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PROTOSCAR LAMPO2:

ENTWICKLUNG, INTEGRATION UND EVALUATION VIER UNTERSCHIEDLICHEN LADESYSTEME FÜR EIN HOCHLEISTUNGS-ELEKTROFAHRZEUG MIT LI-PO BATTERIEN.

Final report

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Abstract

The development, the integration and the analysis of 4 different charging types (onboard AC monophase with 2 power levels, onboard AC 3-phases and off-board DC fast Charging) on the LAMPO^2 electric vehicle are key points of this study. The overall charging efficiency of the 4 charging systems is measured, evaluated and compared on the same vehicle LAMPO^2 and under the same conditions. This is also the first step towards a deeper investigation on how the different charging systems could influence the efficiency of prismatic Lithium Polymer Batteries. With the help of the performed measurements and of the analysed Smart-Charging functionalities, the charging process is optimized on system efficiency.
At the moment, Protoscar is working very actively on this project with differend national and international leading companies in the electric mobility field.

Zusammenfassung

Die Entwicklung, die Integration und die Analyse von 4 verschiedenen Ladesystemen (on-board AC monophasig in zwei Leistungsstufen, on-board AC dreiphasig, off-board DC Schnellladung) für das LAMPO^2 Elektrofahrzeug sind die Schwerpunkte dieses Projektes. Innovativ werden die Ladewirkungsgrade für die verschiedenen Ladesystemen für das selbe Fahrzeug unter gleichen Bedingungen evaluiert und verglichen. Das ist der erste Schritt für eine spätere Studie, deren Ziel den Einfluss von den unterschiedlichen Ladesystemen auf die Effizienz moderner prismatischer Lithium-Polymer Batterien zu erforschen ist. Anhand der durchgeführten Messungen werden die Ladevorgänge auf Systemeffizienz optimiert.
Mit diesem Projekt arbeitet Protoscar momentan mit diversen führenden nationalen und internationalen Spezialisten im Bereich Elektromobilität zusammen.

1. Introduction

In this report, a comparison among 4 different charging systems, in terms of charging efficiency is presented and accurately evaluated. The logging data are collected both in the EV black box and in the grid analyzer for the case of “off board” charging. In a second step, those measurement data are accurately superposed in order to have a complete overview of the charging system.
Since LAMPO^2 is a research project, it is important to evaluate the behavior of the new charging components (i.e. DC fast charging capability) and how they interact with each other.
The efficiency of the charging process (onboard and offboard battery chargers) is obtained by handling the registered logging values according the equations described in chapter 4.
In the third chapter, the methods used to select and convert the data, as well as the way to perform the calculation are illustrated. In the fourth part, the whole calculation process is accurately described and the end results are presented.

2. Goals

- For the first time, different charging systems are tested and analyzed on the same vehicle, under the same conditions (batteries, AC and DC chargers, other components).
- After having evaluated the charging data, the goal is to optimize the charging process in terms of system efficiency. In a second step, there is the plan to investigate if a correlation between charging system (charging power) and battery lifetime (long-term battery characteristics) exists. In case of a positive response, the purpose is to try to quantify this dependency.
- To intensify relationships with national and international leading companies in the field of electric mobility.

3. Approach

Protoscar has developed the electric vehicle LAMPO^2 as the follow up of the LAMPO. The innovation is now focused on the optimization of the system efficiency while charging – and this with different charging types. For the charging efficiency, up to now scientific studies have been investigating the behavior of individual cells or – scarcely - individual modules, but almost nobody has focused on complete battery modules in the overall electric vehicle system (including chargers).
Therefore, with the help of the LAMPO^2, 4 different charging systems – and their influence on the system efficiency of the 32 kWh Li-Po Batteries – have been accurately analyzed.

Those 4 different charging systems are (figure 1):

- A standard monophase “onboard” charging system – for typical overnight charging – up to 3.3 kW.
- A standard monophase “onboard” charging system – typical for public charging infrastructure – up to 6.6 kW.
- A standard threephase “onboard” charging system – charging from “industrial plugs” – up to 9.9 kW charging power.
- An interface for an “offboard” CHAdeMO DC charging system (50+ kW power output). This allows increasing the range of 100 additional kms in only 20 minutes.

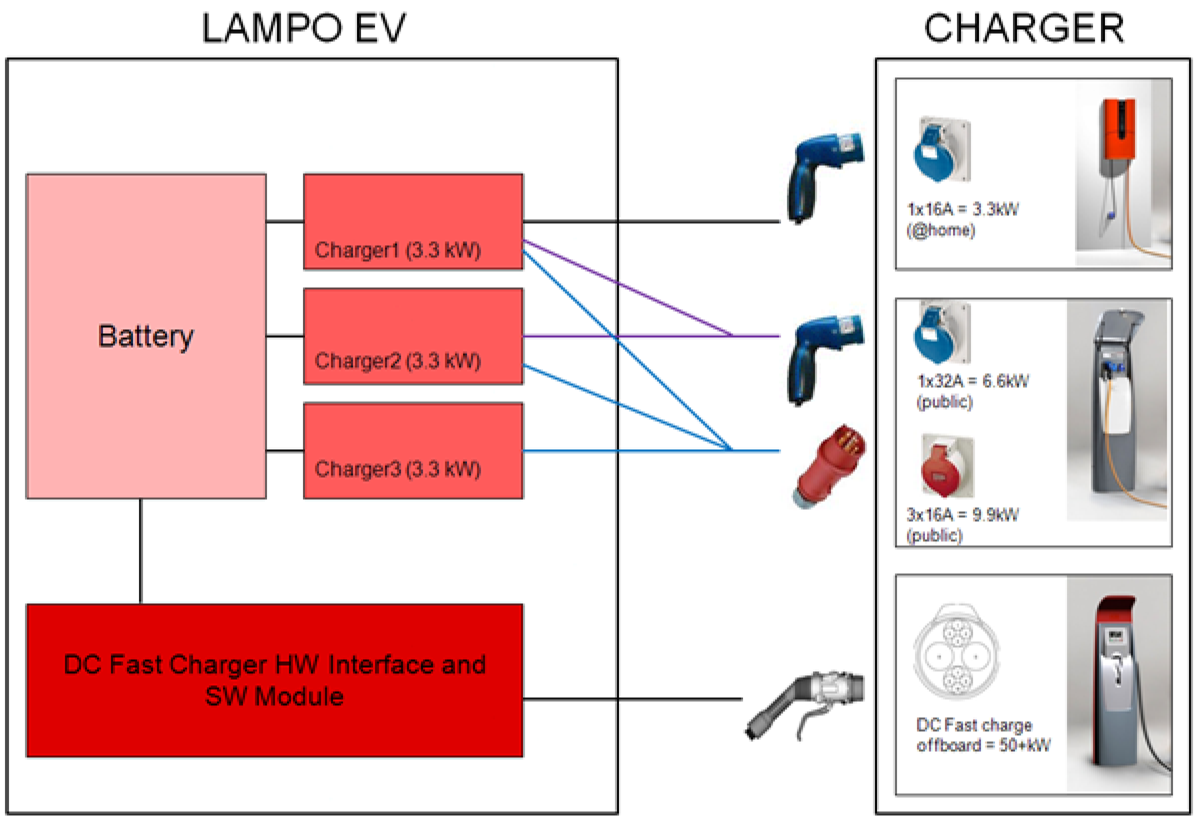

***Figure 1**: 4 different charging systems implemented on the LAMPO^2 electric vehicle*

In the Protoscar LAMPO2 electric car, every electronic control unit of the various subsystems is communicating with the vehicle control unit via CAN-bus (Controller-Area Network). Every message and signal that is transmitted via CAN within the vehicle is registered in a black box. Typically, 2 GB of internal memory are enough to save between 10 and 20 hours of data (considering every message transmitted – depending on the type of use – charging / driving), recorded every 5 milliseconds. The raw binary logging data (.blf format) are imported in a PC with the **Vector Logging Configurator** Software of Vector Gmbh and then converted (in .mdf format) and displayed by the help of the **CAN-graph** software. The data are then exported in **Matlab** format for the further analysis.
Following the same process, the raw data stored in the grid analyzer for off-board charging measurements are converted via ASCII in Matlab format for the final computation.

As we can understand from picture 1, the measurement setup is completely different for normal (on-board) and fast (offboard) charging. Thus, the 2 charging systems will be treated separately for the rest of this report. In the same way, two different routines have been written in Matlab in order to find out interesting parameters describing the charging process: energy, power, efficiency, temperature.

The LAMPO are the first European electric vehicles which have been predisposed with the DC fast charging ability. This requires the following work at car side: first of all, the control signals between vehicle and charging station have to be coupled in the vehicle control box. The switching on of the high voltage cables from the main power circuit to the dedicated CHAdeMO plug is also realized. The second step to get the CHAdeMO DC charging capability in the vehicle is represented by the Software module: as for the different electronic components in the car, also between vehicle and charging station the communication occurs via CAN-BUS. The vehicle control unit, after having received the maximal values from the DC fast charging station, aligns them with the requirements of the battery, and then it sends a voltage and current request back to the charger.
In the specific case, the CHAdeMO fast charge capability on the LAMPO electric vehicles could be tested, measured and optimized with a certified charging unit of the Japanese manufacturer Takaoka, which was installed directly at the Protoscar work shop in Riva San Vitale.

4. Results and discussion

PROCEDURE

Tests have been accurately planned before the start of the investigation (Table 1). Since every CAN-BUS data is permanently recorded in the logging unit, for the case of normal charging the measurement procedure was easier: The vehicle was used in its everyday life and every charging process was logged and analyzed. On the other hand, for DC charging each charging process had to be specifically planned in advance, since the measurement requires a dedicated grid analyzer to be installed at the charger side. The parameters to be varied among the different measurements, which are divided and classified according the charging modality and power, are:

- DOD at charging start
- DOD at charging stop
- Delta DOD
- Temperature at charging start
- Temperature at charging stop
- Delta Temperature

As a premise, it should be pointed out that the resulting efficiency of the charging process is pretty constant for each charging system and charging power. This is to be explained with the fact that the different parameters mentioned above don't have a relevant influence on the final efficiency calculation. Thus, the amount of the measurement samples – although it could be increased for deeper analysis – is largely sufficient to make consistent conclusions.

	onbord normal charging			offbord fast charging
test number	3.3kW	6.6kW	9.9kW	50kW
	lampo2 - 1NLG	Lampo2 - 2NLG	Lampo2 - 3NLG	Lampo2 - CHAdeMO
1				
2				
3				
4				

Table 1: *Planned tests to be carried out during this study.*

The onboard charging system doesn't require any extra measurement unit, since as already discussed all the necessary CAN data are recorded in a logger box. For the offboard DC charger the setup is more complicated. Since we used a Japanese product, the charger unit comprises of a big transformer which adjusts the voltage at the entrance to meet the requirements of European power supply. The power and energy analyzers are located before the transformer (measurement of the mains) and at the entrance of the charging unit. In this case, we are able to read data at any stages of the process, allowing thus the computation of the efficiency of the transformer and of the charger units respectively. In picture 2, the setup used for DC fast charging measurements is depicted.

MEASUREMENT SETUP

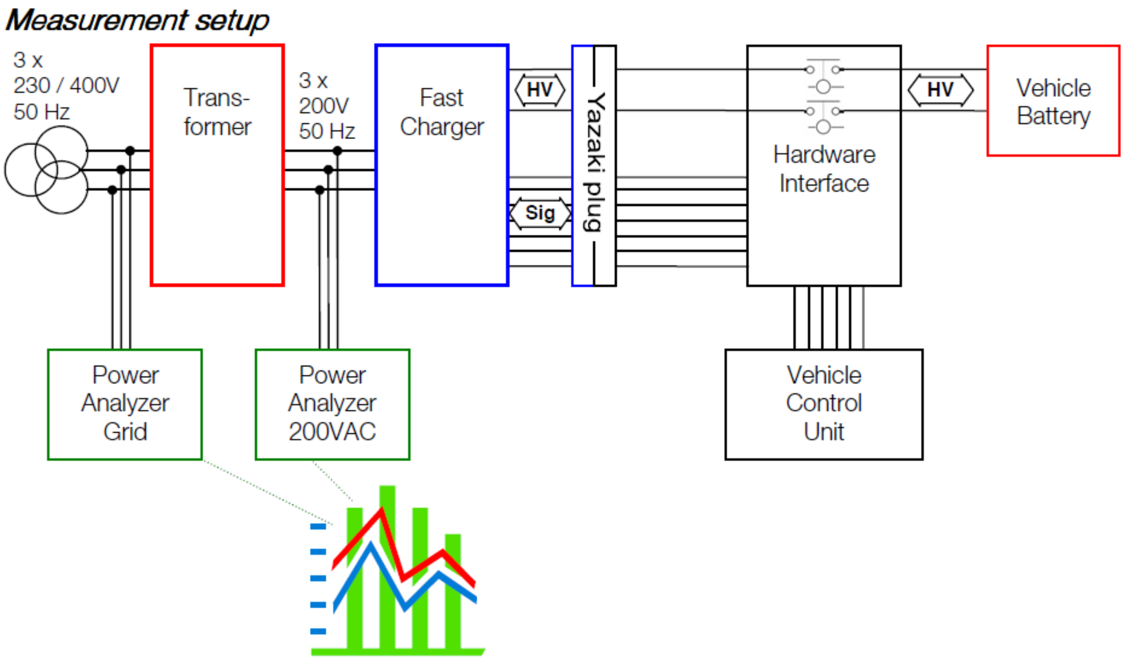

Figure 2: *Setup for DC fast charging measurement.*

In the following picture, the grid and power analyzers for DC fast charging measurements are illustrated.

Figure 3: *Grid and power analyzers for the CHAdeMO DC charger.*

Figure 4 shows how the logic of a CHAdeMO DC fast charger works: once the plug is correctly connected, the vehicle control unit receives a signal from the charger. The maximal values are adjusted in the battery, which returns a message with the desired voltage and current requirements back to the charger.

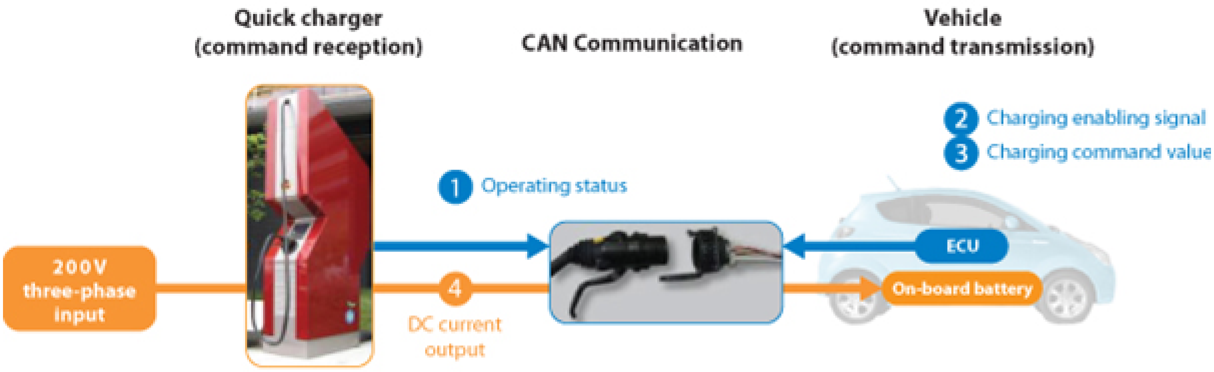

Figure 4: *Scheme of CHAdeMO DC fast charging communication*

Once the measured charging process has terminated, the logged raw data are transferred into a PC by the help of dedicated software. For the case of offboard charging, vehicle measurements have to be superposed with the charger measurements. In order to do that, before the test the times of both measurements systems have been synchronized.
The software **WinPQ mobil** is used for processing the offbord charging data for further analysis, while **CANgraph** is used for handling the vehicle data, display them graphically and translate them into a Matlab readable format. **Matlab** is then used to perform final computations.

Figure 5*: LAMPO^2 being fast charged with a Takaoka charger equipped with an ABB step-down transformer.*

Picture 6 shows a typical fast charging measurement. After the switching on of the charger, the charging power (at transformer mains) increases steeply to reach a value of about 50 kW. After that the power stabilizes, increasing slightly up to 55 kW – which is the limit of the power electronics. Once the DOD (Depth of Discharge) of the battery has arrived to nearly 25%, the current and thus the charging power decrease in order to protect long-term battery characteristics. The charging process is usually automatically interrupted when DOD is between 12% and 15% and the final charging power less than 30 kW.
In the picture we can identify the power and energy data for the 3 different phases and the total sum. It is easy to recognize that the charging power of phase 2 is clearly lower than phases 1 and 3. This is probably due to a different resistance in the correspondent coil in the transformer.
The energy data represent the cumulative amount of energy flown through the fast charger. A complete charging process takes about 30 minutes to fill the LAMPO^2 Li-Po batteries up to 15% DOD.

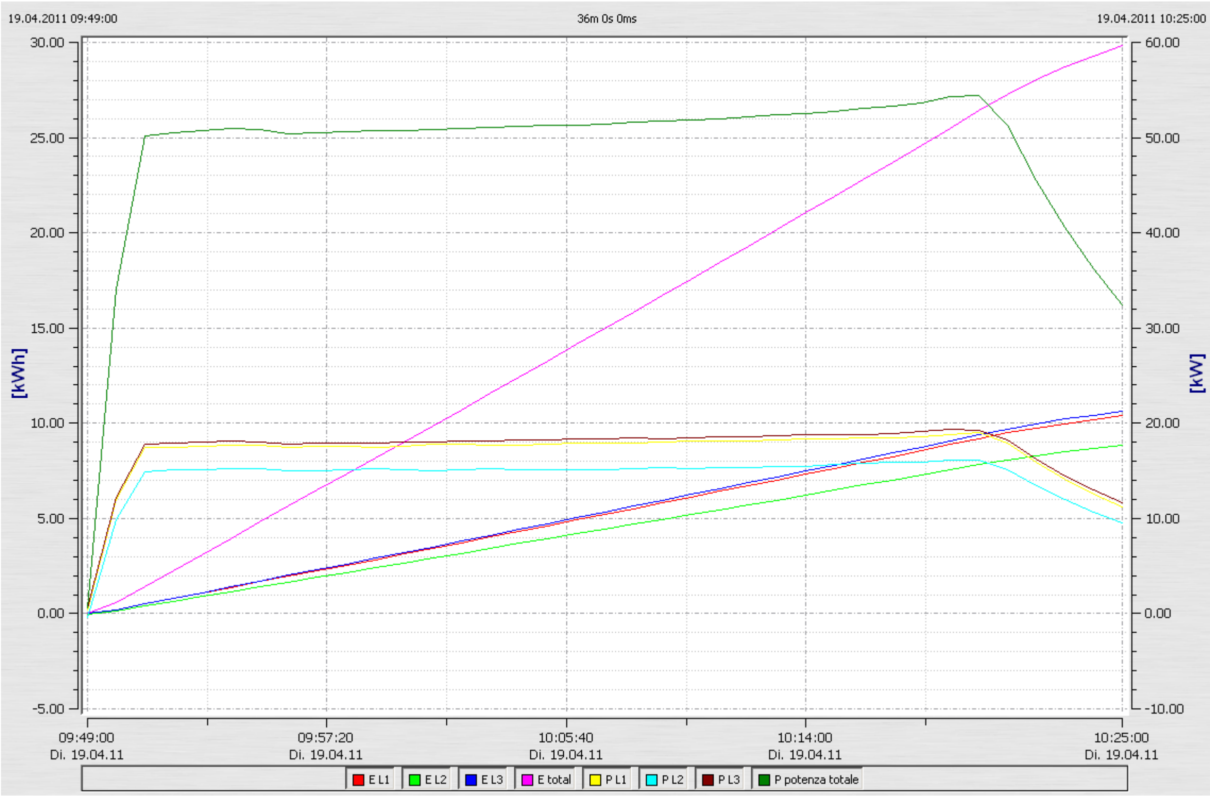

***Figure 6**: Energy and power in a typical DC fast charging process for LAMPO^2.*

EFFICIENCY AND ENERGY FLOWS

Before writing routines in Matlab, some physics principles have to be kept in mind for the calculation of the system charging efficiency. The following block schemes (figure 7 and 8) summarize the energy flows management in electric vehicles.

Battery chargers unit - Onboard charging

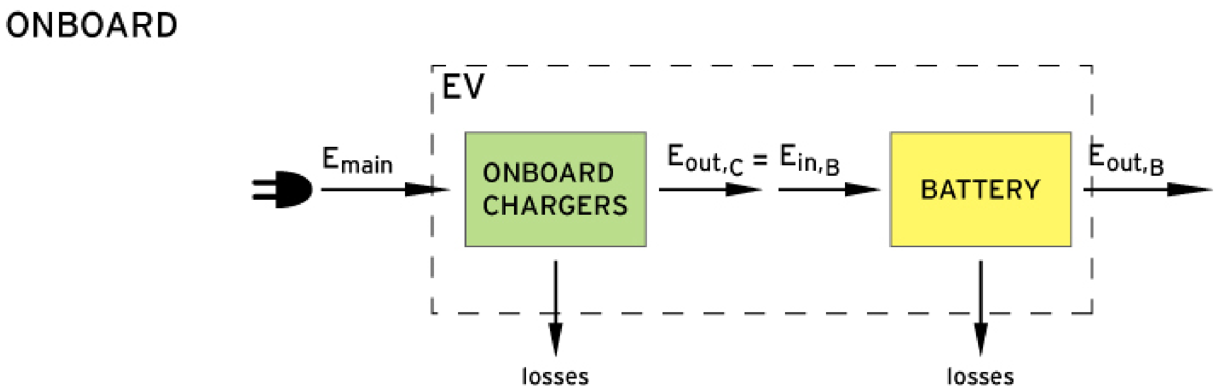

***Figure 7**: Scheme for onboard AC charging.*

The overall energy entered in the onboard batteries chargers (E_{mains}) over a selected interval is the integral over time of the product of grid voltage (effective value at the entrance) and grid current (effective value at the entrance), as shown by equation 1.

$$E_{Mains} = \int_{t1}^{t2} V_{eff} \times I_{eff} \, dt \qquad (1)$$

The overall energy converted by the batteries chargers over a selected interval is the integral over time of the product of tension (at the outlet of the battery charger) and current (at the outlet of the battery charger) (equation 2). The difference between the two is the internal loss in the battery chargers, while the ratio is the system efficiency.

$$E_{out,C} = \int_{t1}^{t2} V_C \times I_C \, dt \qquad (2)$$

The efficiency of the battery chargers is now defined as the ratio between the converted energy and the energy from the mains (equation 3).

$$\mu_C = \frac{E_{out,C}}{E_{Mains}} \qquad (3)$$

Battery chargers unit - Offboard charging

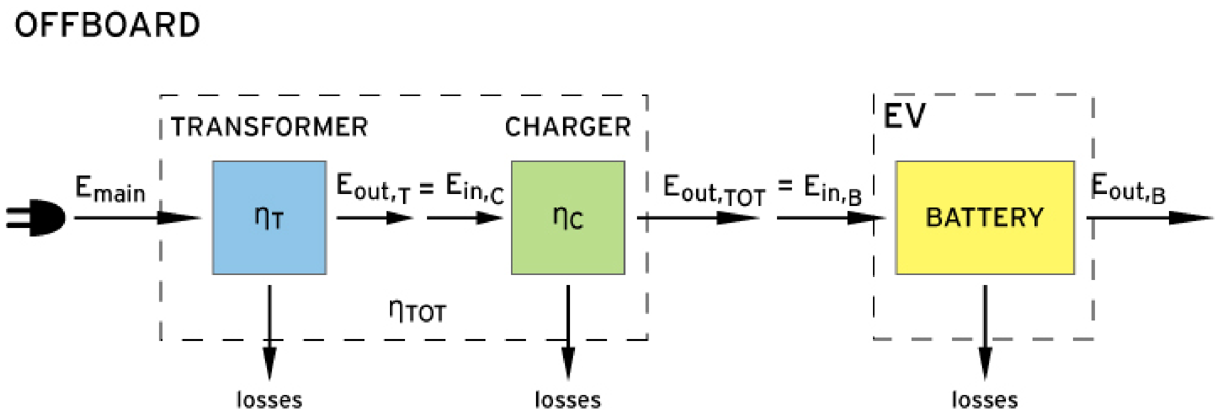

Figure 8: *Scheme for offboard DC charging.*

Assuming that the losses in the high power cables are negligible, the overall energy entered in the batteries ($E_{in,B}$) is equal to the overall energy released by the offboard charger ($E_{out,TOT}$). Since the used Japanese DC fast charger has different power supply requirements in terms of voltage, a step-down transformer is placed between the mains and the charger, causing thus a slight decrease of the charging efficiency.

The overall energy entered in the offboard charger system ($E_{mains)}$ over a selected interval is the integral over time of the product of grid voltage (effective value at the entrance) and grid current (effective value at the entrance), as shows equation 4.

$$E_{Mains} = \int_{t1}^{t2} V_{eff} \times I_{eff} \, dt \tag{4}$$

The overall energy flown through the transformer over a selected interval is the integral over time of the product of tension and current – measured at the outlet side (equation 5). The difference between the two is the internal loss in the transformer, while the ratio is its efficiency (equation 6)

$$E_{out,T} = \int_{t1}^{t2} V_T \times I_T \, dt \tag{5}$$

$$\mu_T = \frac{E_{out,T}}{E_{Mains}} \tag{6}$$

The energy coming out from the transformer is equal to the energy entering the charging unit, always assuming negligible losses in the cables. Since the utilized power analyzer cannot perform measurements at direct current level, the battery data at the inlet side are used to calculate the charger efficiency (equation 7). The difference between the energy entering the charging unit ($E_{in,C}$) and the energy entering the batteries ($E_{in,B}$) is the internal loss of the DC charger unit.

$$\mu_C = \frac{E_{in,B}}{E_{in,C}} \tag{7}$$

The efficiency of the transformer and the efficiency of the charger are then multiplied to obtain the overall efficiency of the charging system (equation 8)

$$\mu_{TOT} = \mu_T \, . \, \mu_C \tag{8}$$

TEMPERATURE AND DOD

The temperatures of the Li-Po batteries have been monitored during the charging process. Since the various test measurements have been performed with different atmospheric conditions, it is interesting to note how they influence the battery temperature. A consistent indicator to measure this behavior is the temperature gradient. It is defined as the battery temperature increase over the energy entered in the batteries at a fixed charging power (equation 9).

$$G_T = \frac{T_{stop} - T_{start}}{E_{in,B}} \tag{9}$$

The DOD (Depth of Discharge) is the opposite of the SOC (State of Charge) and it is expressed in percent. Ideally, 0% DOD means full charged batteries while 100% DOD characterizes empty batteries. A reliable indicator to define the quality of a charging process is represented by the ratio between "delta DOD" and the overall amount of energy entered in the batteries, which is basically the SOC gained caused by the input of 1 kWh of energy. In case of a higher ratio, a good quality charging process is ensured.

RESULTS

Table 2 summarizes the results for onboard charging. It is straightforward to note that the charging efficiency does not depend on the charging power. In fact, all the 3 charging modalities (monophase 16A, monophase 32A and 3-phase 16A) give at the end the same result. The charging efficiency remains steadily between 90.2% and 90.4%.
Tests 1,2,4 and 6 go up nearly to have full charged batteries at the end of the charging process, while tests 3 and 5 show intermediate charges. This means that those tests do not have the typical "equalization phase", characterized by a constant voltage and decreasing currents towards the end of the charging process. During the "equalization phase" the charging efficiency decreases slightly: this can also be identified from the quality parameter "delta DOD / Energy out charger", which denotes higher values for intermediate charging processes (tests 3 and 5).
We can thus demonstrate that the quality of a charging process is not determined by the charging power but rather by the DOD window where it is operated (actually with or without "equalization phase").
The temperature data show that the charging progression has always taken place within the temperature range given by the system: thus, the results are not influenced by the temperature. Nevertheless, it is interesting to note that the biggest temperature gradient [°C/kWh] occurs in the test operated at the lowest initial temperature and charging power.

AC CHARGING								
		3.3kW		6.6kW			9.9kW	
Test ID	[-]	1	2	3	4	5	6	7
Energy in charger	[kWh]	10.124	14.92	5.901	8.869	16.559	32.457	27.488
Energy out charger	[kWh]	9.134	13.46679	5.328	8.01	14.956	29.305	24.824
Charger efficiency	[%]	90.22	90.26	90.29	90.31	90.32	90.29	90.31
Average power in charger	[kW]	3.10	3.28	6.70	7.12	6.90	8.74	8.93
Average power out charger	[kW]	2.799	2.952	6.05	6.43	6.23	7.89	8.05
DOD end	[%]	5.9	3.1	59.5	5	22.1	0.5	0.9
delta DOD	[%]	25.40	37.43	16.30	22.90	45.60	84.44	72.05
delta DOD / Energy out charger	[%/kWh]	2.78	2.77	3.06	2.86	3.05	2.88	2.90
Temperature gradient	[°C/kWh]	0.61	0.48	0	0.23	0.53	0.38	0.34
Temperature start	[°C]	7.5	17.3	0	19.9	19	22.5	24.2
Temperature stop	[°C]	13.1	24.5	0	21.7	26.9	33.7	32.8
delta Temperature	[°C]	5.6	7.2	0	1.8	7.9	11.2	8.6

Table 2: *Onboard charging results summary.*

Table 3 summarizes the results for DC offboard charging.

DC CHARGING				
		50kW		
Test ID	[-]	1	2	3
Energy in trafo	[kWh]	29.84	27.168	14.078
Energy in charger	[kWh]	29.32	26.703	13.567
Energy out charger	[kWh]	26.59	24.19	12.31
Trafo efficiency	[%]	98.25	98.28	96.38
Charger efficiency	[%]	90.68	90.59	90.75
Overall efficiency	[%]	89.11	89.03	87.46
Average power in bat	[kW]	43.43	43.52	42.63
DOD end	[%]	13.8	14.1	14.5
delta DOD	[%]	80.2	73.1	37.88
delta DOD / Energy out charger	[%/kWh]	3.02	3.02	3.07
Temperature gradient	[°C/kWh]	0.41	0.47	0.68
Temperature start	[°C]	22.4	21.4	23.2
Temperature stop	[°C]	33.4	32.8	31.6
delta Temperature	[°C]	11	11.4	8.4
Constant charging	[%]	88.2	81.8	76.8

Table 3: *DC Offboard charging results summary.*

The efficiency of DC offboard charging is also pretty constant and show values in the range from 90.5% to 90.8%, taking into account only the charging unit. The utilized step-down transformer has efficiencies between 96.3% and 98.3%, so that the resulting charging system efficiency varies between 87.4% and 89.1%. Compared with onboard battery chargers, DC offboard charging systems evidence almost the same overall efficiency, which is actually very high above the 90% barrier.
The charging process usually stop by a DOD range varying between 13% and 15%, while the maximal charging currents start to decrease when the DOD reaches the 25% level.
The last item in table 3 represents the portion of energy charged at constant power, as depicted in figure 6. This amount varies between 76% and 88%. The cause of such diversity is difficult to identify and requires further investigation to formulate a reliable explanation.

As pointed out before, the most important conclusion is that DC offboard charging systems evidence almost the same overall efficiency if compared to onboard chargers. This is a promising result for a charging technology which is relatively new and destined to undergo an important expansion in the next years. Those are the first DC charging measurements which are going to be increased in number and completed for further investigation also in relation to long-term battery characteristics. This topic will also be part of the LAMPO[3] study next year.

Figure 9 summarizes the above discussed quality parameter represented in function of the DOD window for both onboard and offboard charging. The black circle indicates the charging start while the white one the charging stop. The color specifies the power level as depicted in tables 2 and 3. From the picture we can underline that charging process which do not reach their completion have better quality (higher indicator).

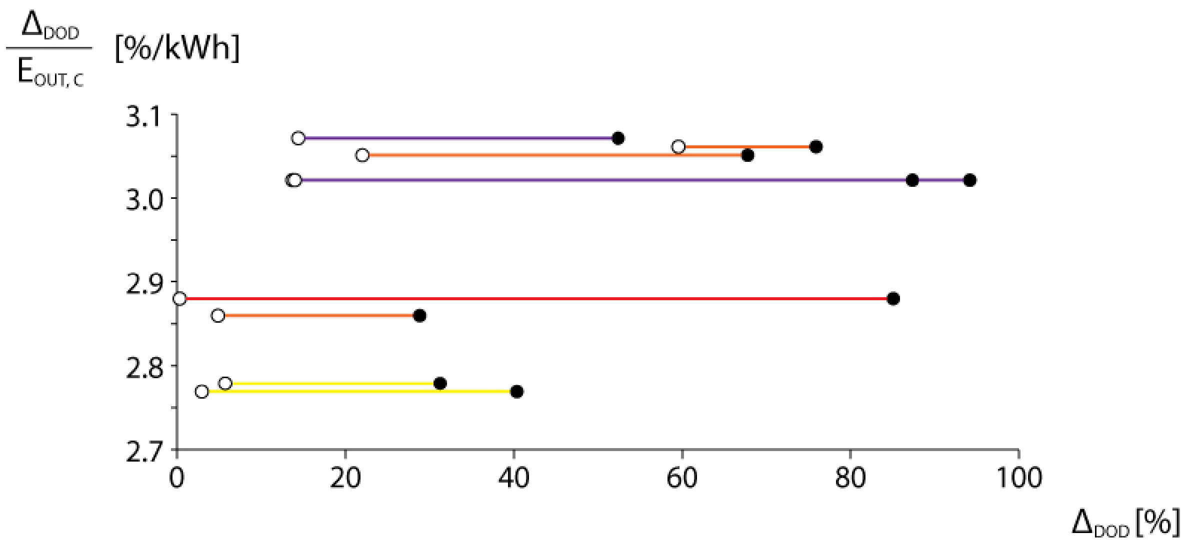

Figure 9: Quality indicator for onboard and offboard charging systems.

EY FINDINGS

Based on the analysis and the comparison of the 4 different charging systems installed on the LAMPO[2] electric vehicle, following key findings can be summarized:

- The charging efficiency of the onboard battery chargers has a fixed and constant value between 90.2% and 90.4%. The different charging power used, from 3.3kW to 9.9kW, have no relevant influence on the charging efficiency.
- Since the first measurement has been performed in the late 2010 and the last one in May 2011, giving exactly the same results in terms of charging efficiency, the quality and affordability of the power electronics used is demonstrated.
- DC offboard charging systems have a promising high efficiency. Compared with onboard systems, the charging efficiency (from the mains to the battery) is practically the same, just slightly above the 90% barrier if we consider a charging unit optimized for European power supply (without step-down transformer).
- Further analysis on DC fast charging systems and their influence on long-term battery characteristics will be carried out in the next study for LAMPO[3].

Glossary

Efficiency

The efficiency of a process is generally described as the ratio between total amount of energy resulting by the conversion and total amount of energy entering the process. Regarding automotive application, in common combustion engines the efficiency is typically intended as the ratio between mechanical energy supplied to the wheels and chemical energy of the fuel used to drive a determinate distance. We speak about fuel efficiency in this case.
In the field of EVs, where the “fuel electricity” is not converted in another form, but only used to drive an electric motor, we speak generally about “energy efficiency”.

References

[1] Vector, ***CANgraph user manual,*** 2009.

[2] Brusa, ***Datasheets of different electronic components,*** 2009.