is used to evaluate battery behaviour in normal vehicle operation. All these simulations are performed to evaluate the influence of temperature, state of charge and rate of charge on the ageing phenomena. In the end, it came out that the most influencing factor for cycle ageing and calendar ageing is the temperature. Cell temperature is influenced by ambient temperature and current. SOC also influences degradation but less than temperature.

Chapter 3

Requisites of V2H system

These requisites regard the functionality of the complete system but also the safety point of view. It is important to state that these observations are made to give a complete overview of the entire system, including all the challenges and problems that would arise in the case of a decision to follow this technology path. Then in the following chapters, the proper project design and development will come. In this section, the interested subsystems of the motorbike architecture will be analyzed, to evaluate modifications that shall be adopted to comply with new working conditions.

3.1 Charger

This component is of fundamental importance for the successful exploitation of bidirectional charging for V2H purposes.

It receives AC in input and can supply AC or DC depending on the type of charger and vehicle.

The current charger supplies the Low Voltage (LV) battery of the vehicle with DC, so it is composed of an AC/DC converter followed by a DC/DC converter. The first is aimed at converting the AC coming from the grid through the wall socket to DC, and the second is used to convert the DC to a voltage range suitable to charge the battery without causing any damage. In the case of an HV battery, the DC voltage to charge the battery would be higher than the one used on the current models, requiring a different charger.

To make possible bidirectional charging, it will be needed to use a charger made by a bidirectional inverter and a bidirectional DC/DC converter. In the next chapter, it will not be proposed a proper bidirectional charger due to the new development effort that would come. Instead, the charger will be maintained as the current one, adding an inverter to guarantee the bidirectional capability of the charger seen as a single component at this point.

Regarding the use cases that should be implemented, in total, these are:

- Plugged and charging, in which the power flow is from the wall socket to the battery. This is the case in which PV is producing more energy concerning what is the request of the household or during off-peak periods to take advantage of the lower energy price. In this use case, a fundamental requisite is that the battery SOC must not be above a certain threshold, to prevent overcharging that would lead to faster aging.

- Plugged and discharging, in which the power flow is from the battery to the house grid. This is the case in which the household needs more power than that provided by the grid, or the grid is under outage or simply releasing energy during peak periods to avoid higher prices from the public grid. In this use case, the fundamental requisite is that the battery SOC must not be below a determined threshold, to prevent over-discharging that would lead to faster ageing.

- Plugged but not charging nor discharging. This is the condition in which it will be possible to find the vehicle when the requisites of the first two points will not be met.

3.2 Inverter

An alternative solution to the bidirectional off-board charger, using the on-board inverter to generate AC that is feasible to be fed into the grid. In this case, some modifications to the inverter will be needed.

The fundamental requirement is a switch, it must be capable of routing the power exiting from the inverter through two distinct paths. To the motor, like in traditional EVs during normal driving conditions, allowing for bidirectional power flow in case of traction or regenerative braking. To the AC wall socket, during V2H condition, to make it possible to discharge the battery to satisfy power request from the household.

Output AC power type should be interchangeable based on the working condition, for the traditional one it does not need any updates, but for the V2H operation, it should be able to provide AC 230 V 50 Hz. An inverter optimization around this frequency would provide a higher efficiency to better exploit the V2H potentialities during the plugged period.

Through this type of usage, the components will undergo a way higher number of cycles concerning the current dimensioning with only traditional use, so an aging assessment would be useful to verify the proper functioning of all the parts after a defined operation time.

3.3 Battery and BMS

The current battery pack has been developed and tested to undergo a specified number of cycles, which will be for sure exceeded with the use of V2H technology. On the other hand, these additional cycles will be performed at a low rate of discharge and in steady-state conditions. The traditional use of a motorbike shows a high rate of discharge, following a highly irregular pattern regarding the power requested from the battery, in which torque and rotational speed of the motor are characterized by many peaks along a drive cycle.

Regarding the charging phase, it will be carried out as a traditional one, but the discharge phase will present new working conditions. The most challenging one will be the operation with the vehicle in steady condition. Studies must be performed to define if these new discharging conditions will be compliant with cell limits, mainly regarding temperature since the convection coefficient of external air cooling will surely be lower, caused by the vehicle standing still.

This will be a new use case to implement because there will be bidirectional communication between battery and charger to manage charging and discharging phases based on indicators like household power demand and battery state of charge (SOC).

Both LV and HV solutions will be considered. It is possible to expect better behaviour with the HV battery pack, but there is also an interest regarding the application of V2H technology to the existing model, instead of starting with the idea of developing a completely new motorbike. The application on LV motorbikes could be a test bench for the approach of the technology to the vehicle, focusing the development on the V2H capability only.

3.4 Grid

An important feature from a safety point of view is the disconnection from the grid when an outage is detected, this must be done to avoid the chance of having a power flow from the battery to the public grid during maintenance or repairing interventions performed by operators that would be injured from a power flow that should not be present in the grid in that moment. There are two possible ways to comply with this requisite:

- Shutting down the system. This is the simpler way to proceed, when the power meter detects a public grid outage it shuts down the V2H bidirectional charging process, disabling the possibility to feed the household grid discharging the vehicle battery. In this way the backup capability of the system will be compromised, so the V2H technology would be used only to smooth peak power demand and to accumulate excess power produced by renewable resources and release it when needed.
- Isolating the household grid through an islanding process. This other solution is more complex but is the one that allows the exploitation of all the features of the V2H system. The functioning principle is that when the power meter detects a public grid outage, a switch interrupts the connection between the public grid and the household, allowing the V2H to remain active, enabling the discharging process to satisfy the household power needs that during this period will entirely rely on vehicle battery.

An alternative solution that could be adopted in the early phase is the adoption of a switch that has to be manually activated to detach the house from the grid, enabling V2H during an outage, without the need to have a complex fully integrated electrical system.

Based on the overall architecture of the HEMS, the charger complexity may increase or not. In the case of implementation of PV and V2H, the charger will no longer have only the task of managing the charging and discharging of the battery, but it will also need to measure the power coming from the PV and define whether it is preferable to charge the battery, discharge the battery, feed the house directly with PV or either split the power from the PV to supply the household and charge the battery. In this way, all the system's power flows will have to merge to a single component that in this case could be the charger, and this could require important changes from the house perspective. In this case, it will be possible to study an alternative system, in which V2H and PV could share the same inverter, simplifying the overall system.

Chapter 4

Layout solutions under investigation

First, here the three considered architectures solutions will be presented. It is worth mentioning that each of the three architectures will be simulated with the adoption of the two battery types distinguished by different voltage levels. Basing on the battery type, different solutions will be implemented to manage and solve electrical challenges, such as voltage steps to be performed.

Then, always in Chapter 5 an analysis based on the simulation of these will be made to define which one will be the most suitable with the requisites from the bidirectional charging side and the vehicle project side.

In each of the proposed solutions regarding system architecture, to have a complete automation of the process, it should be needed the installation of an energy meter at the main grid connection point. This is an important component that is needed to be able to manage the power flows in the household, through the energy meter the best moments for battery charging and discharging can be detected and most importantly the whole system will be managed to reduce as much as possible the power required from the grid. To exploit this feature at the maximum an integration with a PV system would be optimal. All these alternatives could be invasive operations that will reduce the plug-and-play characteristics that were one of the initial objectives of the project.

Anyway, this project's aim is the feasibility and potential analysis of this technology. To do that, in the following, the optimal feasible solutions will be considered to allow performing an evaluation considering the best adoptable solution and not limiting the analysis to the first possible implementation.

4.1 Bidirectional off-board charger

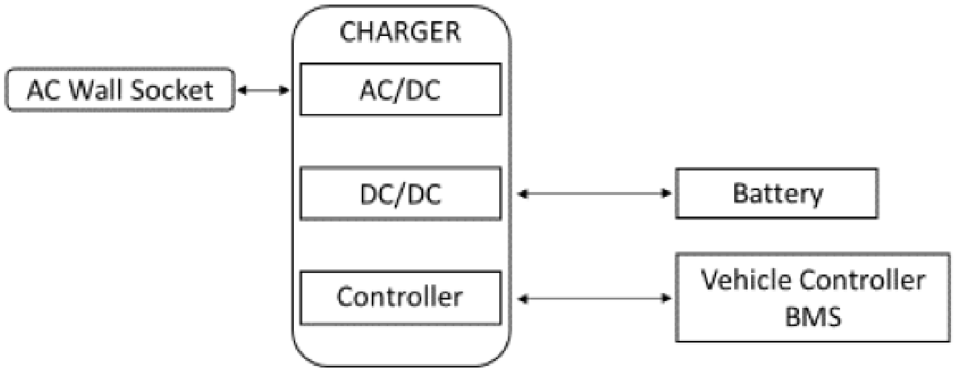

Figure 4.1: Bidirectional charger scheme

This is the simpler solution from a vehicle point of view and the most modular option. These aspects apply to this layout for one main reason, being it an off-board charger, there are not stringent weight or volume constraints, that as it will be possible to understand, are a limiting factor in the next solutions. The system requirements variation concerning the current conventional charger would mainly be the bidirectional capability through a bidirectional AC/DC converter or using an additional single-phase inverter. Basing on the battery voltage level, also a DC/DC converter could be mandatory. As it will be explained in detail in a separate section, the low-voltage battery will need a boost DC/DC converter to make it possible to raise its voltage to a value feasible to be used to produce grid AC.

Another relevant aspect is the eventual synchronization with the grid during the V2H operation phase. As deeply analyzed by [14], the synchronization phase is a really important part of the design of the whole system, and due to that, the use cases of the entire system will be heavily affected by this. If not properly or not at all synchronized, the system cannot be connected to a powered grid, so the only solution for the exploiting of V2H is to take as possible use cases the time intervals in which the grid is not providing power to the house. These cases can be split into the first condition which is an outage, so the utilization of the system as a backup battery, and the second condition in which the house is disconnected on purpose from the grid to make possible the exploitation of the battery energy.

However, from the company's point of view, there is no interest in developing a proper complete charging station, with a complex and hard-to-implement configuration. So, the focus will stay on the vehicle architecture and the existing charger, with the needed updates to stay within the requirements.

4.2 Discharging operation through on-board traction inverter

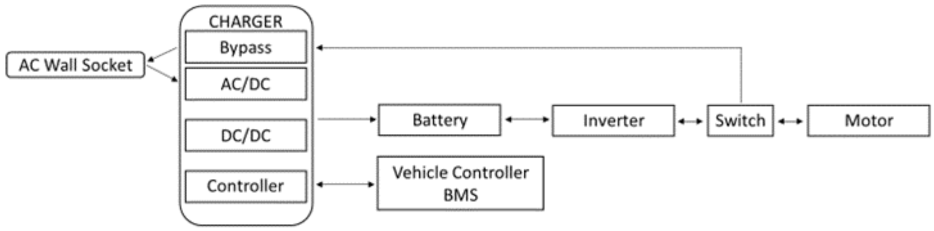

Figure 4.2: Discharging through traction inverter scheme

This solution is characterized by an augmented vehicle integration between sub-systems, but this leads to a lower modularity. In this way, it would be possible to use existing components to perform tasks that in the previous case were performed by additional components. This is achieved through the on-board traction inverter, which is a three-phase inverter. It is possible to produce a single-phase AC exploiting two of the three legs of the inverter. In this case, the inverter will need to work in steady state conditions to have an output frequency of 50Hz to make it possible to be used to supply loads of the household grid.

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4.3 Integrated on-board charger

This solution is the less modular but the one with the highest vehicle integration between sub-systems. With the adoption of this architecture, it would be possible to use the on-board devices to convert grid AC and charge the battery. A detailed description of the system and its working principle is given by [15], but a clearer explanation is provided by [16]: «iOBCs use AC line as an input, using the motor winding. Each leg of the traction inverter is connected to each phase of motor

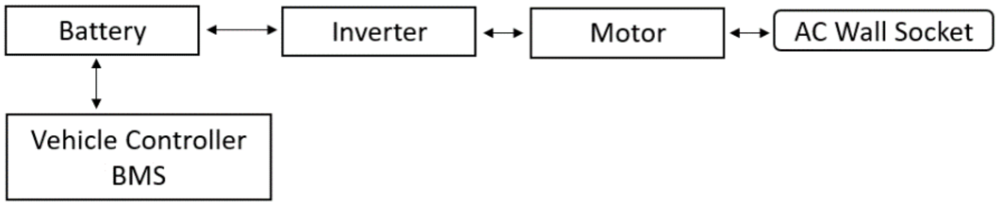

Figure 4.3: Integrated on-board charger

winding. Thus, the inverter can be used as an active front-end (AFE) rectifier during charging. The non-isolated iOBC can also be built using a three-phase and multiphase machine.». Also in this case, the inverter will need to be able to work in a steady state to have an output frequency of 50Hz that would make it feasible with loads of the household grid.

Another relevant aspect is the eventual synchronization with the grid during the V2H operation phase. As deeply analyzed by [14], the synchronization phase is a really important part of the design of the whole system, and due to that, the use cases of the entire system will be heavily affected by this. If not properly or not at all synchronized, the system cannot be connected to a powered grid, so the only solution for the exploiting of V2H is to take as possible use cases the time intervals in which the grid is not providing power to the house. These cases can be split into the first condition which is an outage, so the utilization of the system as a backup battery, and the second condition in which the house is disconnected on purpose from the grid to make possible the exploitation of the battery energy.

Many papers on this topic have been consulted during the development of this project, the most relevant ones and helpful in understanding in a general way the chances to implement this kind of technology on a vehicle have been [17] and [18]. From these two collections of ways to implement an iOBC in a vehicle, what came out is that the feasibility of this technology is strictly related to the motor type that is employed in the vehicle traction system. Following the logic that has been adopted until now, reducing to the minimum possible changes regarding components, the motor is assumed to remain unchanged concerning the current one adopted which is an internal permanent magnet synchronous machine (IPMSM). From the literature that has been consulted, the only solution that has been studied with this kind of motor is the one studied in [19]. The problem of this solution is that that kind of architecture can only be exploited to achieve a fully integrated charging process leading to a complete avoidance of the off-board charger but cannot support a bidirectional charging functionality.

There has not been found any other documentation concerning bidirectional functionality for iOBC equipped with an IPMSM motor, in that case, an off-board charger would be needed to ensure bidirectional charging, and the concept would be no more as attractive as it would be for a traditional motorbike with no V2H capability. In fact, in this case, the development should focus on the charger and a completely new vehicle architecture.

For these reasons, this type of architecture and technology will not be taken into account in the next project phases. It was worth to mention it, but the drawbacks are too important, so a positive trade-off cannot be reached considering current technology limits and boundaries imposed to the project concerning the changes in the vehicle architecture as a whole.

Chapter 5

Physical model for the short-time horizon

This kind of model has been developed to create and simulate in a detailed way the system that needs to be implemented. Different versions have been created, one for every battery type and every different architecture. The detailed modelling of the components makes the simulation heavy to run, and that is why the results that will be shown will derive from a few seconds of simulations. The time interval that has been chosen is enough to include all the transient responses of the system until the steady state condition is reached.

In the following sections, the various subsystems will be analyzed in depth and a description will be given.

5.1 Subsystem description

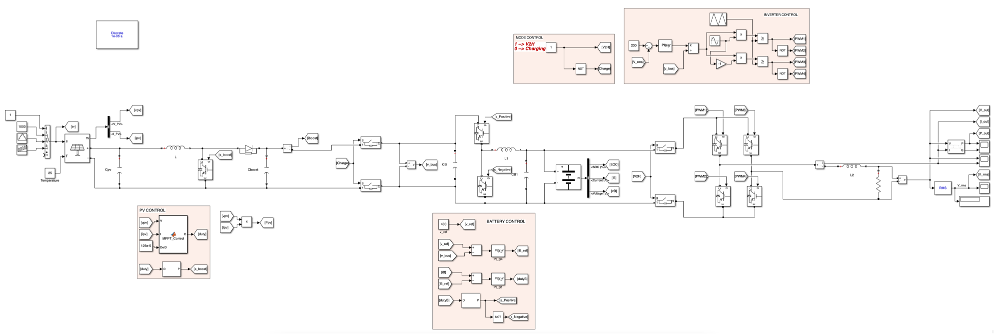

Figure 5.1: Complete V2H physical model

In Figure 5.1, a representation of a complete system is provided, it represents only one of the studied layouts, but for the sake of simplicity and briefness, the components will be all explained in this section and the picture's aim is for a better understanding of the next chapters details explanation. In this section, the entire system will be analyzed in depth. To do that more understandably, it will be analyzed one subsystem or component at a time. In this way, an organized description of the system will be given, and anyone will be able to put more focus on the interested field.

5.1.1 DC bus

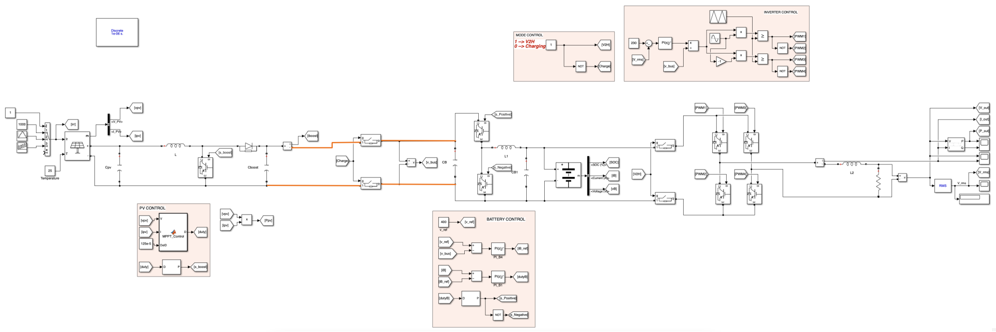

Figure 5.2: DC bus physical model (highlighted in orange)

This is not a proper component, but it is a power distribution system, and its role is fundamental. «The loads or subsystems are connected to the DC bus [...]. The DC bus is typically composed of two conductors, a positive conductor, and a negative conductor, which are connected to a power source and connected to the loads [...]. The voltage on the DC bus is typically regulated to ensure that the loads receive a consistent and stable power supply.»[20]. DC bus voltage is typically high to maintain low currents into the conductors to ensure higher power transfer efficiency. In this case, the DC bus voltage has been fixed to 400 V, and this choice has been made due to several reasons. The first is that the HV battery of the motorbike and the PV array voltages are near this value, as will be explained in-depth in the dedicated chapters. The second reason derives from the V2H scope of the project, and this is the production of AC power for European users, so 230 V AC. To reach 230 V_{rms}, the minimum DC bus voltage that is equal to the peak voltage in the sinusoidal wave must be $V_{DCbus} = V_{ACpeak} = \sqrt{2}V_{RMS}$, around 325V, and considering the voltage drop due to filters, it is reasonable to assume a voltage above the nominal one, so 400 V is a favourable choice.

5.1.2 PV system

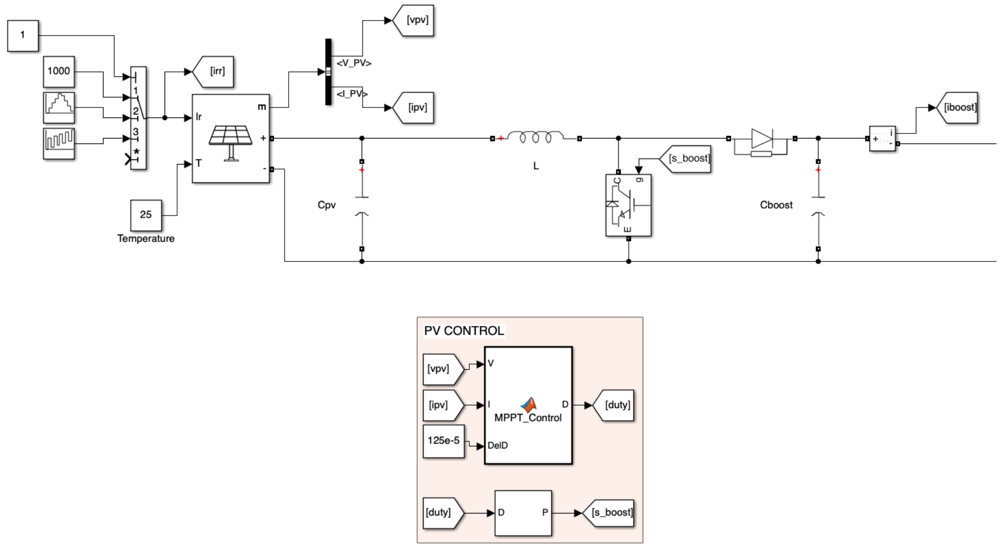

Figure 5.3: PV system model

This subsystem includes the "PV Array" block, the Maximum Power Point Tracking (MPPT) control and a DC/DC step-up boost converter.

The PV array characteristics have been defined starting from [21] that suggests systems between 2.4 kW and 6.4 kW for houses ranging from 3 to 5 bedrooms, and [22] that classifies as small PV systems typical of residential buildings installations all the systems below 5 kW. That is the reason why the system has been designed to have a power level in the range of 4-5 kW, in this case, the plant is composed of 20 modules (2 parallel strings and 10 series-connected modules per string) with a maximum power conversion of 213.15 W each for a total of 4263 W. Each module is composed by 60 cells, has an open circuit voltage of 36.3 V and a short-circuit current of 7.84 A.

Regarding the MPPT control, the technique used is "Perturb and Observe". «In this procedure, the voltage of the PV array is perturbed and the adjustment in its output power is noticed. At each cycle, the voltage and current of the PV are measured by the tracker and derived the real PV power by observing the variations in power. Until reaching the MPP, this situation is recapitulated. »[23].

The DC/DC step-up boost converter's function, instead, is to regulate the DC bus voltage. The PV system does not convert energy at a constant voltage, so a converter is needed to allow the DC bus to maintain that constant voltage.

5.1.3 Charger

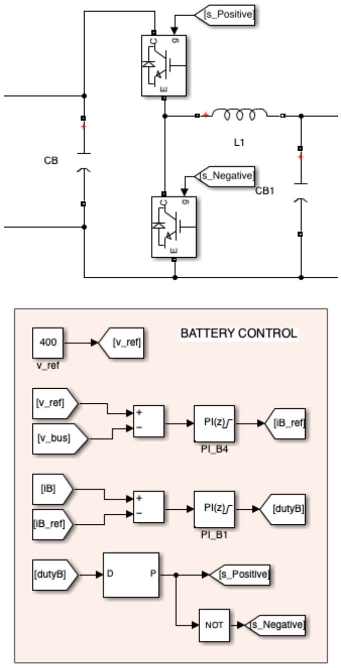

Figure 5.4: Charger model

This component has not been completely modelled, and the reason is that KTM already has a working charger and is also already working on the development of different power levels for the charging operation. Due to that, it was decided to not invest time and resources in this component. So, in this kind of model, the charging phase would not be achievable from the grid as it could be with a conventional charger, but only through a DC link with voltage regulation from the DC bus. For this reason, the charging phase has been made possible by employing a bidirectional DC/DC buck-boost converter, which is used to connect the battery to the entire system. This component allows the system to have battery voltage and DC bus voltage quite different from each other, stepping down the voltage during charging operation. The higher the step to be performed, the more difficult it will be to achieve it with acceptable performance and quality, but this will be deeply analyzed when speaking about the working conditions.

5.1.4 Battery

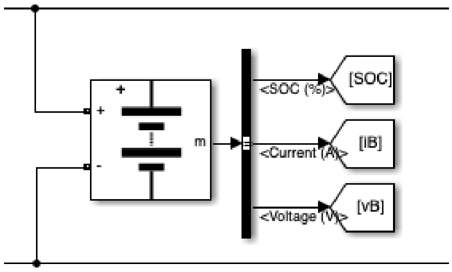

Figure 5.5: Battery model

The battery subsystem is one of those that plays a fundamental role in the model and the simulations' outcomes. Presented batteries are state-of-the-art lithium-ion (Li-ion) batteries, «Compared to other high-quality rechargeable battery technologies (nickel-cadmium, nickel-metal-hydride, or lead-acid), Li-ion batteries have a number of advantages. They have one of the highest energy densities of any commercial battery technology [. . .]. In addition, Li-ion cells [. . .] suitable for high-power applications like transportation. Li-ion batteries are comparatively low maintenance, and do not require scheduled cycling to maintain their battery life. Li-ion batteries have no memory effect, a detrimental process where repeated partial discharge/charge cycles can cause a battery to 'remember' a lower capacity. Li-ion batteries also have a low self-discharge rate of around 1.5-2% per month [. . .]. High energy densities and long lifespans have made Li-ion batteries the market leader in portable electronic devices and electrified transportation, including electric vehicles (EVs) [. . .]. In terms of decarbonizing our economy's energy use, Li-ion technology has its greatest potential in EVs »[24]. As it is easy to understand, these are the main reasons why most automotive companies moved to Li-ion batteries for energy storage in electric vehicles (EVs) and hybrid vehicles (HEVs).

From the battery perspective, 2 models have been developed, to make it possible to simulate and compare the results coming from the utilization of the different batteries.

The first is the Low Voltage (LV) one. The main characteristics are 50.4 V of nominal voltage and 99 Ah of rated capacity, from which it is easy to find out the maximum energy content of 4989.6 Wh.

The second is the High Voltage (HV) one. The main characteristics are 388.8 V of nominal voltage and 13.5 Ah of rated capacity, from which it is easy to find out the maximum energy content of 5248.8 Wh.

To make possible a faster and easier comparison between the characteristics of the batteries, a resume is given in Table 5.1.

	LV	HV
Nominal Voltage [V]	50.8	388.8
Rated Capacity [Ah]	99.0	13.5
Rated Energy [Wh]	4989.6	5248.8

Table 5.1: Batteries characteristics comparison

In this first part of the project, with the short-time model, the main characteristic on which it will be needed to focus is the voltage. This is because the time horizon of this model goes from half a second to a few seconds, due to the computational effort coming from this kind of simulation, that to achieve a good result quality is run with 1 µs time step. The main difference between the two batteries' voltages is that the LV one needs a change in voltage with a ratio of about 1:8, and this amount of voltage difference is not simple to achieve. For the HV case, it is not a problem since its voltage is directly suitable to produce household grid 230V AC.

5.1.5 Inverter and inverter control

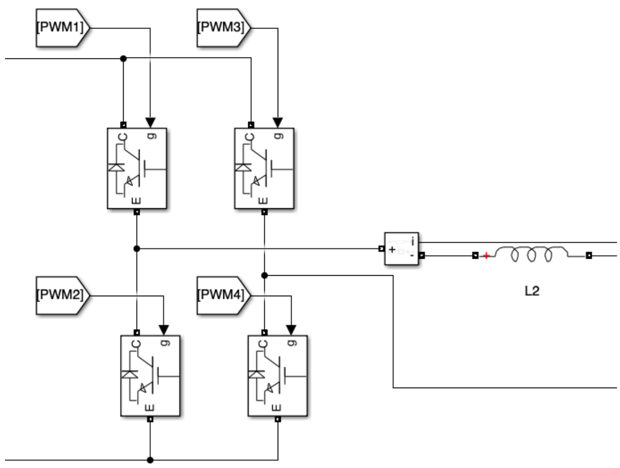

Figure 5.6: Inverter model

An inverter is a power electronic device that can transform Direct Current (DC) into Alternating Current (AC). The modelled one is a particular topology of an

H-bridge inverter called full-bridge inverter. It is composed of 4 diodes and 4 controlled switches, the control strategy of which will be described in the following section. This component is simulated identically in every model, but it will be replaced by 2 different components in the real application based on the model type. When considered as an off-board charger, it will be of the same type as the modelled one. Instead, in the other models, the inverter used to produce AC is the traction inverter of the motorbike, which is a three-phase inverter. In this case, the model is the same as before because it is assumed that one of the three legs is left open to make possible the production of a single-phase AC instead of a three-phase AC. The traction inverter must remain a three-phase one because it is one of the most important traction components, and a modification to the inverter would compromise the whole functionality of the motorbike, needing a redesign of all the traction components. In this case, an inductor has been used in series on the output of the inverter to filter the Pulse Width Modulation (PWM) waveform and produce a smoother, sine wave output. The inductor acts as a low-pass filter, allowing the AC component of the PWM waveform to pass through while blocking the DC component. This results in a more stable output voltage, that is necessary to comply with requisites of the appliances of the household.

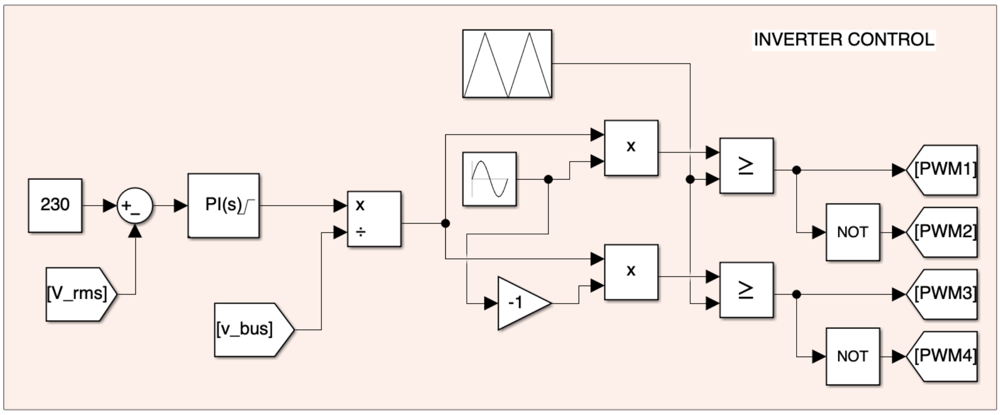

Figure 5.7: Inverter control

An inverter control is strictly related to the function the inverter needs to absolve. So, to proceed it is necessary to define the main requirements that the system must comply with. The AC produced must be 230 V and 50 Hz since all the electrical utilities in a house have been developed and produced to work safely and efficiently at this voltage and frequency. This statement is valid for the greatest part of the world's countries, the application of this system in other countries with different regulations would result in at least a mandatory modification of the inverter's control logic. The inverter control aims to create the 4 PWM signals for the 4 controlled switches, to allow the inverter to work properly and follow the requirements. In the presented case, the control aimed to make the AC follow a sine wave, pulsating at 50 Hz. This is achieved through a PI controller whose KP and KI have been finely tuned. Furthermore, limits on the output have been imposed and the anti-windup method has been used. The limits on the output of the PI controller were thought to limit the maximum voltage output that could be reached, meanwhile, the anti-windup is used to reduce the error given by the integrator, reducing the response delay and the convergence speed to the desired value. Regarding the windup phenomenon, «It happens when the integral term is used with some nonlinear saturation in the loop, such as when a physical variable reach its limit. When that happens, the feedback loop breaks, causing error accumulation in the integrator. This results in worse step and disturbance responses than the case of pure linear system.»[25].

5.1.6 House

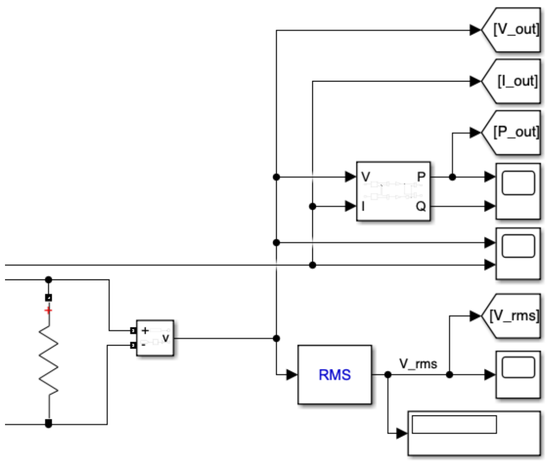

Figure 5.8: House model

In this simplified model, the household load has been modelled as a resistive load. The load can be changed to simulate different values of power consumption coming from the house. Simulations have been performed based on three loads. The first, which describes the full load operation, is an 18 Ohm resistive load. With this resistance, the power absorbed by the load can be simply calculated through the Ohm law $P = V^2/R$, and is around 2939 W, near the 3-kW limit imposed in a major part of houses. Moreover, if the house would be allowed to work at a higher power level, in this case, it will not be allowed to reach that, due to the limited capacity of the battery, that at such higher power demands would not last enough to make meaningful a V2H working mode. The second resistance value is a 180 Ohm load, which provides a power absorption of 293.9 W which can be assumed as a low power request from the household. The condition of no power request is simulated through the third resistance, and it is 1800 Ohm, for which the power request is 29.4 W, a negligible value considering all the appliances that are usually employed at any time in a house.

5.2 Configurations description

As discussed at the beginning of this chapter, not only has a configuration been designed and developed but different layouts have been considered and compared. The architectures that will be compared are three and these are: Off-board charger/discharger, On-board discharger with transformer and On-board discharger with DC/DC converter. Then, every layout has been assessed with LV and HV batteries, leading to a total number of 6 models. The structure of the models will be similar, but the greatest changes will be noticed in the AC production part, while the PV system, battery and load will remain unchanged from a modelling point of view. The charging phase will not be further investigated in this Simulink model, since in all the architectures, the charging phase will rely on the current existing technology. Due to that, in the following sections, only the discharging capability will be presented and investigated. Also, results comparison will be conducted exclusively for the discharging phase, considering that the charging phase and structure will be kept constant.

5.2.1 Off-board charger-discharger

In this configuration, it is simulated that at the current off-board charger will be added also an inverter to allow discharging of the battery. Another solution could surely be the implementation of a proper bidirectional charger, but this would lead to a whole new system and component development, so this will not be considered as an option during this thesis work. As it is possible to see in Figure 5.9, the system is composed of a charger that ensures both charging and discharging capability. This device can be considered a linking point between motorbike battery, household, and PV system.

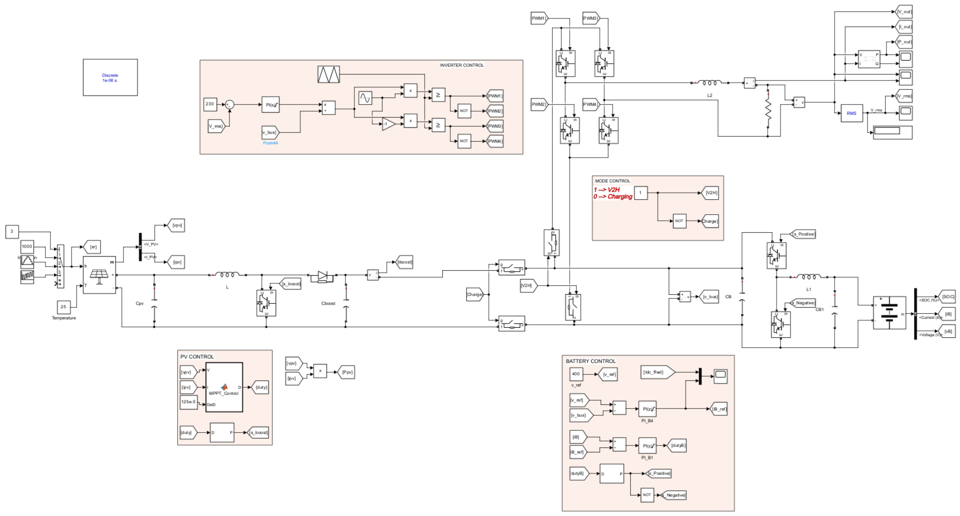

Figure 5.9: V2H model for off-board charger-discharger configuration

5.2.2 On-board discharger

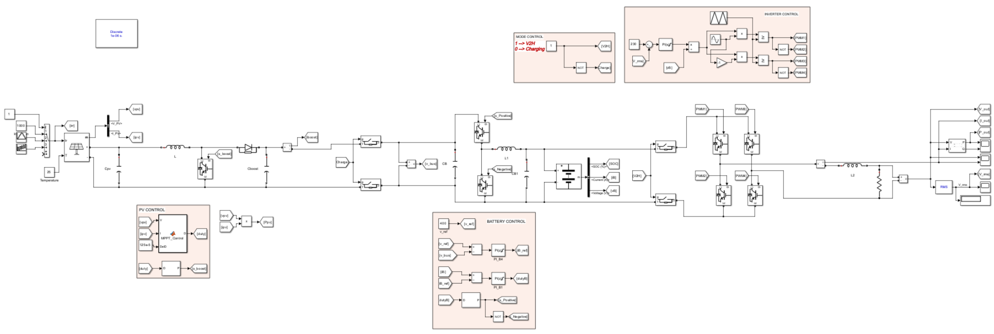

Figure 5.10: V2H model for on-board discharger

As previously stated, this layout uses the on-board traction inverter to produce AC to power the household. The simulations were performed considering the right part of the architecture depicted in Figure 5.10, since the DC bus as it is intended in this model, is not present on a normal motorbike between battery and inverter, so the connection from the motorbike to the outside, is directly in AC. To make it simpler to understand, a brief description of the energy flow is provided here:

the charging phase is performed as usual, with an off-board charger. Instead, the discharging is performed through the traction inverter, which directly outputs the AC. In this case, the output is already of the right voltage, which allows the direct use of the power given by the battery. From a system perspective, this solution presents one main problem, and it is that the cable connecting the charger to the motorbike would be very bulky since it must carry DC during charging and AC during discharging, and these two need to be separated because they need different devices inside the charger and come from different parts of the motorbike. To these, it must also be added all the signal wires that are needed to make a charger and BMS communicate to manage charging and discharging processes, which are mandatory for safety matters.

5.2.3 On-board discharger with transformer

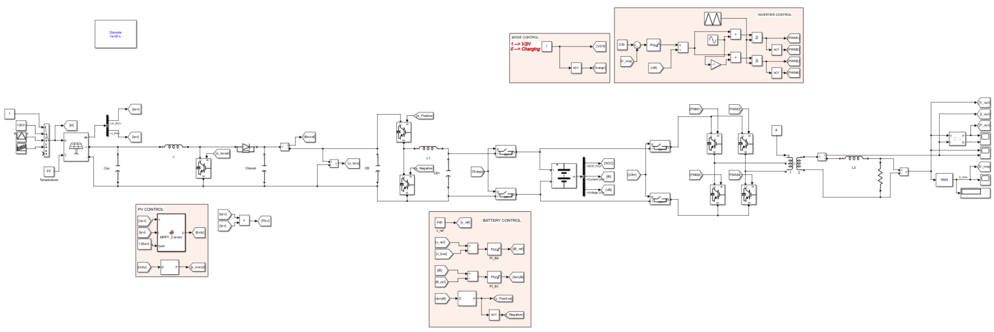

Figure 5.11: V2H model for on-board discharger with transformer

As in the previous layout, this architecture uses the on-board traction inverter to produce AC to power the household. The simulations were performed considering the right part of the architecture depicted in Figure 5.11, since the DC bus as it is intended in this model, is not present on a normal motorbike between battery and inverter, so the connection from the motorbike to the outside, is directly in AC. To make it simpler to understand, a brief description of the energy flow is provided here: the charging phase is performed as usual, with an off-board charger. Instead, the discharging is performed through the traction inverter, which directly outputs the AC. In this case, the output is of a voltage lower than the one needed to power a house, so in this case, a transformer is used after the inverter to raise the voltage to the required one. From a practical point of view, it would be a problem to always carry this extra weight on the motorbike so that the transformer could be put in the charger case. From a system perspective, this solution presents one main problem, and it is that the cable connecting the charger to the motorbike would be very bulky since it must carry DC during charging and AC during discharging, and these two need to be separated because they need different devices inside the charger and come from different parts of the motorbike. To these, it must also be added all the signal wires that are needed to make charger and BMS communicate to manage the charging and discharging processes, which are mandatory for safety manner.

5.2.4 On-board discharger with DC/DC converter

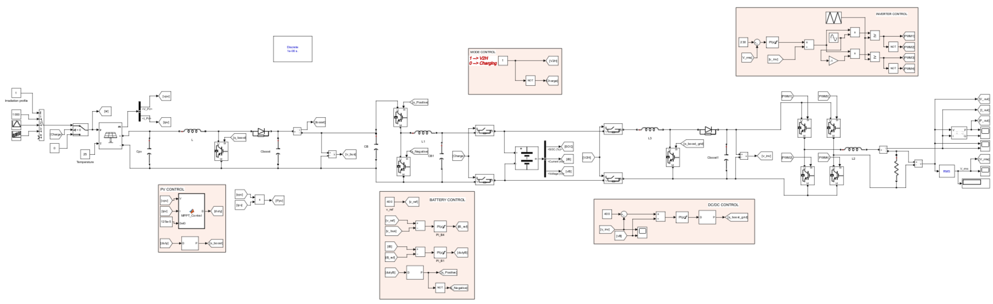

Figure 5.12: V2H model for on-board discharger with DC/DC converter

As stated also in the previous section, this architecture aims at using the on-board traction inverter to produce AC to power the household. The simulations were performed considering the right part of the architecture depicted in Figure 5.12, since the DC bus as it is intended in this model, is not present on a normal motorbike between battery and inverter, so the connection from the motorbike to the outside, is directly in AC. To make it simpler to understand, a brief description of the energy flow is provided here: the charging phase is performed as usual, with an off-board charger. Instead, the discharging is performed through the traction inverter, which directly outputs the AC. In this case, the output is of a voltage lower than the one needed to power a house, so in this case, a DC/DC converter is used between the battery and inverter to raise the voltage to the required one.

From a practical point of view, it would be a problem to carry extra weight on the motorbike every time so that the transformer could be put in the charger case. From a system perspective, this solution presents two main problems, the first is that the cable connecting the charger to the motorbike would be very bulky since it must carry DC during charging and AC during discharging, and these two need to be separated because they need different devices inside the charger and come from different parts of the motorbike. To these, it must also be added all the signal wires that are needed to make the charger and BMS communicate to manage the charging and discharging processes, which are mandatory for safety manner. The second problem is that the DC/DC converter should be an integral part of the motorbike, being an extra weight to carry always when using the bike in normal conditions, and an extra component that would for sure lead to packaging problems, since in a motorbike the number and the dimension of every component must be limited to the minimum possible.

5.3 Results discussion

In this section, the results from the previously introduced models will be presented, the main characteristics will be reported and a brief description and comment will be provided. Different loading conditions have been tested and each of these will be reported.

5.3.1 Off-board charger-discharger - HV battery simulation results

As it is clearly noticeable from Figure 5.13, at full load the system response is good and fast in converging to the target RMS voltage, with a convergence time of 0.15 s. The transient behaviour is good also in the partial load and very low load is good and fast, as it can be observed in Figure 5.14 and in Figure 5.15. A necessary clarification has to be made for the low load voltages and currents. The sine waveform is not clean or visible because the output quality of the PWM inverter is low. Proper tuning of the parameters and of the inverter control could provide better results, but it would have been more time-consuming and the results themselves would not change substantially.

The desired frequency of 50 Hz is achieved in each loading condition.

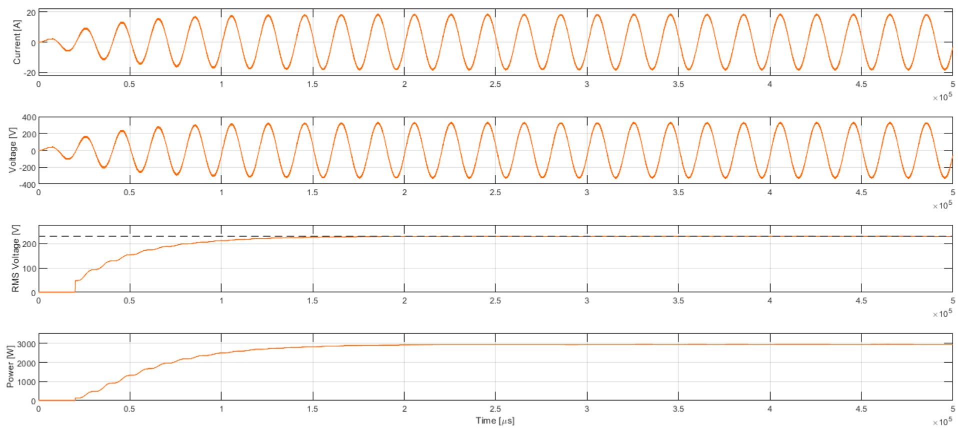

Figure 5.13: Off-board charger-discharger with HV battery - Grid results - 18 Ohm load

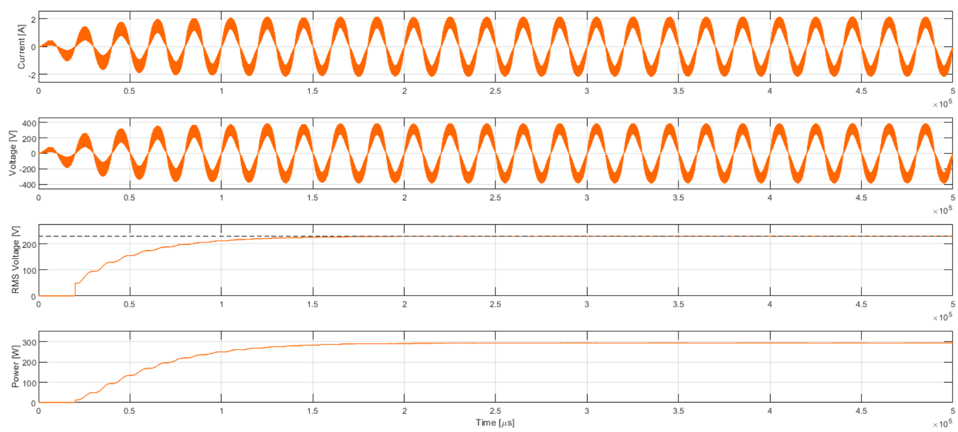

Figure 5.14: Off-board charger-discharger with HV battery - Grid results - 180 Ohm load

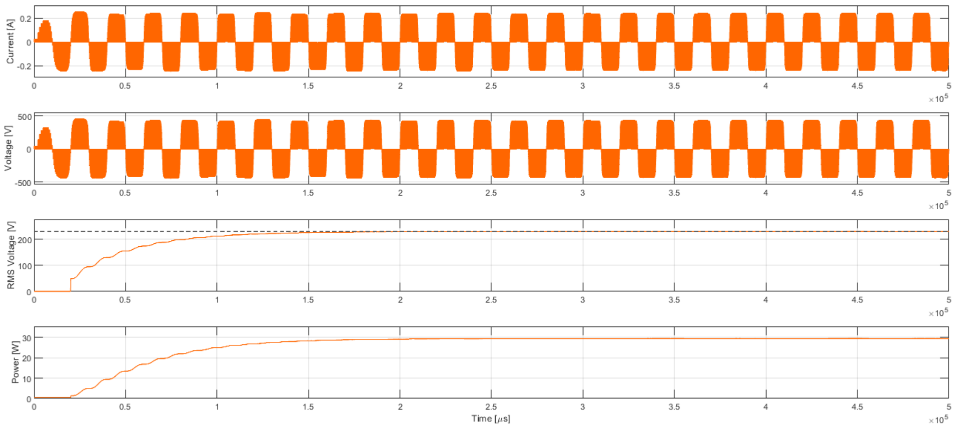

Figure 5.15: Off-board charger-discharger with HV battery - Grid results - 1800 Ohm load

5.3.2 Off-board charger-discharger - LV battery simulation results

The considerations are the same as in the HV case since the inverter is connected to the DC bus, and in this way, being the source the same and properly regulated, the output quality will be very similar to the other one.

As it is possible to notice in Figure 5.16, at full load the system response is good and fast in converging to the target RMS voltage, with a convergence time of 0.15 s. The transient behaviour is good also in the partial load and very low load is good and fast, as it can be observed in Figure 5.17 and in Figure 5.18. A necessary clarification has to be made for the low load voltages and currents. The sine waveform is not clean or visible because the output quality of the PWM inverter is low. Proper tuning of the parameters and of the inverter control could provide better results, but it would have been more time-consuming and the results themselves would not change substantially.

The desired frequency of 50 Hz is achieved in each loading condition.

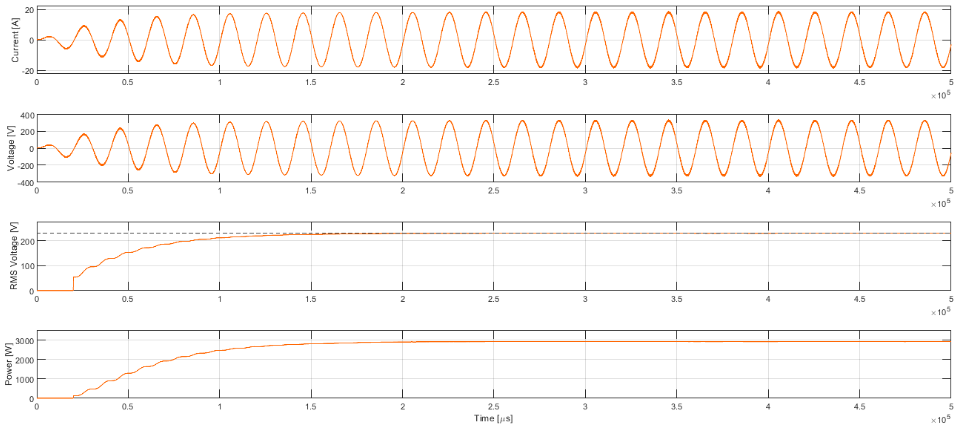

Figure 5.16: Off-board charger-discharger with LV battery - Grid results - 18 Ohm load

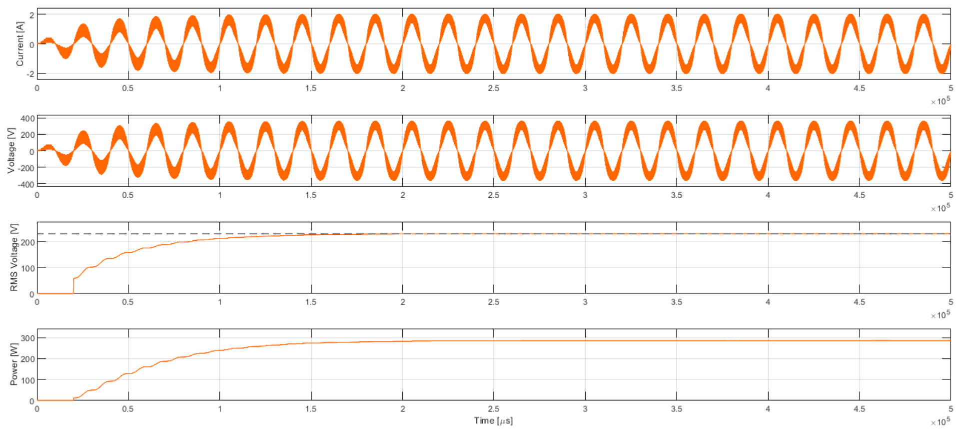

Figure 5.17: Off-board charger-discharger with LV battery - Grid results - 180 Ohm load

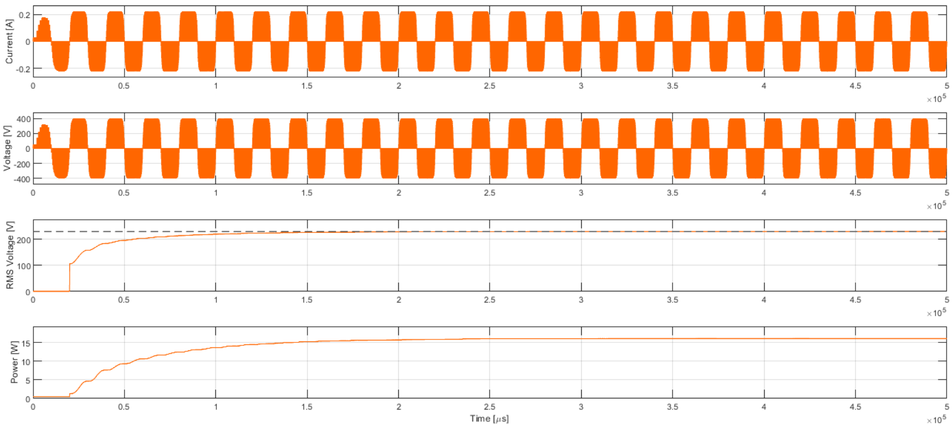

Figure 5.18: Off-board charger-discharger with LV battery - Grid results - 1800 Ohm load

5.3.3 On-board discharger - HV battery simulation results

In Figure 5.19, it is possible to notice that, at full load, the system response is good and fast in converging to the target RMS voltage, with a convergence time of 0.15 s. The transient behaviour is good also in the partial load and very low load is good and fast, as it can be observed in Figure 5.20 and in Figure 5.21. A necessary clarification has to be made for the low load grid voltages and currents. The sine waveform is not clean or visible because the output quality of the PWM inverter is low. Proper tuning of the parameters and of the inverter control could provide better results, but it would have been more time-consuming and the results themselves would not change substantially.

The desired frequency of 50 Hz is achieved in each loading condition.

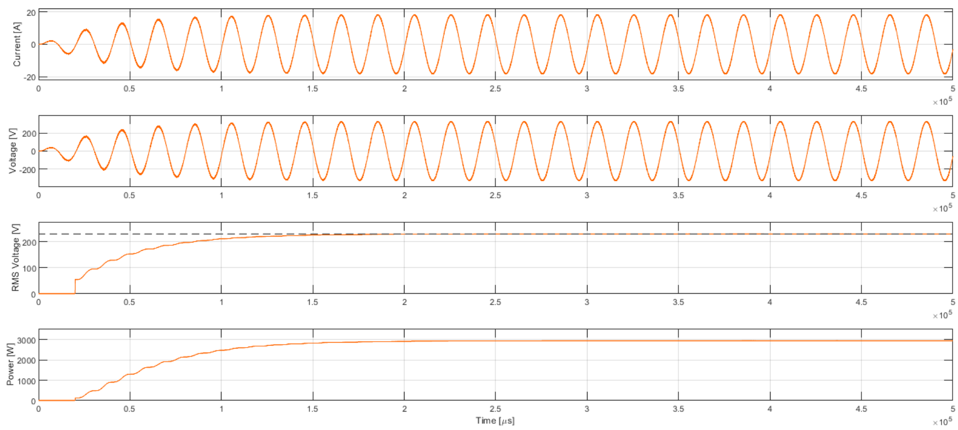

Figure 5.19: On-board discharger with HV battery - Grid results - 18 Ohm load

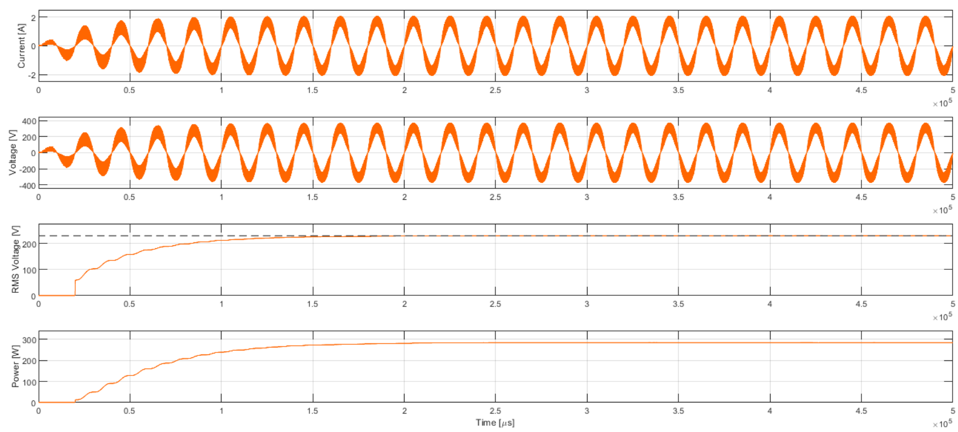

Figure 5.20: On-board discharger with HV battery - Grid results - 180 Ohm load

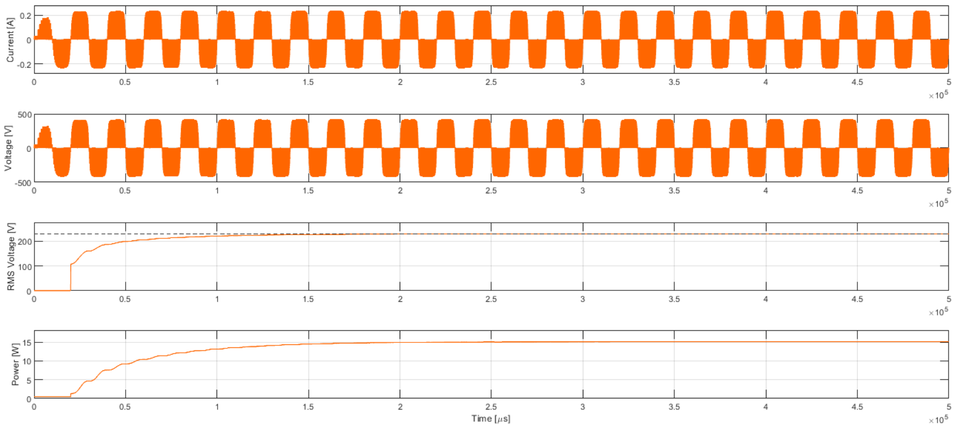

Figure 5.21: On-board discharger with HV battery - Grid results - 1800 Ohm load

5.3.4 On-board discharger with transformer - LV battery simulation results

As it is possible to notice from Figure 5.22, at full load the system response is slow in converging to the target RMS voltage, especially with respect to the other cases, with a convergence time of over 0.3 s. The transient behaviour is similar also in the partial load and very low load, as it can be observed in Figure 5.23 and in Figure 5.24. A necessary clarification has to be made for the low load grid voltages and currents. The sine waveform is not clean or visible because the output quality of the PWM inverter is low. Proper tuning of the parameters and of the inverter control could provide better results, but it would have been more time-consuming and the results themselves would not change substantially.

The desired frequency of 50 Hz is achieved in each loading condition.

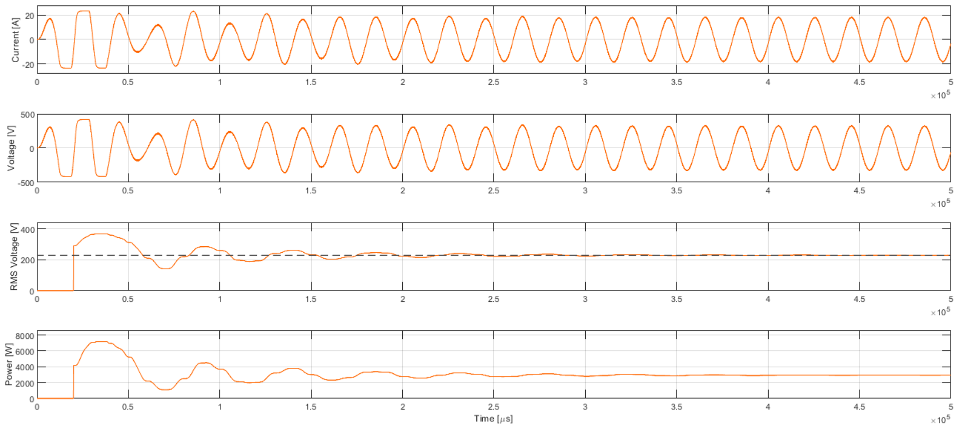

Figure 5.22: On-board discharger with LV battery and transformer - Grid results - 18 Ohm load

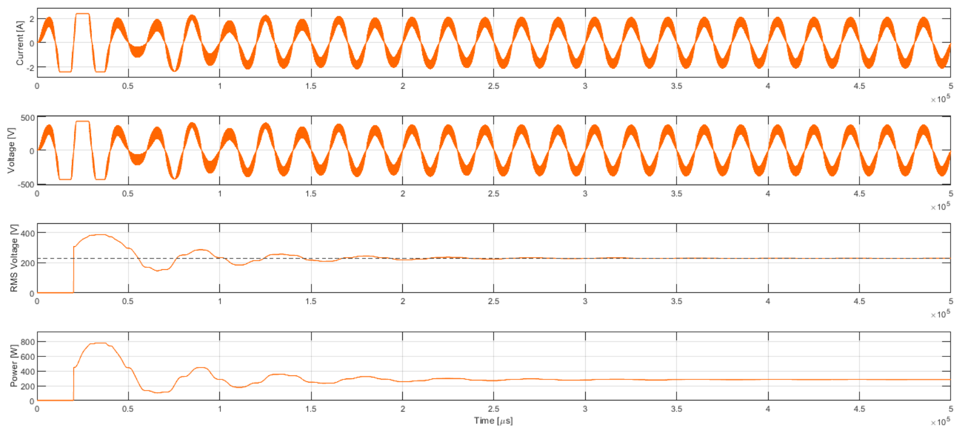

Figure 5.23: On-board discharger with LV battery and transformer - Grid results - 180 Ohm load

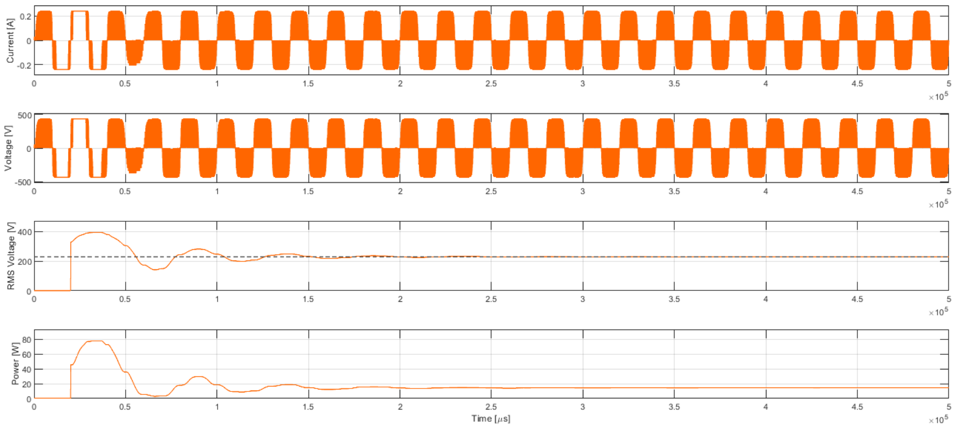

Figure 5.24: On-board discharger with LV battery and transformer - Grid results - 1800 Ohm load

5.3.5 On-board discharger with DC/DC converter - LV battery simulation results

In Figure 5.25, it is possible to notice that, at full load, the system response is the slowest in converging to the target RMS voltage, especially with respect to all previous cases, with a convergence time of over 0.9 s. The transient behaviour is different but always slow also in the partial load and very low load cases, as it can be observed in Figure 5.26 and in Figure 5.27. A necessary clarification has to be made for the low load grid voltages and currents. The sine waveform is not clean or visible because the output quality of the PWM inverter is low. Proper tuning of the parameters and of the inverter control could provide better results, but it would have been more time-consuming and the results themselves would not change substantially.

The desired frequency of 50 Hz is achieved in each loading condition.

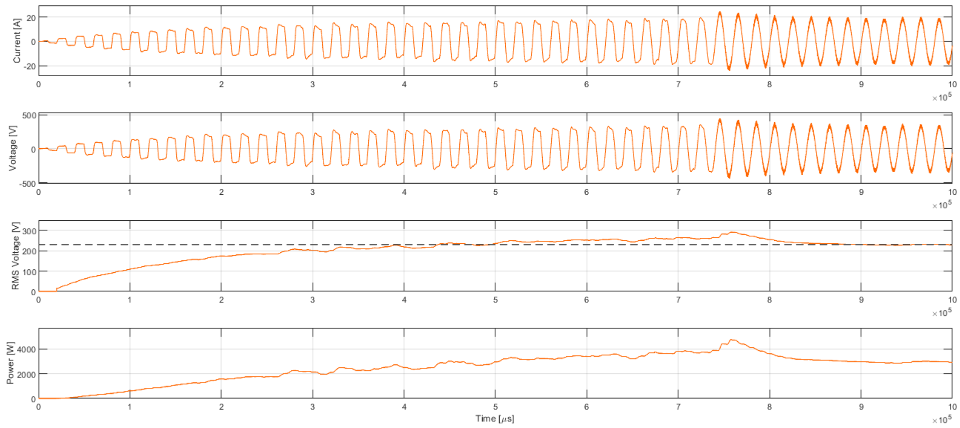

Figure 5.25: On-board discharger with LV battery and DC/DC converter - Grid results - 18 Ohm load

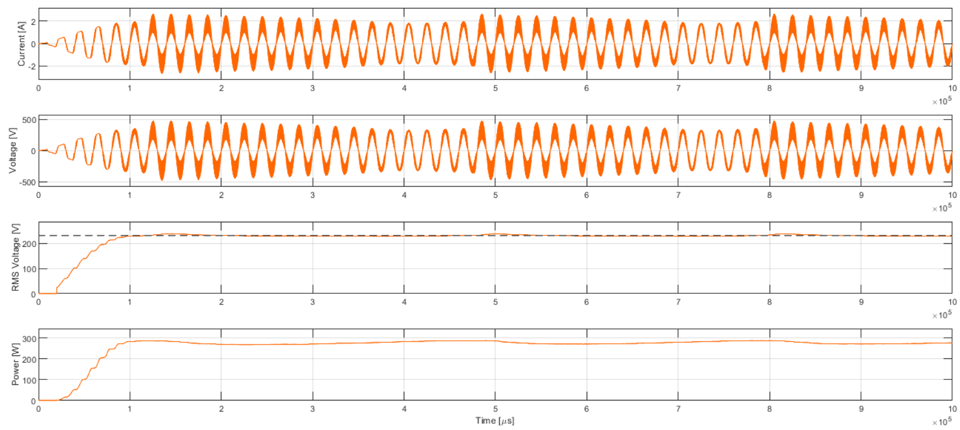

Figure 5.26: On-board discharger with LV battery and DC/DC converter - Grid results - 180 Ohm load

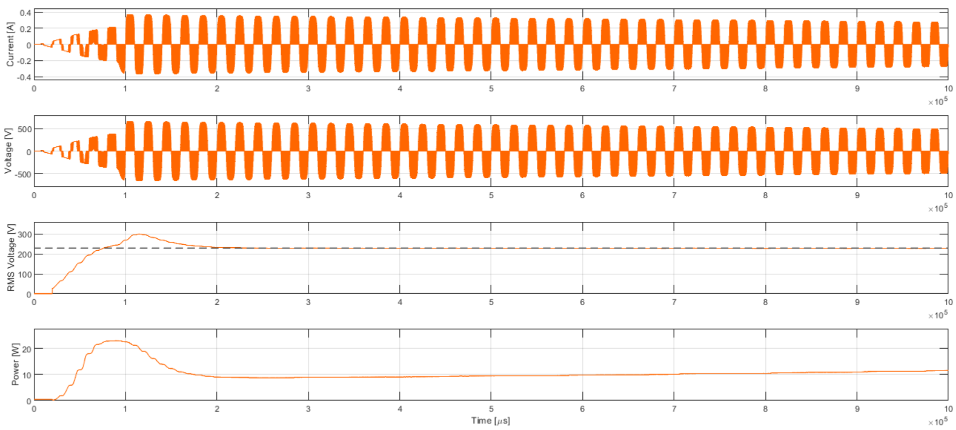

Figure 5.27: On-board discharger with LV battery and DC/DC converter - Grid results - 1800 Ohm load

5.4 Best solution evaluation

From the grid power production quality, the best choices are the Off-board charger-discharger with HV battery, the Off-board charger-discharger with LV battery and the On-board discharger with HV battery. These were the ones providing the better and faster transient response among the others. To make a choice between these three architectures, it has been needed to have a look again from a system perspective since they all performed in a similar way. The feature that has been considered the most, is the difference in components and complexity with respect to the current model on the market. This has been done to reduce the effort in the development of a new system, and the On-board discharger is the architecture that fits the best with these requirements. Both the off-board architectures deeded at least a DC bus at a voltage that is different from the current one, and a DC/DC converter to feed an additional inverter for the AC production. On the other hand, the On-board discharger features components that are already present on the current motorbike.

As it is possible to see from Figure 5.28, Figure 5.29 and Figure 5.30, also the behaviour of the system with respect to the battery is good, only at full load the PWM regulation current ripples reach the battery, but in the other cases of low and very low load the current stabilizes at a constant value.

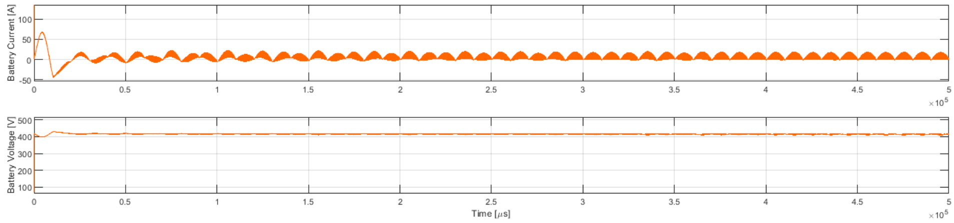

Figure 5.28: On-board discharger with HV battery - Battery results - 18 Ohm load

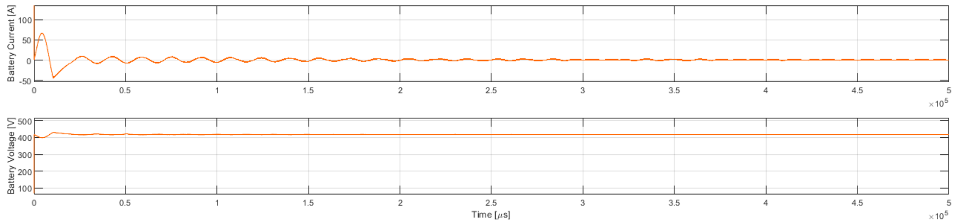

Figure 5.29: On-board discharger with HV battery - Battery results - 180 Ohm load

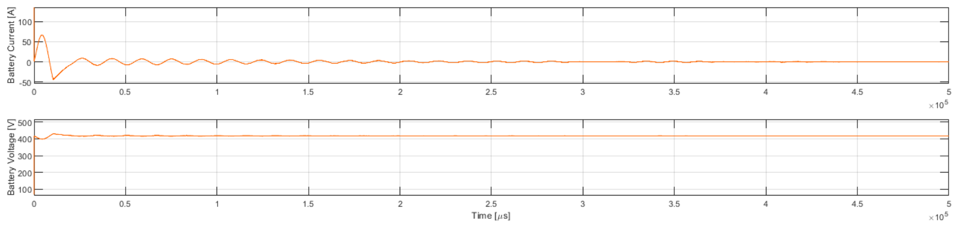

Figure 5.30: On-board discharger with HV battery - Battery results - 1800 Ohm load

5.5 System efficiency definition

In Figure 5.31 the system efficiency is presented and plotted for each analysed load. The efficiency at really low load is between 0.1 and 0.2 and is not stable since the system's control becomes difficult to keep with a power drawn that is less than 30 W. Instead, in the other two cases, in which the power request is 293.9 W for the 180 Ohm load and 2939 W for the 18 Ohm load, the efficiency is more stable and comparable with each other. The overall efficiency of the system is 0.7 at full load and 0.67 for a low load application. As it will be deeply analysed in Chapter 6, the greatest part of the day, the power request from the house is not full load but low load, around 300 W. So, the efficiency that will be adopted for the long-time horizon simulations will be 0.67, the one corresponding with the low load.

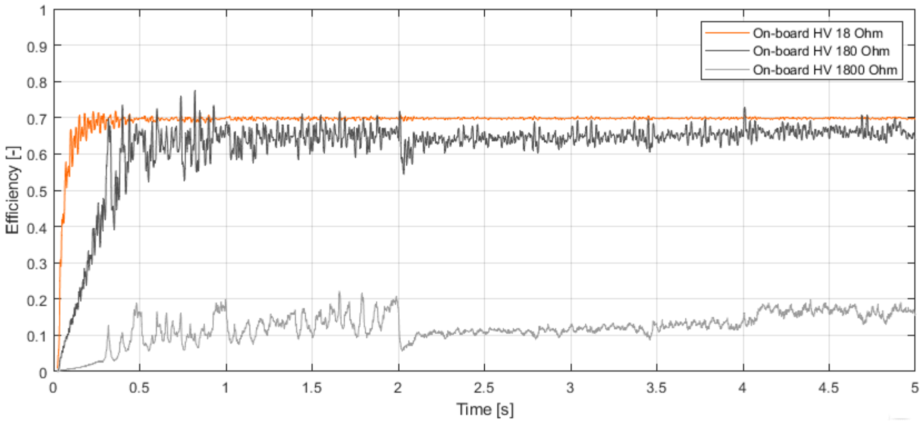

Figure 5.31: On-board discharger with HV battery system efficiency

Chapter 6

Long-time horizon model description

This type of model has a completely different objective with respect to the previous one. This long-time model aims to evaluate in a precise way, the energy transfers that take place in the analyzed system. This model will be again divided into sections, and in this case, these are used to explain where the data comes from and how these have been used to reach the results that will be presented in the last section of this chapter. The main objective is to simulate an entire year of energy transfer, to make observations about charging and discharging cycles, efficient use of the battery depending on the month or season of the year. In this model, the calculations and simulations will be performed by using the HV battery. The reason for that choice is that from the results obtained in the previous chapter, the optimal trade-off has been this one, all the analysis conducted can be found in Chapter 5.

6.1 Model description

This model has been completely developed in Matlab environment, and this allowed for great freedom in choosing every parameter and every run constraint in an easy-to-understand and reliable way. Also, this model started from a subdivision of the two main data needed which were the PV panels' power profile and household load profile. To find these data, several databases were consulted, and in the next sections, the reasons for the choices will be provided. Data have been at first cleared up from the excessive information, and reordered in a chronological way to make it possible to interface them one with the other.

Then the model was built in a nested way, the core is a function that is used to track energy transfer from and to the battery, this is done mainly by updating the SOC of the battery at every iteration and storing it in a vector. This updating process takes place every time the function is called, in this model every minute. Then, the outer layer of the model has the scope of running the function every minute for an entire month. The last step is the one that makes it possible to run every month until the complete year has been processed.

In the following, details about resources and data will be provided and analysis of the results will be performed.

6.1.1 PV panels power profile

To get this kind of data, many databases were consulted, but the most complete and user-friendly has been [26], a tool provided by the European Commission that allows choosing an exact position from the map, the orientation of PV panels, and many other specific parameters, and after that, it gives a `.csv` dataset of global, direct and indirect irradiation, temperature, relative humidity, infrared irradiance, wind speed and pressure in the selected location during the chosen year. Due to the purpose of this project, the data used should be as general as possible, so a setting on the website allows the export of data for a "typical meteorological year" (TMY), that is a set of meteorological data with data values for every hour in a year for a given geographical location. These data are selected from hourly data in a longer period, in this case, the reference data are taken in the time interval 2005-2020. The exported data present a time step of 15 minutes, an acceptable precision for this kind of purpose. In the following, Table 6.1 resumes the reference position and which year months have been considered for the TMY.

These data have been then used in a simple Simulink model constituted by a PV Array which got as input the irradiation and the temperature, giving as output the power converted into electric power. The PV array characteristics have been defined starting from [21] that suggests systems between 2.4 kW and 6.4 kW for houses ranging from 3 to 5 bedrooms, and [22] that classifies as small PV systems typical of residential buildings installations all the systems below 5 kW. That is the reason why the system has been designed to have a power level in the range of 4-5 kW, in this case, the plant is composed of 20 modules (2 parallel strings and 10 series-connected modules per string) with a maximum power conversion of 213.15 W each for a total of 4263 W.

Through this simple model, new fundamental data has been obtained, and it is the power coming from solar irradiation conversion by PV panels.

Latitude (decimal degrees): 48.103	
Longitude (decimal degrees): 13.150	
Elevation (m): 459.0	
month	year
1	2014
2	2018
3	2014
4	2009
5	2009
6	2008
7	2020
8	2008
9	2020
10	2020
11	2011
12	2014

Table 6.1: Solar irradiation data

6.1.2 Household load profile

These data have also been taken from [27], an online open-source database. It allows to export of data in different formats and with different time steps, so it was decided to get these with a high-precision time step of only one minute. This kind of possibility has been of relevant importance because it is not difficult to forecast that a battery with an energy content of around 5 kWh, will not be able to supply a household for many hours, so to describe better the energy transfer process during charging and discharging, it has been useful to have a short time step concerning the whole simulation time. For this aim, a power request of 3 kW has been considered as the maximum limit above which the system should shut down or at least saturate.

In Figure 6.1 it is possible to have a first impression of which is the household net load over a week, represented in blue. In orange, it is possible to have a look at how much of the load is supplied by the battery and how much of the excess power is used to charge the battery. As described in Chapter 5, the power drawn from the battery is in the neighbourhood of 300 W, a power level threshold that is represented with the dashed line.

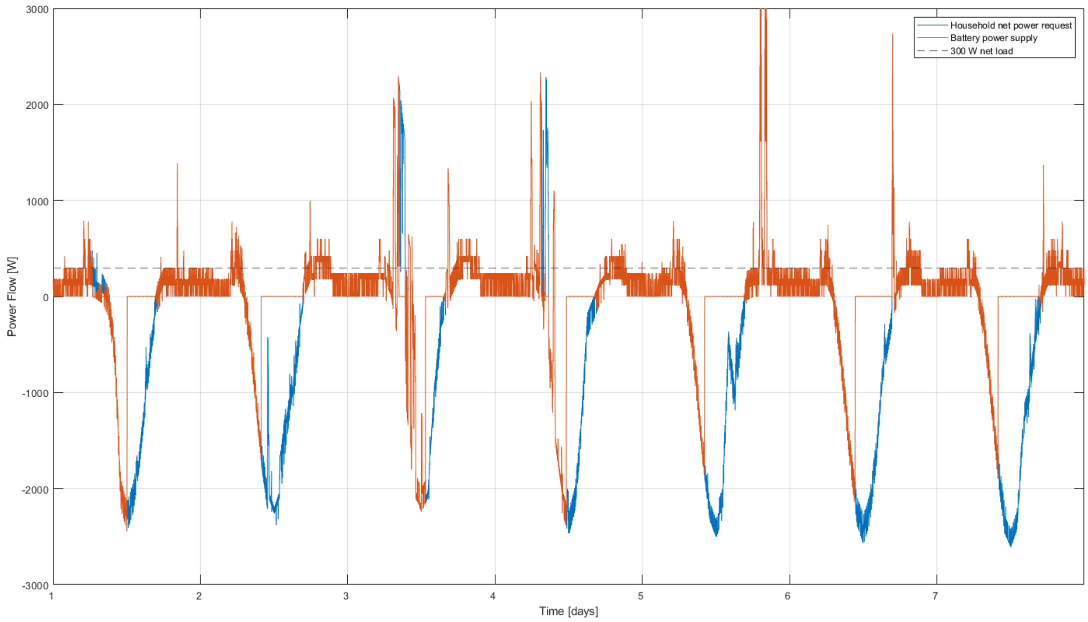

Figure 6.1: Week load example (first week of April)

6.2 Results discussion

The developed model worked and reached the targets that were fixed, running the simulation of an entire year with a time step precision of 1 minute. For the sake of simplicity, the results have been divided per month, assuring a clearer and easier observation of the graphs and a simpler comparison between months of different seasons.

In Figure 6.2 and Figure 6.3, the months of January and July will be compared, and interesting differences can be noticed.

In the month of January, the battery SOC keeps still at the imposed minimum of 0.2, with little charging phases followed by an immediate discharge. This can be attributed to the fact that the PV panels produce low power during winter, and this power can be used to supply the house partially, but almost never excess energy will be produced so the battery charge thanks to the PV panels will be a rare event. Also, if the battery is set with SOC of 0.5 at the beginning of the month the energy will be depleted in a short time.

Instead, the month of July shows a considerably different system behaviour. During this month of use, the battery undergoes regular charge-discharge cycles daily. It is possible to notice that for a major part of the days, the battery saturates at

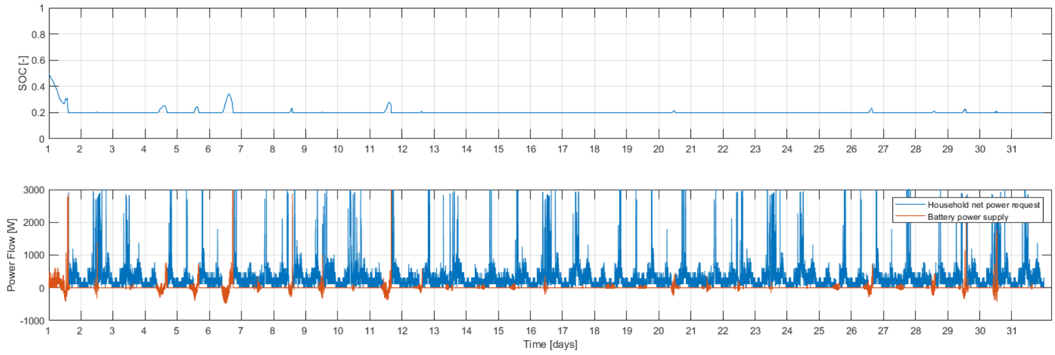

Figure 6.2: Long-time horizon model results - January

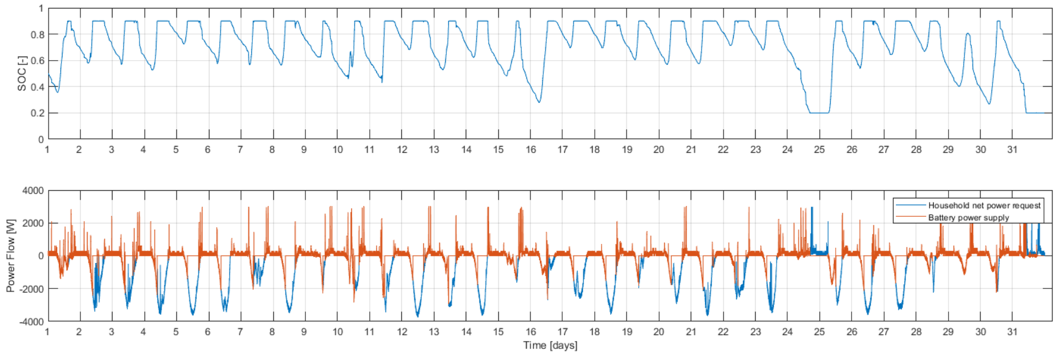

Figure 6.3: Long-time horizon model results - July

the maximum imposed SOC, and usually does not even reach the minimum SOC level of 0.2. From this result it is possible to conclude that in months like this, the house could be powered entirely by PV panels and battery, making also possible an islanding application, detaching completely the house from the public grid.

Furthermore, another simulation has been performed. Due to the low energy capacity of the motorbike battery with respect to the usual vehicles' batteries adopted for V2H operation, the low system effectiveness during winter months could be assessed to the low energy storage capacity. so, a new use case has been adopted, assuming a family in which two motorbikes are held and connected. That's why the results depicted in Figure 6.4 and Figure 6.5 show the system behaviour assuming that two motorbikes are connected, doubling the energy storage capability with respect to the original system.

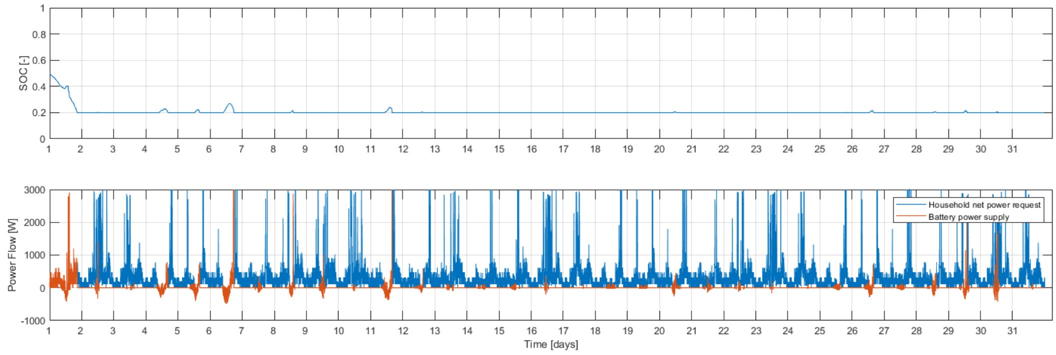

Figure 6.4: Long-time horizon model results with 2 motorbikes - January

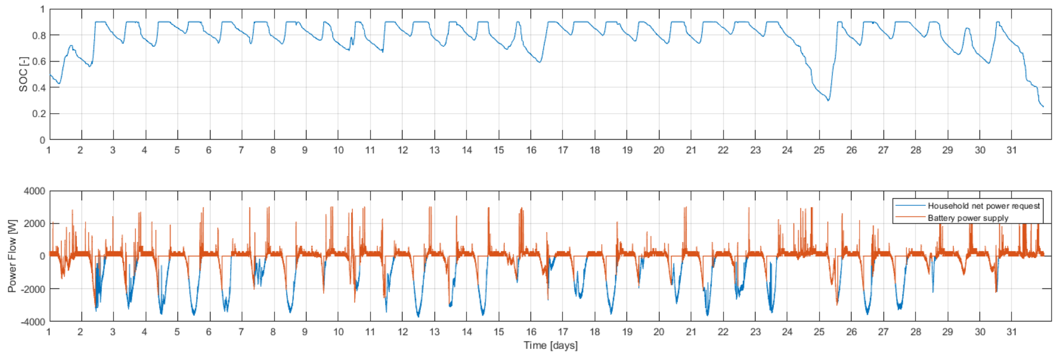

Figure 6.5: Long-time horizon model results with 2 motorbikes - July

The system behaviour during the month of January is nearly the same as before since the net household power request almost never allows charging the battery. While the greatest difference can be found in the month of July, having a mean SOC higher than the single motorbike case, and a backup time capability way longer, never reaching the minimum imposed SOC, as can be noticed on days 24 and 31. This would also have a beneficial effect since as stated by [28], a higher mean SOC would reduce battery ageing effects.

Anyway, the overall effect of the system is not so different from one to two motorbikes. Figure 6.6 shows the yearly energy contribution in kWh of the system, with one or two motorbikes connected. The improvement is 12.48%, passing from 512.922 kWh to 576.941 kWh. These are surely important numbers, but not as much as expected, due to the fact that the main issue is the excess energy coming from PV panels, which during winter months is not enough to charge the batteries.

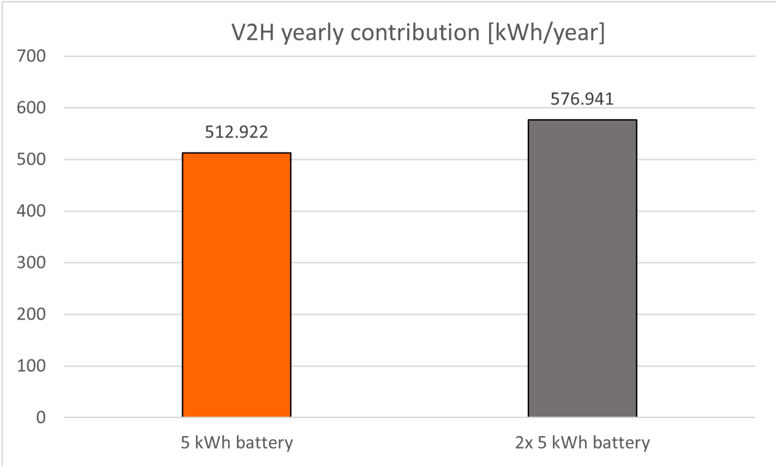

Figure 6.6: V2H yearly contribution depending on energy capacity

To translate overall energy savings into monetary savings for the customers, European energy price statistics [29] updated at the first half of 2022, have been consulted. The average European energy price is represented and then also the price for three specific countries. Austria, since all data used in this project are referred to Austria, Italy and Denmark, the country with the highest energy price in Europe, which leads to the highest monetary savings. Danish data were found already converted in euros from the source.

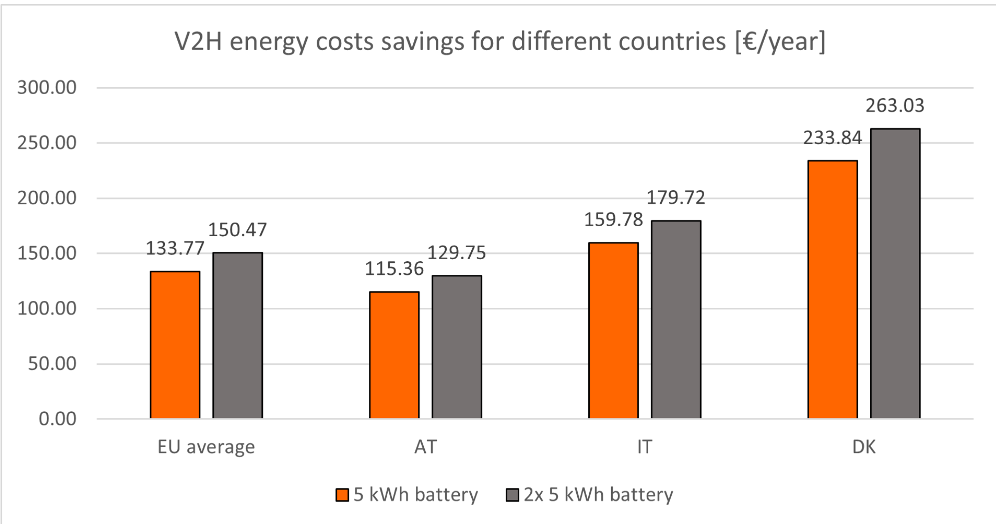

Figure 6.7: V2H yearly energy cost savings depending on country

It is possible to find out that, as already observed concerning Figure 6.6, the economic savings do not differ so much from one motorbike to two motorbikes. The relevant data, instead, are the economic savings coming from the system in general. While from a single motorbike, the average European cost savings are 133.77 €, not an impressive amount of money, for a Danish customer the cost savings rise to 233.84 €, and this yearly amount of money could be attractive for many different customers.

In the end, these results show really promising capability as a battery backup or buffer system, but it must be remembered that the system that has been created, includes a motorbike. It is logical to assume that the summer months are the ones with the larger use of a motorbike, and this may lead to a drop in the effectiveness of this system. Obviously, this situation could be managed to minimize the negative effects described above, but without going on with a deep study and understanding of owners' habits, an estimation could be provided. Considering the utilization of the motorbike during the weekend, so during 2 of the 7 days of the week, the results change as displayed in Figure 6.8. The difference between the two conditions is not negligible, and this kind of study and analysis should be tailor-made for every motorcycle owner because the utilization mode concerning different people from different geographical areas could be completely different one from the other.

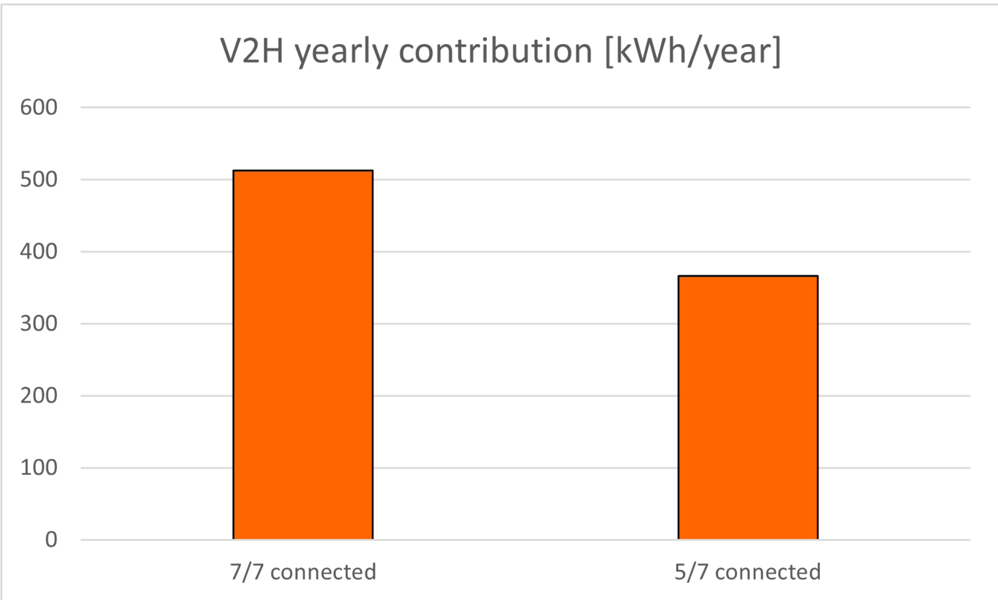

Figure 6.8: V2H yearly contribution depending on connection time

It is possible to make a last observation on the V2H yearly contribution based on the PV panels' power. In this way, it is possible to notice if the PV panels' power production is actually a limiting factor for the system's functionality. As it is possible to evince from Figure 6.9, the problem cannot be completely addressed to the PV panels' power, in fact, after the 3 kW point, there is a noticeable change in slope in the trend line regarding the contribution of V2H in a year, so also doubling the PV power will not produce great effect on the results.

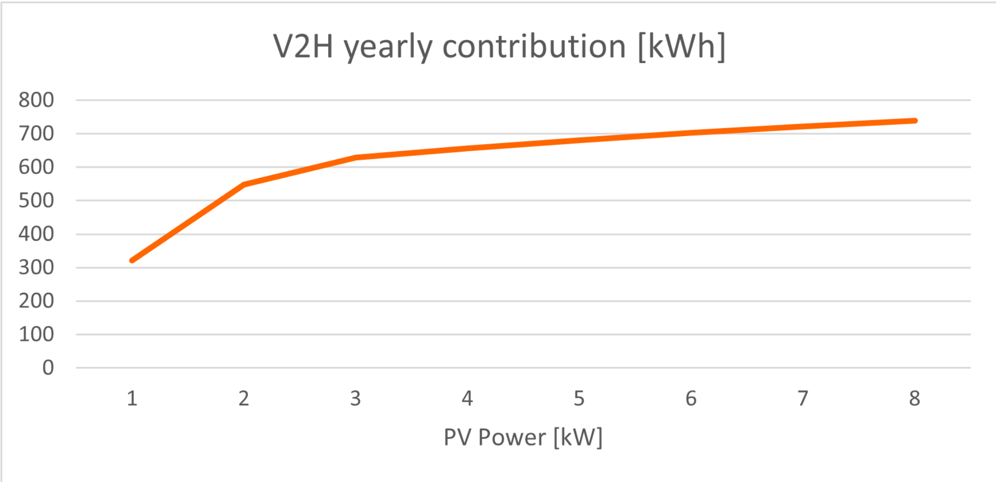

Figure 6.9: V2H yearly contribution depending on PV panels power

This is another confirmation that the power of 4263 W that has been considered for the system is slightly higher but consistent with our purpose and with the considered household load and meteorological conditions, and in this way, neither the battery capacity nor the PV panels power can be considered as the bottleneck of the system.
In Chapter 7 the conclusions based on the presented results will be drawn.

Chapter 7

Conclusions and Future Developments

7.1 Conclusions

With this thesis project, KTM aimed at assessing the feasibility of the implementation of V2H technology in the two-wheeler market. The conducted study has been the first unavoidable step for a future proper proof of concept for this ambitious project.

The aim of this work was to go through a first analysis at the system level of the vehicle architecture and component layout, and the different compared solutions showed distinct results that allowed for a conscious choice for what regards the vehicle layout that needs to be adopted to assure the best overall results.

For what concerns the work conducted, a conclusion can be drawn from each of the two parts in which the project is divided. Regarding the physical model depicted in Chapter 5, five different configurations have been set up and analyzed, leading to the result that the configurations deploying an LV battery have been more difficult to control and slower in the response due to the large voltage step needed from battery voltage to grid voltage. Among the two HV battery solutions, it was decided to adopt the one deploying the traction inverter thanks to the lower complexity of the system and the consequent higher reliability and lower cost. Instead, regarding the long-time horizon model depicted in Chapter 6, basing on the results of the physical model, that architecture's efficiency has been taken as the starting point for the calculation and analysis of the energy transfers of the motorbike battery during an entire year. The final conclusions are strictly dependent on the user habits and highly subjective, but from a project perspective, the overall trade-off is positive since the customer can save on energy costs without great changes in motorbike architecture and components.

Due to time constraints, it has not been possible to perform testing and validation during the internship duration, and due to that, the analysis focused also on the complete system energy balance, to make consideration on energy savings that could be reached thanks to the V2H capability from a customer perspective.

7.2 Future Developments

The future steps of the project will lead to the final objective to realize a complete working system able to reproduce as well as possible the results reported in this thesis.

As a first step, a component-level analysis of the entire system should be performed, with a test bench setup made possible through rapid prototyping devices for power electronics to test single components' behaviour under all the possible working conditions. This would lead to a first validation of the model, allowing for a critical analysis of the current results.

During this phase, it is possible to face various problems, and that's why this phase is so important because these errors and incongruities could be solved before the proper physical realization of the system.

After that, the last step would be a physical mock-up of the complete system, to test and validate the real behaviour of the system which in this case would be composed of real components, removing the uncertainty coming from the simulation of power electronic components.

Further related studies could consist of an analysis focused on battery ageing under the working conditions analyzed in this work, and a proper social-economical analysis could also be performed to allow a more conscious development, knowing which would be the appreciation of such an innovative product on the European and global markets.

Bibliography

[1] *gridX – Vehicle-to-Grid (V2G) and Vehicle-to-Home (V2H) – Challenges and applications*. en. URL: https://www.gridx.ai/blog/how-v2g-v2h-reach-scale (visited on 11/13/2023) (cit. on p. 2).

[2] Liu Chunhua, K.T. Chau, Diyun Wu, and Shuang Gao. «Opportunities and Challenges of Vehicle-to-Home, Vehicle-to-Vehicle, and Vehicle-to-Grid Technologies». In: *Proceedings of the IEEE* 101 (Nov. 2013), pp. 2409–2427. DOI: 10.1109/JPROC.2013.2271951 (cit. on pp. 5–7).

[3] Bassam Zafar and Sami Abdullah Ben Slama. «PV-EV integrated home energy management using vehicle-to-home (V2H) technology and household occupant behaviors». en. In: *Energy Strategy Reviews* 44 (Nov. 2022), p. 101001. ISSN: 2211-467X. DOI: 10.1016/j.esr.2022.101001. URL: https://www.sciencedirect.com/science/article/pii/S2211467X2200195X (visited on 06/02/2023) (cit. on p. 6).

[4] Yubo Wang, Omar Sheikh, Boyang Hu, Chi-Cheng Chu, and Rajit Gadh. «Integration of V2H/V2G hybrid system for demand response in distribution network». en. In: *2014 IEEE International Conference on Smart Grid Communications (SmartGridComm)*. Venice, Italy: IEEE, Nov. 2014, pp. 812–817. ISBN: 978-1-4799-4934-2. DOI: 10.1109/SmartGridComm.2014.7007748. URL: http://ieeexplore.ieee.org/document/7007748/ (visited on 06/01/2023) (cit. on pp. 6, 7).

[5] *A smart algorithm to optimally manage the charging strategy of the Home to Vehicle (H2V) and Vehicle to Home (V2H) technologies in an off-grid home powered by renewable sources*. en. June 2022. DOI: 10.21203/rs.3.rs-1685933/v1. URL: https://www.researchsquare.com (visited on 06/01/2023) (cit. on p. 7).

[6] Carlo Villante, Stefano Ranieri, Francesco Duronio, Angelo De Vita, and Michele Anatone. «An Energy-Based Assessment of Expected Benefits for V2H Charging Systems through a Dedicated Dynamic Simulation and Optimization Tool». en. In: *World Electric Vehicle Journal* 13.6 (June 2022). Number: 6

Publisher: Multidisciplinary Digital Publishing Institute, p. 99. ISSN: 2032-6653. DOI: 10.3390/wevj13060099. URL: https://www.mdpi.com/2032-6653/13/6/99 (visited on 06/13/2023) (cit. on p. 7).

[7] Ardavan Dargahi, Stéphane Ploix, Alireza Soroudi, and Frédéric Wurtz. «Optimal household energy management using V2H flexibilities». en. In: *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering* 33.3 (Apr. 2014). Ed. by Professor Luc Dupré And Dr Guillaume Crevecoeur, pp. 777–792. ISSN: 0332-1649. DOI: 10.1108/COMPEL-10-2012-0223. URL: https://www.emerald.com/insight/content/doi/10.1108/COMPEL-10-2012-0223/full/html (visited on 06/01/2023) (cit. on p. 7).

[8] Ryosuke Kataoka, Akira Shichi, Hiroyuki Yamada, Yumiko Iwafune, and Kazuhiko Ogimoto. «Comparison of the Economic and Environmental Performance of V2H and Residential Stationary Battery: Development of a Multi-Objective Optimization Method for Homes of EV Owners». en. In: *World Electric Vehicle Journal* 10.4 (Dec. 2019). Number: 4 Publisher: Multidisciplinary Digital Publishing Institute, p. 78. ISSN: 2032-6653. DOI: 10.3390/wevj10040078. URL: https://www.mdpi.com/2032-6653/10/4/78 (visited on 06/13/2023) (cit. on p. 7).

[9] Hunyoung Shin and Ross Baldick. «Plug-In Electric Vehicle to Home (V2H) Operation Under a Grid Outage». en. In: *IEEE Transactions on Smart Grid* 8.4 (July 2017), pp. 2032–2041. ISSN: 1949-3053, 1949-3061. DOI: 10.1109/TSG.2016.2603502. URL: http://ieeexplore.ieee.org/document/7553513/ (visited on 06/02/2023) (cit. on p. 7).

[10] Rishabh Ghotge, Ad Van Wijk, and Zofia Lukszo. «Challenges for the design of a Vehicle-to-Grid Living Lab». en. In: *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*. Bucharest, Romania: IEEE, Sept. 2019, pp. 1–5. ISBN: 978-1-5386-8218-0. DOI: 10.1109/ISGTEurope.2019.8905503. URL: https://ieeexplore.ieee.org/document/8905503/ (visited on 05/31/2023) (cit. on p. 8).

[11] Bhagat S, Archana C, Virendra Talele, Khade K, Budukh A, Bhosale A, and Mathew Vk. «Simulation of Li-ion Battery using MATLAB-Simulink for Charging and Discharging». en. In: *E3S Web of Conferences* 353 (2022). Ed. by R. Absi and I. El Abbassi, p. 03001. ISSN: 2267-1242. DOI: 10.1051/e3sconf/202235303001. URL: https://www.e3s-conferences.org/10.1051/e3sconf/202235303001 (visited on 06/07/2023) (cit. on p. 9).

[12] Alan Millner. «Modeling Lithium Ion battery degradation in electric vehicles». In: Oct. 2010, pp. 349–356. DOI: 10.1109/CITRES.2010.5619782 (cit. on p. 10).

[13] Olof Juhlin. «Modeling of Battery Degradation in Electrified Vehicles». en. In: () (cit. on p. 10).

[14] Pragya Gawhade and Amit Ojha. «Recent advances in synchronization techniques for grid-tied PV system: A review». In: *Energy Reports* 7 (Nov. 2021), pp. 6581–6599. ISSN: 2352-4847. DOI: 10.1016/j.egyr.2021.09.006. URL: https://www.sciencedirect.com/science/article/pii/S2352484721008118 (visited on 10/23/2023) (cit. on pp. 17–19).

[15] Wally E. Rippel. «Integrated traction inverter and battery charger apparatus». US4920475A. Apr. 1990. URL: https://patents.google.com/patent/US4920475A/en (visited on 07/10/2023) (cit. on p. 18).

[16] *Integrated On-Board Charger-Traction Systems*. en. URL: https://encyclopedia.pub/entry/26147 (visited on 07/10/2023) (cit. on p. 18).

[17] Mohamed Metwly, Mahmoud Abdel-majeed, Ayman Abdel-Khalik, Ragi Hamdy, Mostafa Hamad, and Shehab Ahmed. «A Review of Integrated On-Board EV Battery Chargers: Advanced Topologies, Recent Developments and Optimal Selection of FSCW Slot/Pole Combination». In: *IEEE Access* PP (May 2020), pp. 1–1. DOI: 10.1109/ACCESS.2020.2992741 (cit. on p. 19).

[18] Caroline Ann Sam and V Jegathesan. «Bidirectional integrated on-board chargers for electric vehicles—a review». en. In: *Sādhanā* 46.1 (Dec. 2021), p. 26. ISSN: 0256-2499, 0973-7677. DOI: 10.1007/s12046-020-01556-2. URL: http://link.springer.com/10.1007/s12046-020-01556-2 (visited on 07/13/2023) (cit. on p. 19).

[19] G. Pellegrino, E. Armando, and P. Guglielmi. «An Integral Battery Charger With Power Factor Correction for Electric Scooter». In: *IEEE Transactions on Power Electronics* 25.3 (Mar. 2010), pp. 751–759. ISSN: 0885-8993, 1941-0107. DOI: 10.1109/TPEL.2009.2033187. URL: http://ieeexplore.ieee.org/document/5272097/ (visited on 07/10/2023) (cit. on p. 19).

[20] *what is DC bus?* URL: https://www.otomasyonavm.com/en/what-is-dc-bus (visited on 10/12/2023) (cit. on p. 22).

[21] *How Many Solar Panels Do I Need in the UK? | GreenMatch*. en-GB. URL: https://www.greenmatch.co.uk/blog/how-many-solar-panels-do-i-need (visited on 10/12/2023) (cit. on pp. 23, 47).

[22] Anonymous Anonymous. «EXISTING AND FUTURE PV PROSUMER CONCEPTS». en. In: () (cit. on pp. 23, 47).

[23] Amit Podder, Naruttam Roy, and Hemanshu Pota. «MPPT Methods for Solar PV Systems: A Critical Review Based on Tracking Nature». In: *IET Renewable Power Generation* 13 (May 2019). DOI: 10.1049/iet-rpg.2018.5946 (cit. on p. 23).

[24] *Lithium-Ion Battery - Clean Energy Institute*. URL: https://www.cei.washington.edu/research/energy-storage/lithium-ion-battery/ (visited on 10/12/2023) (cit. on p. 25).

[25] *PID Anti-Windup Schemes | Scilab*. URL: https://www.scilab.org/pid-anti-windup-schemes (visited on 10/17/2023) (cit. on p. 28).

[26] *JRC Photovoltaic Geographical Information System (PVGIS) - European Commission*. URL: https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP (visited on 10/25/2023) (cit. on p. 47).

[27] *Data Platform – Open Power System Data*. URL: https://data.open-power-system-data.org/household_data/ (visited on 10/25/2023) (cit. on p. 48).

[28] *BU-808: How to Prolong Lithium-based Batteries*. en. Sept. 2010. URL: https://batteryuniversity.com/article/bu-808-how-to-prolong-lithium-based-batteries (visited on 11/10/2023) (cit. on p. 51).

[29] *Electricity price statistics*. en. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics (visited on 10/24/2023) (cit. on p. 52).