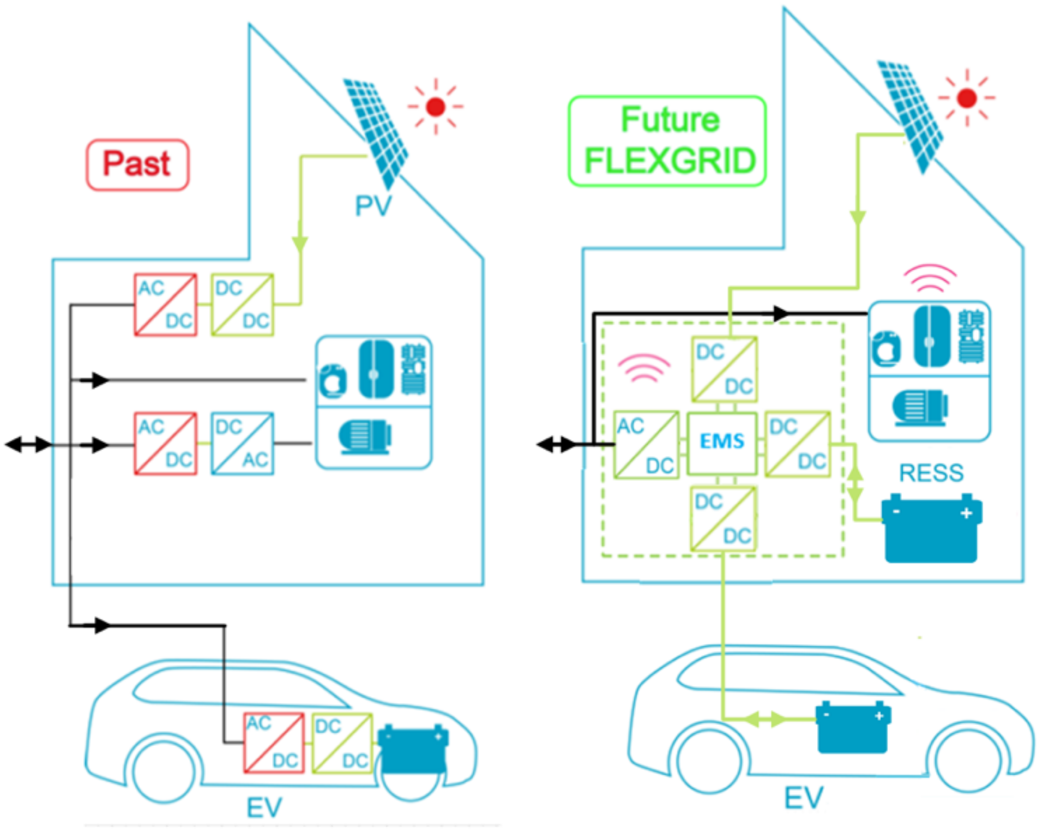
Report: FLEXgrid project



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Report Written by:
Prof. Dr. P. (Pavol) Bauer, Full professor
Dr. G.R. (Gautham Ram) Chandra Mouli, Assistant Professor (Electric Mobility)
Ir. W. (Wiljan) Vermeer, PhD researcher

Delft University of Technology / TU Delft
DC systems, Energy conversion & Storage group
Dept. of Electrical Sustainable Energy
Faculty of Electrical Engineering, Mathematics and Computer Science
Mekelweg 4, 2628 CD, Delft, The Netherlands
E G.R.ChandraMouli@tudelft.nl
E P.Bauer@tudelft.nl
W http://www.dcs.ewi.tudelft.nl/

A. Project details

- Project number: 1621403
- Project title: Enabling Flexibility of Distribution Networks Using Residential Energy Storage, Electric Vehicles & Demand Response
- Coordinator and participants: TU Delft (coordinator), Alfen, Stedin, PRE
- Project period: 15 Sept 2018 - 15 Sept 2022

B. Introduction & Summary

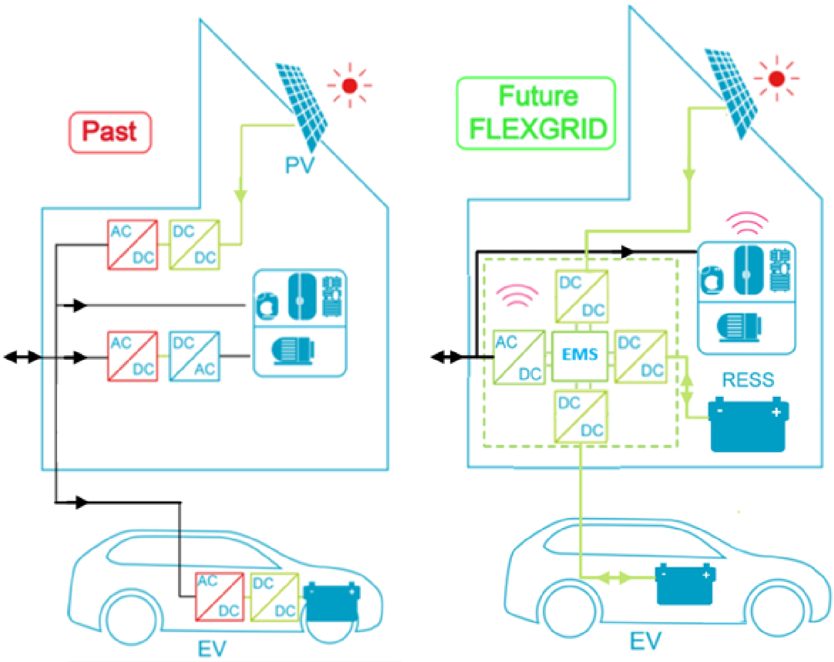

Figure 1: Schematic representation of: (left) a conventional AC integrated EV-PV charging system, and (right) the proposed FLEXgrid system: integrating EV charging, BS charging and PV, all on one DC-integrated converter.

In recent years, the amount of renewable energy, such as wind and solar energy, has grown rapidly in the distribution networks. In the future, the use of electric vehicles and the use of stationary energy storage is expected to increase dramatically. At present, the infrastructure of the distribution network does not have sufficient flexibility to cope with the relatively large increase in the demand for energy. In practice, the lack of flexibility creates a range of technical problems, including congestion management, frequency control, local under- or overvoltage and increased peak load. To solve these problems, it is required to develop an integrated sustainable modular system at the local level that uses advanced charging algorithms.

TKI FLEXGRID is a multidisciplinary project that aims to exploit the flexibility of distribution networks through a new modular system for the efficient integration of battery storage (BS), photovoltaic generation (PV) together with smart charging strategies for electric vehicles with vehicle-to-grid (V2G).

This modular system was developed with the help of project partners Power Research Electronics B.V., Alfen B.V. and Stedin, and subsequently led to the publication of various scientific articles and development of new Flexgrid power converter system. These include literature research into the aging processes in lithium battery degradation and their modelling, modelling a smart charging algorithm that optimizes the power transfers in the integrated EV-PV-BS and optimally dimensions the various components. This algorithm also considers battery degradation, participation in the primary frequency control market and the applicability of the algorithm for different grid support techniques. Furthermore, a modular power electronics system has been developed which is controlled by the smart charging algorithm. As part of the development of the smart charging system, new modulation techniques have been developed for a bidirectional DC-DC inverter. During the development of the entire system, different norms and standards have been considered so that the entire system is directly applicable in today's society. The publications can be found at IEEE Xplore, MDPI, and google scholar. A total of five articles have been written for scientific journals. In addition, three conference articles were written and presented at the relevant congresses.

C. Objective

The primary goal of this project is to exploit the flexibility within distribution networks through a new modular system for smart charging of stationery and vehicle energy storage based on solar energy. The objective is formulated as follows:

"Increasing the flexibility and storage of power through intelligent operation of electric vehicles and battery storage based on photovoltaic generation using a modular multi-port power converter"

D. Procedure

The above objective is achieved by breaking it down into the following research questions:

RQ1. What are the degradation mechanisms of lithium ion batteries and how can we improve their cycle life?

RQ2. How do we design a high efficiency, high power density power converter that can simultaneously control EV, PV and BS while connected to the grid?

RQ3. How can the integrated EV-PV-BS system be optimally dimensioned and controlled to reduce energy costs and provide support services to the distribution network?

RQ4. What is the flexibility that the smart multi-port system provides compared to conventional systems?

To answer all research questions, a combination of literature review, modeling, and prototype development was performed. More specifically:

RQ1: What are the degradation mechanisms of lithium ion batteries and how can we improve their cycle life?

A literature survey was conducted on the characteristics of different battery technologies. Lithium-ion batteries were selected since they are a mature technology and provide the highest trade-off between energy/power density, cost, and age. Next, to increase the cycle life, a literature review on empirical and semi-empirical battery aging models was performed. Additionally, multiple models from literature were benchmarked against each other. It became clear that, to properly use these models a significant amount of knowledge in battery aging and the shortcomings of the models was required.

After studying this, a review paper was written on the characteristics and modelling of li-ion battery aging. This paper is published in IEEE Transactions on Transportation Electrification: *W. Vermeer, G. R. Chandra Mouli and P. Bauer, "A Comprehensive Review on the Characteristics and Modelling of Lithium-ion Battery Ageing," in IEEE Transactions on Transportation Electrification, 2021, vol. 8, no. 2, pp. 2205-2232, June 2022, doi: 10.1109/TTE.2021.3138357*

Next, the knowledge gained from the aging study was applied to the smart charging model, by adding a battery degradation model. This allowed the smart charging algorithm to optimize the battery degradation of both the EV and BS system. Additionally, the effect of battery degradation was considered when sizing the system. Both helped to increase the cycle-life of the EV and BS batteries. A paper on this has been written and published in the Open Journal of Industrial Electronics: *W. Vermeer,* *G. R. Chandra Mouli and P. Bauer, "Optimal Sizing and Control of a PV-EV-BES Charging System Integrating Frequency Containment Reserve and Component Degradation", IEEE Open Journal of the Industrial Electronics Society, vol. 3, pp. 236-251, 2022, doi: 10.1109/OJIES.2022.3161091.*

RQ2: How do we design a high efficiency, high power density power converter that can simultaneously control EV, PV and BS while connected to the grid?

Based on a literature survey of multi-port converters, it was chosen to develop a DC-integrated multi-port system. This allowed to integrate multiple inherently DC-ports (EV, PV, and BS) with only one AC/DC conversion step. This improves efficiency and power density while reducing the costs, compared to conventional AC integrated solutions.
Compared to high-frequency AC integrated solutions, the DC-integration allows for a modular design of the converter, where the power of each port can be increased or decreased based on a particular application. This makes the design more versatile and therefore potentially cheaper.

The multi-port charging system was developed by elaborating on existing knowledge and hardware, based on a previous project (Chandra Mouli, G. R. (2018). Charging electric vehicles from solar energy: Power converter, charging algorithm and system design. https://doi.org/10.4233/uuid:dec62be4-d7cb-4345-a8ae-65152c78b80f). In the FLEXgrid project the EV and DC/AC converter of this project were re-used, and the research was focussed on the development of a multi-functional non-isolated 10kW buck-boost converter, which could serve as both battery charger and PV maximum power point tracker. By using one converter for both the PV and BS, we could further reduce the total cost of the system.

During the design of the multi-functional four switch buck-boost converter, the research was focussed on a new modulation technique based on qausi-resonant boundary conduction mode (QR-BCM) The proposed control was the first to integrate QR-BCM on the four-switch buck-boost converter (FSBBC), while solving the problem of power control discontinuity during multi-mode variable frequency behaviour. The efficiency, power density, and complexity of the proposed modulation was compared with three other soft-switching modulation schemes for the FSBBC. A paper on the desing and modulation comparison of the FSBBC converter was written: *W. Vermeer, M. Wolleswinkel, J. van Schijffelen, G.R. Chandra Mouli, and P. Bauer, "Design and Modulation Comparison of a Wide-Voltage Range Soft-Switching Four-Switch Buck-Boost Converter" (under review).*At the time of writing, the paper is under review for publication in IEEE Transactions on Industrial Electronics.

Next, the FSBBC was integrated onto the existing EV charging hardware, and the smart charging control was integrated. A paper on this has been written, and is currently under review for IEEE Transactions on Transportation Electrification: *W. Vermeer, M. Wolleswinkel, J. van Schijffelen, G.R. Chandra Mouli, and P. Bauer, "A 10kW Solar-Powered Smart Charging System: Design and Experimental Verification" (under review).*

RQ3: How can the integrated EV-PV-BS system be optimally dimensioned and controlled to reduce energy costs and provide support services to the distribution network?

To optimally utilize the flexibility offered from EV, PV, and BS, a hierarchical smart charging system was developed. The smart charging algorithm optimizes the power flows inside the system to reduce the total cost of energy. This includes finding the overall trade-off between: grid energy costs, different ancillary services such as primary frequency control markets and peak-power capacity mechanisms, battery degradation (both EV and BS), and initinial investments costs. A paper on the proposed optimization model was written and published in OJ-IES (see the details above). Additionally, the effect of real-time error forecasting control, vehicle-to-grid, and optimal smart charging on the total cost of energy was investigated in: *W. Vermeer, G.R. Chandra Mouli and P. Bauer, "Real-Time Building Smart Charging System Based on PV Forecast and Li-Ion Battery Degradation", Energies, 2020, 13, 3415.*

RQ4: What is the flexibility that the smart multi-port system provides compared to conventional systems?

The above-mentioned smart charging algorithm was finally implemented on the developed multi-port charger to verify the theoretical results. The results of this are discussed in the paper regarding the experimental verification of the smart charging system, currently under review in IEEE Transactions on Transportation Electrification.

E. Results

The results obtained are explained in the list of publications attached to this document. In total, five articles have been written for scientific journals, at the time of writing three of the five articles have been accepted for publication. The remaining two are currently under review and considered for publication, as mentioned above. In addition, three conference articles were written and presented at the relevant congresses.

The main findings and conclusions of each article are summarized below:

1. *W. Vermeer, G. R. C. Mouli and P. Bauer, "Optimal Sizing and Control of a PV-EV-BES Charging System Including Primary Frequency Control and Component Degradation," in IEEE Open Journal of the Industrial Electronics Society, vol. 3, pp. 236-251, 2022, doi: 10.1109/OJIES.2022.3161091.*

This paper presents an optimization model which finds the optimal component sizes and power management for an energy management system that integrates a PV system, EV charging, and a BS system. Furthermore, it includes constraints that allow it to reserve power for the frequency containment reserve (FCR) market. In its power management, the proposed method combines a unique combination of different business cases, such as energy arbitrage, PV self-consumption, FCR market participation, and second-life BS value. It is concluded that the highest revenue can be obtained when all aspects are optimally integrated. Additionally, our results indicate that the return on investment for BS systems is still too high in case optimal control is missing (conventional BS). However, optimal power management adds additional business cases for the BS, such as energy arbitrage and FCR market participation, making the BES very profitable. Finally, by using a moving horizon window control, the significance of PV and BS degradation on total lifetime revenue has been investigated. To summarize, including the FCR market increases lifetime cost-saving by 36% and 460% compared to optimal power management without FCR market participation and nonoptimal power management, respectively, if the second-life value of the BES system is considered. Furthermore, our results showed the importance of including component degradation and FCR power provision on lifetime revenue. Investigating the effect of degradation on the reserved powers showed a one-to-one correlation, resulting in a total decrease in FCR market participation of 27.7% at the end of the BES lifetime.

2. *W. Vermeer, G. R. Chandra Mouli and P. Bauer, "A Comprehensive Review on the Characteristics and Modelling of Lithium-ion Battery Ageing," in IEEE Transactions on Transportation Electrification, 2021, vol. 8, no. 2, pp. 2205-2232, June 2022, doi: 10.1109/TTE.2021.3138357.*

In this paper, a review on the behaviour and empirical modelling of LIB ageing was presented, focussing on the effect and interdependency of operational stress factors. The presented review concludes that it is very difficult to generalize ageing behaviour, with respect to the effect of operational conditions. Usually, the resulting ageing is caused by a combination of stress factors rather than attributable to a single stress factor.

To this extent, users of empirical and semi-empirical battery ageing models should be cautious of their models' limitations and the correlations between the stress factors. To summarize some of the key findings:

- Solid-electrolyte-interphase (SEI) layer growth is the most important ageing mechanism for both cycling and calendar ageing. A strong correlation with anode potential is observed during idle conditions: a higher state of charge (SoC) results in increased SEI layer growth. However, other kinetic effects during cycling can accelerate ageing at low SoC. SoC-dependent calendar ageing is often modelled to exponentially dependent, whereas its effect on cyclic ageing can have different forms depending on the operating conditions.
- Because of the passivation character of the SEI layer, the ageing behaviour is most modelled using a power-law relationship based on time or throughput. Unfortunately, many cyclic ageing models do not differentiate between cyclic and calendar ageing, and therefore measure their combined effect. Others have subtracted calendar ageing from their cyclic ageing results to model the effect of cyclic ageing only, resulting in higher modelling accuracy.
- The Arrhenius law is an effective model for the temperature dependence of calendar ageing. However, during cycling, different ageing mechanisms are observed above and below room temperature. These should be considered when modelling cyclic ageing below room temperature. Since most studies are based on accelerated test conditions, this is frequently overlooked. Possible solutions include combining positive and negative activation energy in Arrhenius laws or including parabolic temperature dependencies.
- The effect of C-rate is often modelled to be exponentially dependent. Several studies, however, have found insignificant differences at C-rates less than 2. Furthermore, multiple studies have found a strong correlation between C-rate and temperature; as temperature rises, the impact of C-rate decreases significantly. Many models do not take this into account, which is in part due to accelerated testing conditions.
- Several studies modelled the depth-of-discharge (DoD) dependent degradation based on Wohler curves or other exponential curves. However, the effect of DoD is directly related to other SoC associated mechanisms and is therefore probably the most difficult stress factor to model. Additionally, the impact of DoD is affected by volume change due to electrode phase transitions and is thus also related to C-rate and temperature.

The summation of conclusions are all examples of the challenges involved in modelling lithium-ion battery ageing behaviour. Readers and modellers can mitigate these challenges by improving the design of ageing tests, ageing models, and ageing model applications using the knowledge provided in this paper. The authors hope that by doing so, they can help with overcoming the challenges of LIBs

3. *W. Vermeer, G.R. Chandra Mouli and P. Bauer, "Real-Time Building Smart Charging System Based on PV Forecast and Li-Ion Battery Degradation", Energies, 2020, 13, 3415.*

This paper presents a building smart charging algorithm for a multi-port system integrating EV, PV, BS, and a heat pump (HP). Here the HP and appliance load were assumed fixed. Then based on forecasts of PV production and load, the smart charging algorithm minimizes the total cost of energy incorporating, grid electricity costs, PV investment and installation costs, EV/BS operational costs and revenue obtained from operating as primary frequency regulation reserve. It has been shown that the proposed algorithm is very effective as it reduced 98.6% of the total cost of energy, compared to an uncontrolled EV-PV-HP case. Additionally, the potential of vehicle-to-grid (V2G) and the importance of forecasting error handling using a real-time moving horizon control scheme are discussed. Finally, it has been shown that EV/BS degradation costs, as well as PV investment and installation costs, are non-negligible parts of an objective function which tries to minimize the total cost of energy in an EV-PV-BES-HP system.

4. *W. Vermeer, M. Wolleswinkel, J. van Schijffelen, G.R. Chandra Mouli, and P. Bauer, "Design and Modulation Comparison of a Wide-Voltage-Range Soft-Switching Four Switch Buck Boost Converter" (under review for IEEE Transactions on Industrial Electronics).*

This paper presents a closed-loop QR-BCM control scheme for the FSBBC, which addresses the problem of power control discontinuity under multi-mode variable frequency operation. The proposed control is applicable for both single- and multi-phase converters. A two-phase 10kW experimental prototype has been developed. Our experiments have shown that it is possible to provide almost instantaneous transitions between operating modes, without loss of output power. Additionally, with 99.5% peak efficiency, the measured efficiency equals the highest in literature, despite a larger power- and voltage-operating range and based on a significantly simpler control scheme. This, in turn, is made possible by the ability to transition between different operating modes and optimize the modulation based on the voltage gain. Finally, a comparison with a quadrilateral current modulation (QCM) and a bipolar QR-BCM modulation scheme has been performed. It is concluded that the proposed modulation scheme shows the highest overall efficiency, especially for wide-voltage-range applications, with limited- to no compromise in power density and complexity. Using the proposed modulation, the losses can be reduced by up to 60% compared to the QCM and bipolar QR-BCM modulation schemes.

5. *W. Vermeer, M. Wolleswinkel, J. van Schijffelen, G.R. Chandra Mouli, and P. Bauer, "A 10kW Solar-Powered Multi-Port EV-Battery Smart Charging System: Design and Experimental Validation" (under review for IEEE Transactions on Transportation Electrification)*

This paper integrates all of the above work by integrating the developed FSBBC into the existing EV charging system. Additionally, the smart charging algorithm is integrated by establishing a CANopen communication network existing of all converters and a computer, which is running the algorithm. Our results summarize the results on a power electronic level: it shows the quasi-resonant (soft-switching) behaviour of all DC-DC converters), it discusses the multi-mode operation of the FSBBC converters, and it discusses the different layers of control loops which are integrated. Including the cascaded I-V control loops for the EV and BS chargers, the under- and over-voltage protection circuits and control to prevent inverter overloading. Finally it shows the experimental waveforms of the smart charging system.

A schematic representation of the developed DC-integrated system is shown in Figure 2.

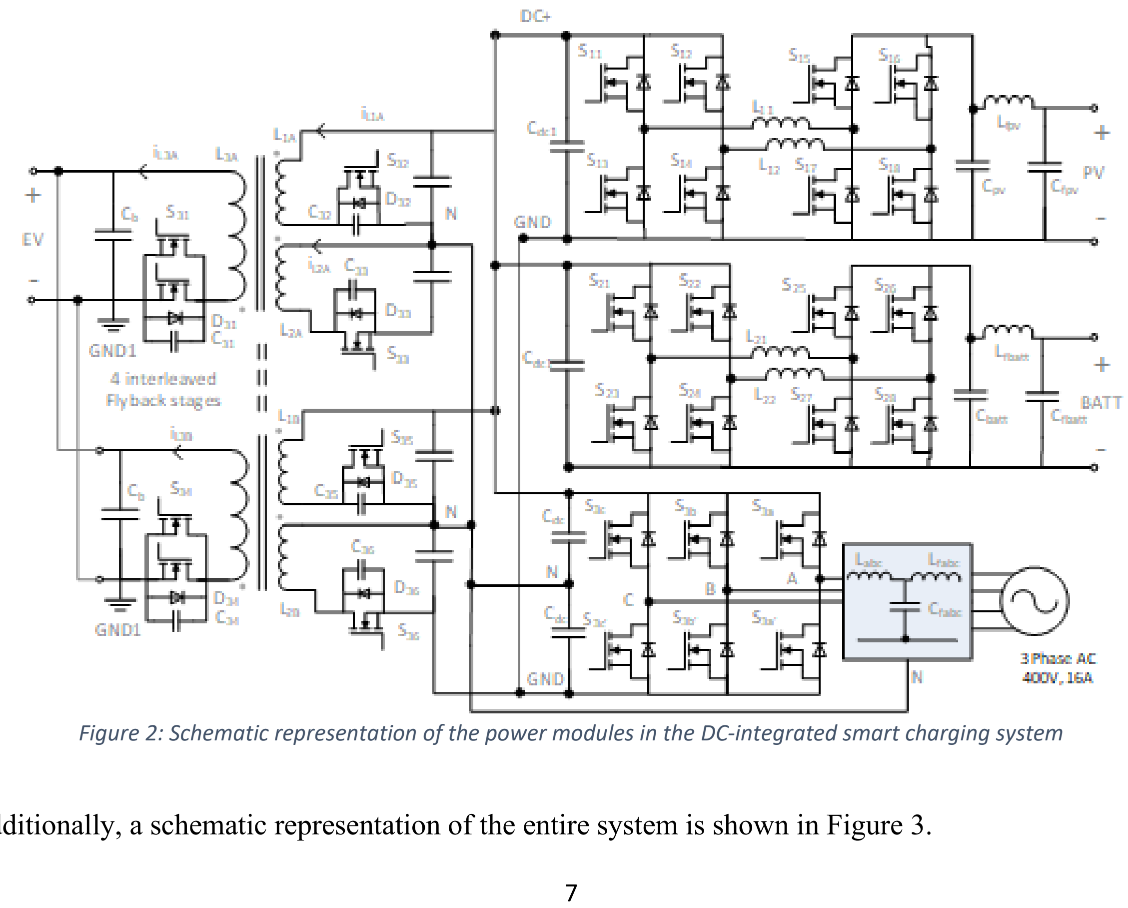

Figure 2: Schematic representation of the power modules in the DC-integrated smart charging system

Additionally, a schematic representation of the entire system is shown in Figure 3.

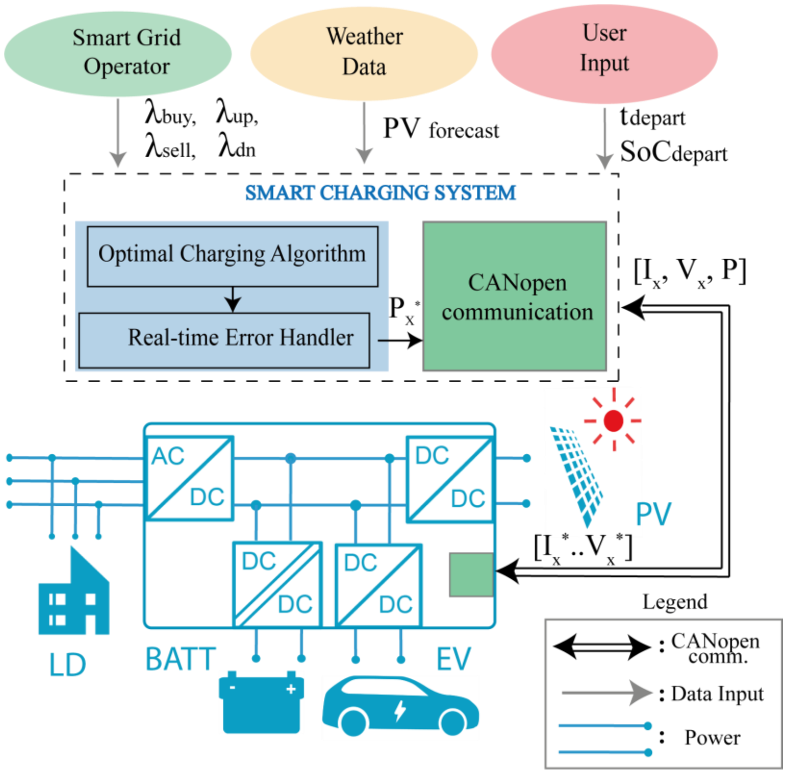

Figure 3: Schematic representation of the 10kW smart charging system.

Finally, a picture of the developed 10kW smart charging system is shown in Figure 4.

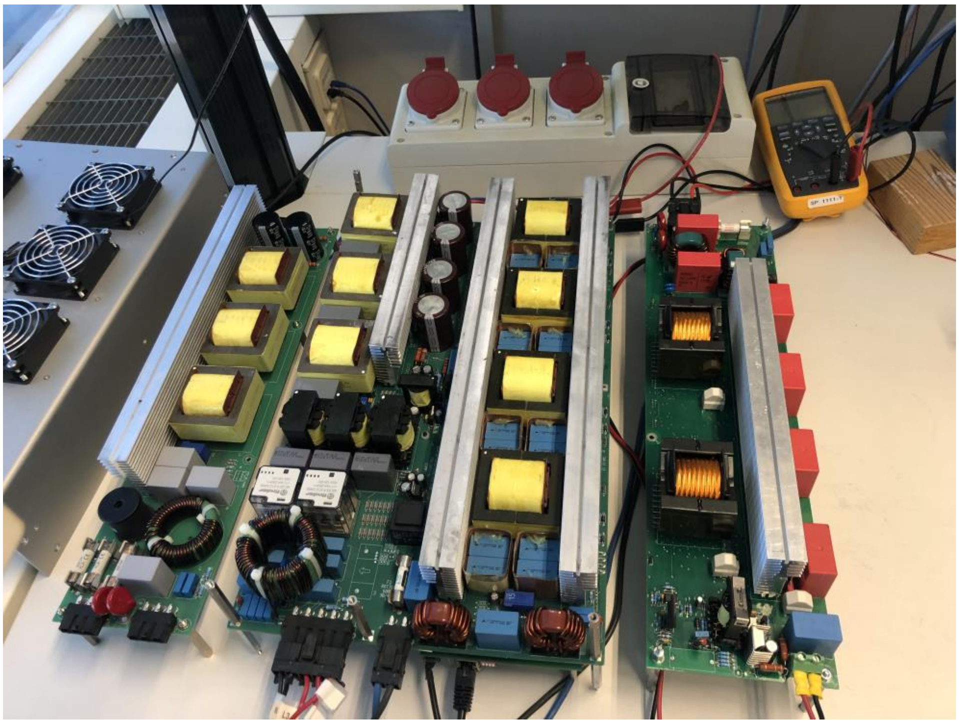

Figure 4:Experimental prototype of the 10kW DC-integrated smart charging system.

The findings and developments resulting from FLEXgrid have led to the preparation of three subsequent PhD studies, each focusing on different aspects of the research within the MOOI Fleixnet project 1. Developing underground power electronics for smart charging EVs. 2. Developing an algorithm for the optimization of thermal and electrical flexibility in residential areas. 3. Developing future local energy markets to stimulate local energy optimization.

F. Implementation of the project

a. The problems (technical and organisational) that have arisen during the project and the way in which these problems have been solved.

The restrictions due to the national and international lockdown due to COVID-19 have had a significant impact on the way of collaborating and consulting with colleagues. These eventually came across through video appointments, and the search for the right combination of working from home and working in the office (and in the lab) with sufficient distance. In the end, a three-month extension was borrowed from the PhD candidate to compensate for the delay caused by working from home.

b. Explanation of changes to the project plan

Based on the specific objectives mentioned in the proposal ("section 0. Openbare Samenvatting"), the following things have been done differently:

i. Flexgrid has focussed on Li-ion batteries and has spent only little time on different batteries options such as NaS and flow batteries.
ii. Recommendations for innovative electricity markets has been investigated in two MSc theses. However, this has not been included in the final work of FLEXgrid.

c. Explanation of the differences between the budget and the costs actually incurred.

Refer to financial reporting documents

d. Explanation of the way in which knowledge is disseminated

The scientific contributions are summarized in 5 articles and have been merged into the dissertation which is still being completed at the time of writing. Furthermore, a workshop was done in the TU Delft green village on May 16h. Here the most important finds were shared with project partners, other researchers, and people from the industry.

Additionally, the joint development of the power electronics have been shared with Power Research Electronics B.V., including the electronic diagrams, circuit board design, and software.

e. Explanation PR project and further PR possibilities

Presentations at the following conferences/events were given:

i. Flexgrid workshop -
ii. PEMC 2020: As part of the research on how to increase battery cycle-life, a literature review study on the pulsed charging of li-ion batteries was presented at PEMC 2020. In this paper, a summary and review on the effects of pulsed charging of Li-ion batteries was performed. This includes sinusoidal, square and triangular pulses. It has been shown that most of the reviewed papers report advantageous effects in terms of charging efficiency, charging time, and battery degradation. However, results are not uni-lateral. Furthermore, a strong correlation of the results with pulse frequency has been found. More specifically, when charging with a pulse frequency equal to the minimum impedance frequency, ten out of twelve reviewed studies claim positive results. No correlation with cathode chemistry has been found. A consensus exists that these results can be explained by the prevention/reduction of an internal gradient build up in the electrolyte and the

double-layer capacitance. Which increases conductivity and as a result improves efficiency, charging time/power transfer rate and ageing.

W. Vermeer, M. Stecca, G. R. C. Mouli and P. Bauer, "A Critical Review on The Effects of Pulse Charging of Li-ion Batteries," 2021 IEEE 19th International Power Electronics and Motion Control Conference (PEMC), 2021, pp. 217-224, doi: 10.1109/PEMC48073.2021.9432555.

iii. ITEC 2022: for project partner Stedin, a multi-objective design optimization algorithm was developed for the optimal sizing of PV and BS for EV fast charging stations. Our analysis shows of the EV demand shows a significant seasonal variation in EV charging demand, in both charging instances as well as energy demand per charging instance. Furthermore, using the provided multi-objective optimization it is shown that with only an 8% decrease in profit, a significantly more sustainable and less fluctuating EV charging demand can be achieved.

W. Vermeer, G. R. Chandra Mouli and P. Bauer, "A Multi-Objective Design Approach for PV-Battery Assisted Fast Charging Stations Based on Real Data," 2022 IEEE Transportation Electrification Conference & Expo (ITEC), 2022, pp. 114-118, doi: 10.1109/ITEC53557.2022.9814016.

iv. PEMC 2022: A paper on the demand response potential of heat pumps was presented, which was co-authored with a MSc student. The results of the optimization for winter evidenced that high costs reduction could be achieved with the proposed system. It was demonstrated that the feed-in tariff (FIT) had a significant influence on the system's cost minimization strategy. A high FIT resulted in a cost minimization through selling high amounts of energy to the grid while with the reduced FIT the minimization was performed by enhancing self-consumption of the PV produced energy and by using the energy stored in the BES/EV. During winter, the minimized costs between the high and reduced FIT cases differed approximately by 10%. In average, the optimization resulted in a minimized cost of 8.58 €/day. By assuming that this cost would be the same per each day of the whole season, this would represent a total energy cost of 755 €. When compared to a system where demand response is not performed, the system costs rose to 17.04 €/day, meaning a seasonal energy cost of 1500 €. Therefore, it can be concluded that during winter the proposed system could generate around 50% energy cost reduction when acting under a demand response program. The minimized costs were also compared to a non-optimized case where no minimization was performed. The results are showed in the following tables

D. Gaona, W. Vermeer, G. R. C. Mouli and P. Bauer, "Assessing the Demand Response Potential of Heat Pumps in All-Electric Buildings Equipped with PV, EV (V2G) and BES to Minimize Energy Costs," 2022 IEEE 20th International Power Electronics and Motion Control Conference (PEMC), 2022, pp. 174-181, doi: 10.1109/PEMC51159.2022.9962913.