skeleton

WHITE PAPER

SUPERCAPACITOR FAST CHARGING FOR URBAN PUBLIC TRANSPORTATION

This white paper describes Skeleton Technologies' supercapacitor-based fast-charging station concept for electric vehicles. In this case, specifically for autonomous buses, utilized for public transportation in an urban setting. In a connected white paper, titled "Supercapacitor- and SuperBattery-powered fast charging", we also delve into how the supercapacitor-based fast charging solution can be implemented in other industries besides electric vehicles and public transportation, as well as the impact of using high power and a higher energy density energy storage technology, namely, Skeleton's SuperBatteries, instead of supercapacitor energy storage.

The concepts, data, and results shared in this white paper are largely based on Skeleton Technologies' "Ultracapacitor Opportunity Charging" (UOC) project. The aim of the project was to develop an ultracapacitor-based fast charging system, specifically for use in autonomous vehicles. The main project goals were to overcome technological challenges including the development and design of the electrical connection between vehicle and station during the charging event, the development of a communication concept between station and vehicle, and the development, design and pilot testing with an autonomous vehicle.

Challenges in developing fast charging solutions to enable electrification

Skeleton's ultracapacitor-based charging station

The main problem in opportunity charging for electrified vehicles is not the energy storage technology on the vehicle side, but the localized supply of high power for charging events, which is multiplied by the number of stops needed on the route.

The grid limitations, and with it, the extra running costs, can be overcome with local energy storage, which would allow to draw only average power from the grid.This can be managed with ultracapacitor-to-ultracapacitor charging. Skeleton's ultracapacitor-based quick charging system results in both more efficiency and reduced costs.

Fast charging with supercapacitors

Skeleton Technologies have designed and built a supercapacitor-based fast charging station to tackle the challenge of both the slow charging times and the high demand for power grids. Comprising four main components:

- Grid converter: manages the slow draw of power from the grid, and SoC of the buffer energy storage system (ESS)
- Grid buffer: ESS which buffers the energy during the slow charge, and discharges fast during the fast charging of the vehicle.
- Charger converter: manages the power flow to the vehicle, and ensures the safety during such event
- Vehicle storage: responsible for storing the energy needed on the vehicle for its proper operation (driving)

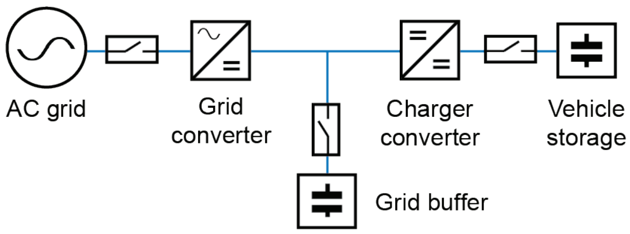

Figure 1. SLD of the charging station.

Both converters can be mono-directional, as their goal is to draw energy from the grid, but they are not supposed to regenerate power into it.

Other smaller components are not depicted here, but of course are necessary such as connectors, PLC, communication network and electrical protection systems.

Charging station concept development

General overview and concept

Charging is designed to take limited power from the grid to charge the charging station energy storage. This allows the charging station to be installed into grids that otherwise would not be able to accept high power chargers. Once a vehicle reaches the charging station, the high-power charging will deplete the charging station side energy storage and charge up the vehicle energy storage.

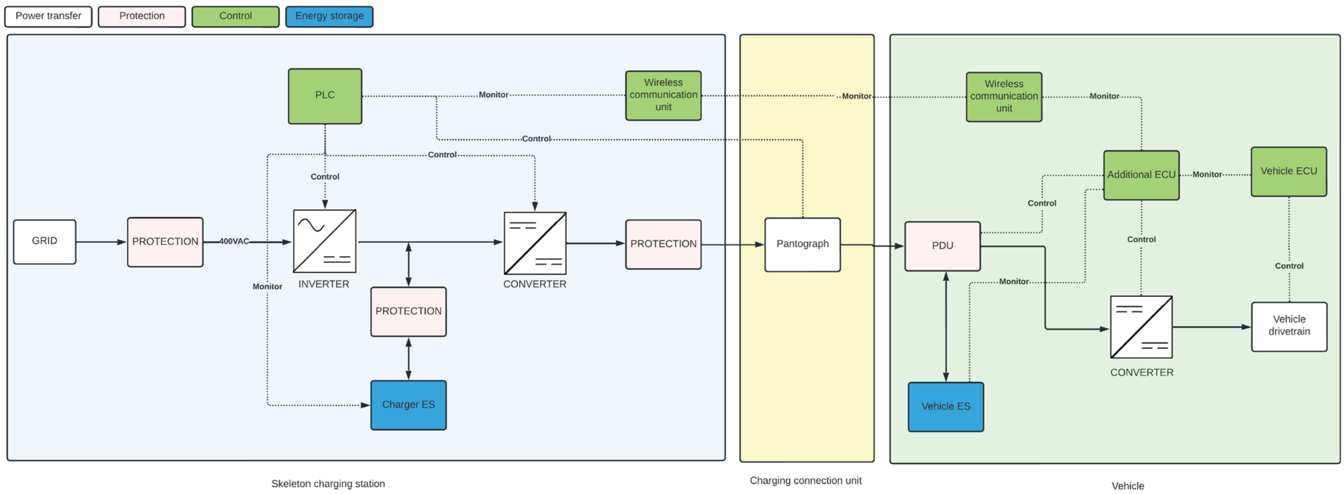

Figure 2. Charging concept overview.

The charging concept is relatively complex and consists of several steps. detailed overview of the charging concept can be seen in the Figure 2 above.

Starting from grid side, the protection block between the grid and the inverter consists of residual current monitoring, circuit breaker, fusing and main switch - all to protect the charging station from faults coming from the grid and vice versa.

The inverter is selected to be an AFE (active front end) type inverter. This allows to feed the energy back to the grid in case there is a need. For example, if the vehicle that comes in is malfunctioning or needs to go to maintenance, the AFE inverter will be able to transfer the excess energy from the EV back into the grid.

The protection between the charger energy storage and the DC link is sized for high currents. It consists of a high-power contactor and fuses. The DCDC converter in the charging station charges vehicle with current up to 1500A. Equipped with high-power contactors also on the EV side, it allows to disconnect all the main parts from each other in case of unexpected failure or emergency. Everything is monitored and controlled at the charging station side by the PLC.

The charging connection unit consists of a pantograph, charging controller and wireless transmitter. Pantograph will be connecting to the vehicle when control unit from charger side gives the command. Prior to it the charging controllers will exchange information over wireless link and determine if the charging can be started.

On the vehicle side, power will be transferred through the power distribution unit (PDU) that is controlled by an additional electronic control unit (ECU). The PDU is the central hub for power transfer. The power required to move the vehicle drivetrain will go through additional conversion as the vehicle drivetrain is designed for low voltage DC, which makes fast energy transfer problematic. An additional ECU is required to minimize changes on the vehicle side and have more flexibility in the development phase. The concept is designed to provide high charging currents during a short period of time. The charging profile is shown in Figure 3 below.

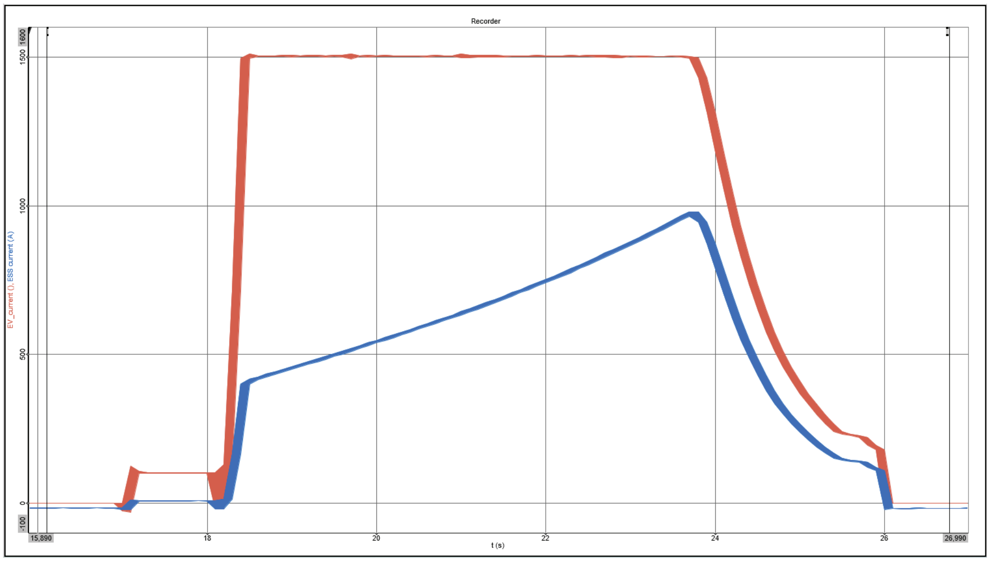

Figure 3. Charging profile currents.

It is important to point out that the charging station current and voltage are values that charging station controller manages via the DCDC converter. Essentially, there are 3 main variables to determine the efficiency of a charging station: charging voltage, charging current, and charging speed. Achieving the most optimum combination of those three variables was determined through a series of real-life tests.

In addition, it is important to note that the charging current has two limitations:

a) The higher the current the more costly is equipment. All power transfer and transmission components need to withstand the high currents.

b) Current is directly influencing losses. Higher current means higher losses and decreases the efficiency

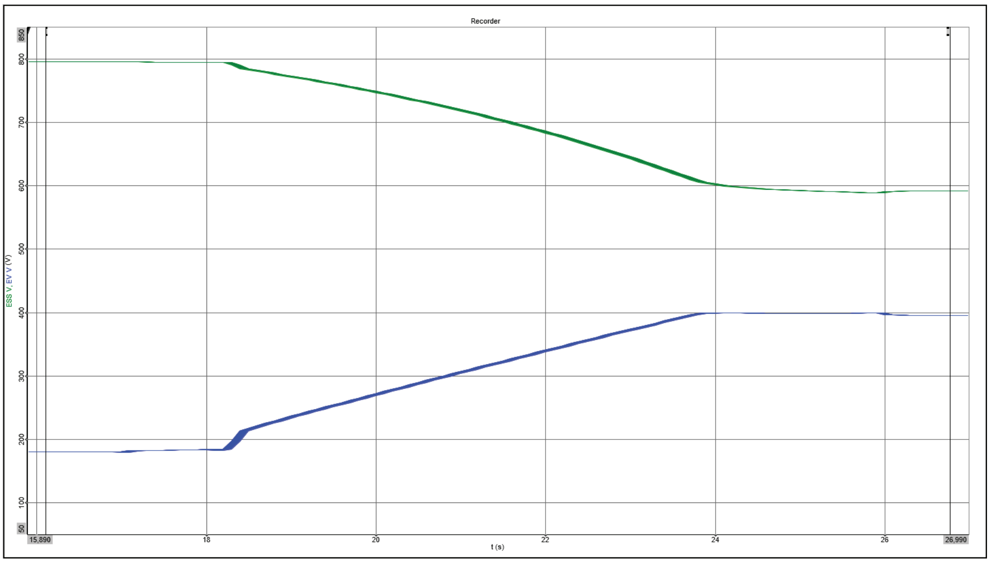

Figure 4. Charging profile voltages.

Voltage limitations are due to technical limitations. Grid voltage determines the minimum DC link voltage:

$$V_{DC} = 1{,}05 * \frac{3 * \sqrt{2}}{\pi} * V_{L(RMS)}$$

This is due to the AC rectification and additional 5% is required as a margin for AFE control algorithm error. Resulting an absolute lowest value of 567VDC on DC link. We cannot operate below that voltage level without losing the control of the AFE inverter. The maximum DC link voltage of 797VDC is limitation from both the inverter and the converter hardware side. This results an operating window from 567 -797VDC on the DC link, where the charger ES is directly connected. The vehicle side will be limited by the number of modules we have and by the rule that the DCDC converter high side voltage (DC link or charger energy storage) must always be higher than the low side (EV side in this case). Otherwise, the control is lost, and energy will start flowing without control through the DCDC converter.

The charging station

One of the key elements in the solution is the charging station. A detailed layout of the charging station is shown in Figure 5.

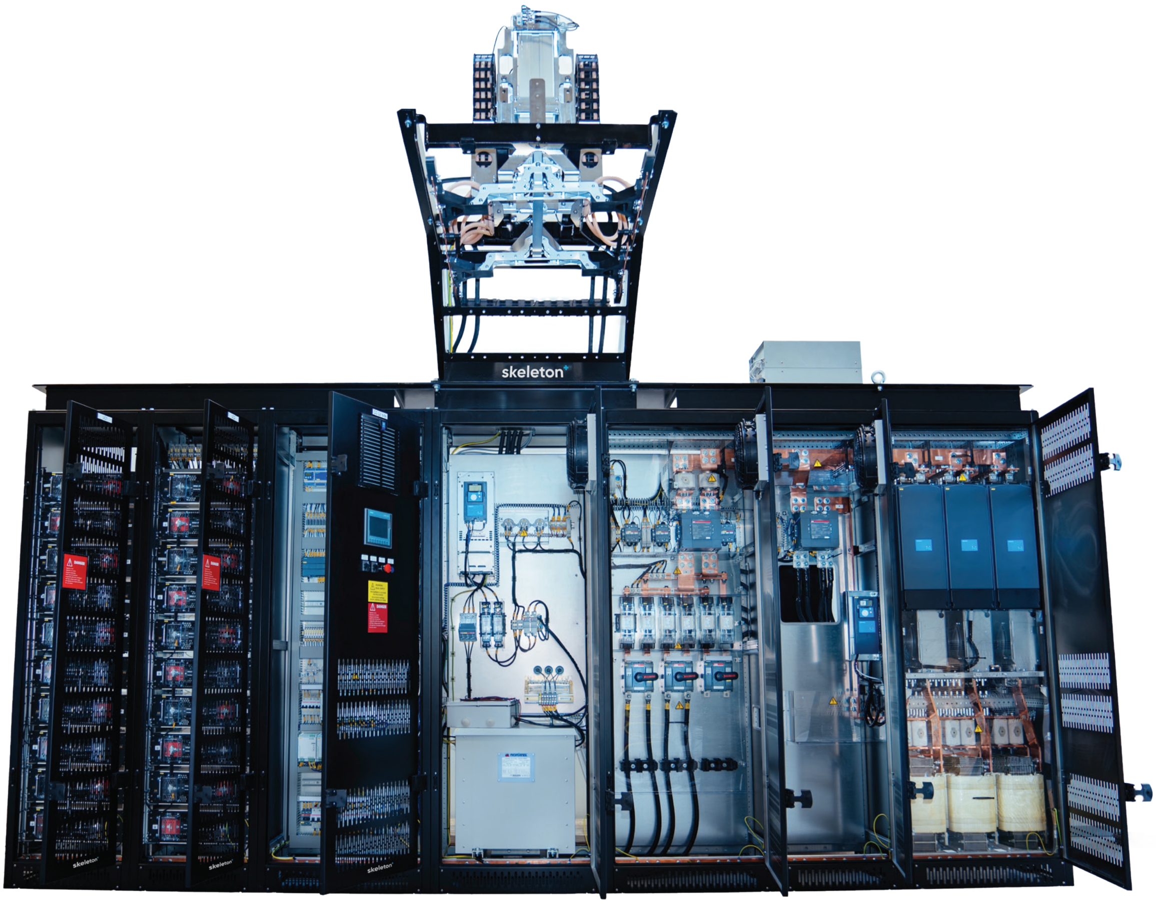

Figure 5. Charging station layout.

The charging station consists of several sub-sections with the following components and functional purpose:

Automation and grid connection
The automation section includes the main automation components needed to control and monitor the charging station. The main PLC unit controls the inverter and converter units based on the information received from the vehicle and energy storage CMS. The Charger ES is located in a separate cabinet. Communication and auxiliary power connections are connected into the charger station automation section. Additional to control and monitoring units, the automation section contains grid connection, low voltage power supplies and low voltage distribution circuitry. This includes power to charger ES cooling system that operates on low DC voltage (24VDC).

Inverter
The inverter section contains the isolating transformer, an inverter unit, and the filter for the inverter. The transformer's main purpose is to provide galvanic isolation of the drive system. Otherwise the common mode problems can be transferred to the grid. This is undesirable for other consumers in the same grid.

Charger ES connection
This section is meant for the charger energy storage connection. The energy storage is placed in a separate cabinet. The section includes protective fuses, disconnect-switches, power contactor, pre-charge, and discharge. Pre-charge circuit is needed to bring the ES voltage up from 0VDC and connect it to the DC link without creating an inrush current peak. Discharge circuit is used only for emergency cases when it's not possible to give energy back to the grid or we need to discharge ES entirely.

Vehicle ES connection
This section is dedicated for making the connection to the pantograph and from there to the electric vehicle. Currently it only contains a power contactor and reserve space that can be used for additional fusing or switch disconnector when required.

Converter
This section includes the DCDC converter that pulls energy from the charger ES and pushes it into the vehicle ES. In the middle are located the converter power electronic units. Both at the top and bottom protected by fuses and at the very bottom of the electrical switchboard are chokes which are needed to smooth the current output of a converter.

The charging station includes some safety features. Starting from the grid side, we have implemented an RCD (residual current device) to spot any AC current leaks and disconnect from the grid in case of a fault. There are two IMD's (insulation monitoring device) placed on either side of the DCDC converter. One to actively monitor the insulation of the charger ES and its circuitry, the other to monitor the pantograph and vehicle ES insulation.

Finally, an emergency stop relay is incorporated into the circuitry controlling the two power contactors, the inverter, and the converter. An emergency stop is triggered by the PLC or by an emergency top button on the cabinet. Additional trigger inputs can be integrated depending on the need of the level of safety required.

Automation concept development

Pantograph

The current design of the system includes a pantograph and charging rail system from Schunk Transit Systems GmbH

The pantograph is connected mechanically to a charging structure that Skeleton Technologies has designed based on Auve Tech vehicle parameters. Electrically, the pantograph isconnected to the charging station cabinet vehicle ES connection section. The Schunk depo charger used in the system is designed for:

- Cost-efficient system
- Compact and light weight design to save space and minimize weight for installation on existing infrastructure
- Maximum lifespan of the product via robust frame construction
- Low maintenance design of the entire system
- Appropriate alignment of parking deviations and movements during charging process
- Equal contact force distribution over the whole working range for safe charging process
- Multipole design for safe charging process

Communications

Communication and controls topology is described in Figure 6 below. A more detailed explanation:

- PLC - controls the inverter and converter units on the charging station side. Main communication is done in Profinet communication protocol. CAN to Profinet gateways are used in order to exchange information between the devices that provide information over CAN. HMI is linked with PLC, providing user main information and statuses about the charger and vehicle.

- Additional ECU – the control unit is added to have more flexibility when it comes to communicating on the vehicle side. The system needs to control the PDU, the DCDC converter, and monitor the ES and the vehicle. To mitigate risks, Skeleton has added to the design an additional ECU, which might be removed in later designs depending on the results.

The information exchange between additional ECU in the vehicle and PLC in charging station is done via CAN Wireless Gateway which allows the connection of different CAN buses over IP networks. Connection between vehicle and charging station happens automatically when vehicle reaches gateway WLAN range. This communication is of high importance as the charging can only commence once vehicle control systems have given the acceptance. It also provides user additional info to enable easier troubleshooting.

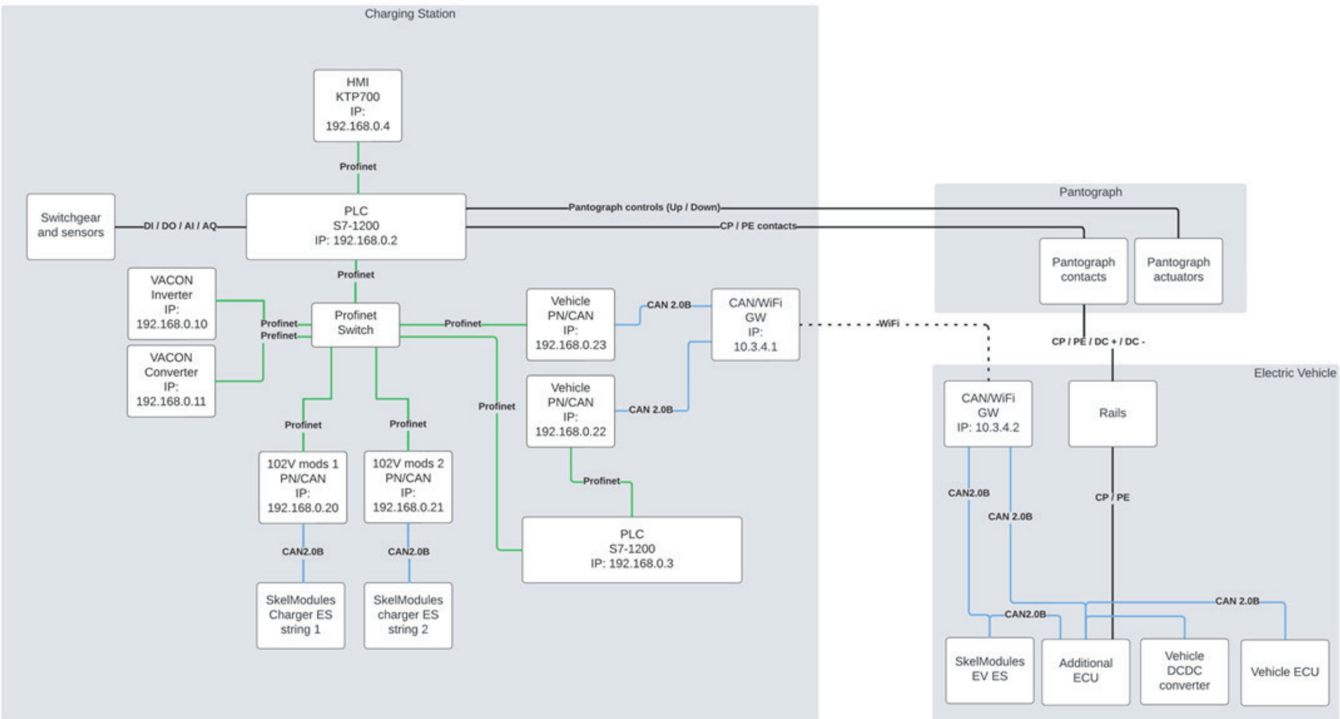

Figure 6. The communications concept.

Charging procedure

Charging station

Starting the charging station for the first time, the AFE inverter pre-charges the DC link through the inverter pre-charge circuit. Once the inverter is online, the DC link voltage is set to 797VDC. This maximizes the voltage difference between the powered DC link and charging station energy storage, which allows for the fastest possible charging of the remaining capacitances that are needed to connect to the DC link.

The next step is to connect the charger side ES to the DC link, but before doing so, the ES message and the IMD information should be checked to validate that there are no malfunctions present before starting the pre-charge of the ES. If any faults are present, the ES will not be charged and both the inverter and the converter will be stopped, until the faults are eliminated.

If no faults are present, the pre-charge circuit to ES will be closed. This will start charging the ES through the resistor, limiting inrush current. This pre-charge is required only when doing the first startup of the charging station or starting up after maintenance or a troubleshooting session. In other operational cases, the ES will remain charged and connected to the DC link.

Pre-charging of the ES takes a significantly longer time than the pre-charging of the DC link. Therefore, it is important to raise the DC link voltage to maximum level of 797VDC. The moment the ES voltage reaches 600VDC, the PLC will set the DC link voltage also to 600VDC and the main contactor to the ES can be closed.

When the charger side ES is connected with the DC link, and we can control the charger through the inverter and the converter. The DC link (and the ES as well as it is now connected to the DC link) should be raised to the maximum allowed voltage to be ready for the vehicle charge. To do so, the inverter DC link must be set to 797VDC. This will make the inverter pull energy from the grid and directly to the ES without any resistive circuits in between.

Now the charging station is online. During the process of bringing the station online, all messages from the IMD, the modules, the converter and the inverter are monitored, and in case of a malfunction, the processes will be stopped.

Charging the vehicle

The power contactor between the DCDC converter and the EV side connections (the pantograph being one of them) needs to be open. This is to avoid any energy transfer that can happen when the pantograph is being connected to the vehicle.

Once the vehicle arrives at the charging point, the procedure will commence as described in the simplified diagram in Figure 8. After arrival to the charging station, vehicle will inform charging station to start charging. For this the wireless communication between station and vehicle has to be established. This allows charging station to receive vehicle status information.

After receiving start command from vehicle, the station will check that both vehicle and station systems are operational, and no faults or alarms are present. Station will then lower the pantograph and inform vehicle that the pantograph has been connected.

Vehicle, after receiving the information that pantograph has been lowered, will close main contactor in PDU and CP line relay. CP line is for additional safety. This is a hard-wired line between vehicle and charging station. In case of a malfunction in the vehicle or unexpected disconnection of pantograph, the CP line will disconnect. Instantly stopping the charging procedure from charging station side. Ensuring that the latency or interference in wireless communication can jeopardize charging process safety. Once CP line is closed the charging station will proceed.

The charging station will then read directly EV main capacitor bank voltage (this is now possible as we have connected pantograph and EV main contactor in PDU).

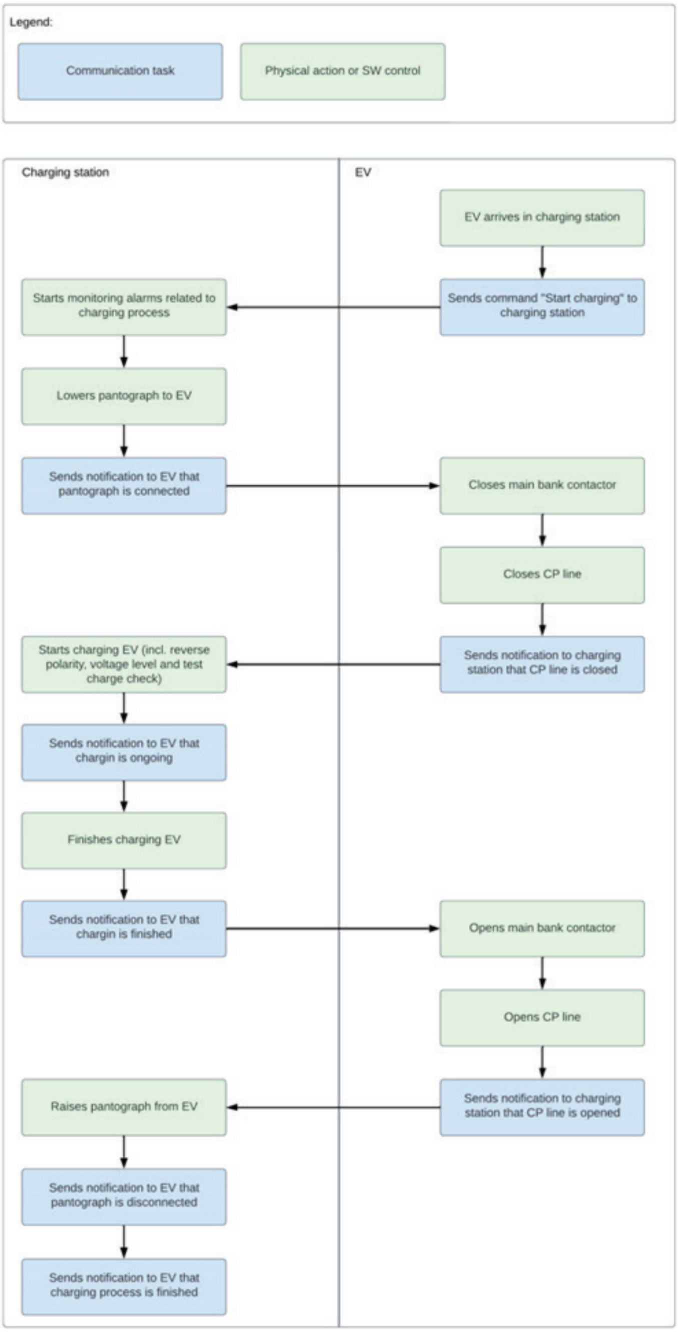

Figure 7. Simplified charging process description.

Charging station will match the DCDC converter voltage with EV main capacitor bank voltage and close charging station side contactor. Information that the charging process is in progress will be communicated to the EV as well. At first, the station will make a 100A 1s charge to the EV main capacitor bank and check the voltage difference from that charge. A voltage drop caused by the current will give information to the charging station on whether there are any problems with trans- mission line resistances or in the EV ES.A high voltage drop indicates high resistance issues, which means that the heat up during charging is going to be significantly higher, or some components can even fuse. If it is within the allowed window then converter will proceed in voltage control mode and charge EV ES with maximum current of 1500A.

Converter will automatically start reducing the charge current before reaching the maximum EV ES voltage of 400VDC. This is done by built in drooping curve provided by the converter manufacturer. Drooping curve working principle is explained in figure 8.

The converter current will be gradually reduced depending on the EV ES maximum voltage level setpoint and actual voltage on the EV ES.

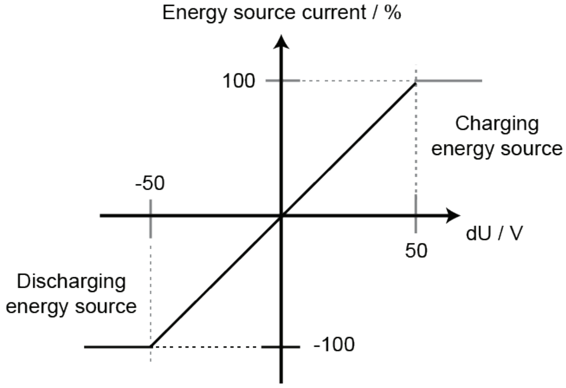

Figure 8. The Drooping curve principle.

The closer voltage rises to the desired setpoint (400VDC), the less current the converter will provide.

Once the charging process is finished, the charging station will inform the EV, which will then open the main contactor in the PDU that connects the main capacitor ES to the charging rails. After this, the EV will open the CP line and notify the charging station that the EV ES is disconnected. The charging station will then raise the pantograph and inform the EV that the pantograph has been disconnected and charging process is finished.

The EV can now proceed with its drive.

List of abbreviations

AFE	Active Front End (type of an inverter)
BEV	Battery Electric Vehicle
EDLC	Electric Double Layer Capacitor
ECU	Electronic Control Unit
ES	Energy Storage
ESS	Energy Storage System
GHG	Green House Gas
IP	Ingress Protection
OCV	Open Circuit Voltage
PDU	Power Distribution Unit
PLC	Programmable Logic Controller
SLD	Single Line Diagram
SoC	State of Charge