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F3

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Department of Control Engineering

Algorithms for feedback power allocation for charging several electric vehicles

Jakub Valerián

Supervisor: doc. Ing. Zdeněk Hurák, Ph.D.
Supervisor–specialist: Felix Freese, M.Sc.
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Declaration

I declare that the presented work was developed independently and that I have listed all sources of information used within it in accordance with the methodical instructions for observing the ethical principles in the preparation of university theses.

Prague, 23. May 2019

Abstract

This thesis focuses on the blackout protection of a fuse by controlling the electric power distribution to a group of electric vehicles, taking into account delays in control and measurements. The blackout protection has to be applied to a shared grid during charging of electric vehicles, wherein unpredictable grid loads occur. A short description of 'Home energy management', the concept which allows the control to be developed, is included as well as description of elements necessary for the control development. The main part is dedicated to the model of the whole system with several simplifications, the theoretical background of the developed algorithms, their Simulink implementation and test cases used to test behaviour and stability of the algorithms. In the conclusion the results and several ideas for improvement of the charging process can be found.

Keywords: electric vehicles, home energy management, charging infrastructure, control delays, control of electric power distribution

Supervisor: doc. Ing. Zdeněk Hurák, Ph.D.
Department of Control Engineering,
Karlovo náměstí 13,
Praha 2

Abstrakt

Tato práce pojednává o prevenci výpadku jističe v domě díky řízení distribuce elektrické energie skupině nabíjejících se elektrických vozidel. Počítá se přitom i se zpožděním jak v části řízení, tak i při získávání měření. Prevenci výpadku je třeba použít v případě připojení nabíječky na společné rozvody, kde se objevuje i jiná, předem neznámá energetická zátěž. Součástí práce je krátký úvod do "Home energy management", které umožňují celý proces nabíjení kontrolovat, společně s přehledem užitých prvků nezbytných pro realizaci řízení nabíjení. Hlavní část se poté věnuje modelování celého systému včetně několika jeho zjednodušení v programu Simulink, teoretickému základu použitých algoritmů a jejich následné simulinkové implementaci včetně jednotlivých testů funkcionality a stability. V závěru práce jsou uvedeny dosažené výsledky a návrhy možných zlepšení celého procesu nabíjení.

Klíčová slova: elektrická vozidla, home energy management, infrastruktura nabíjení, zpoždění v řízení, distribuce elektrické energie

Překlad názvu: Algoritmy pro zpětnovazební alokaci výkonu pro nabíjení několika elektrických vozidel

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Introduction

Electromobility (E-mobility) is becoming more popular in the last several years. Although its advantages and disadvantages are constantly being discussed, the potential of electric driving is recognizable. The price of electricity goes from 1.42 to 2.36CZK per kWh[1], no other fees accounted for. For the electric vehicle (EV) Tesla model S, the manufacturer states that a battery capacity of 75kWh provides enough power to reach 335 miles (approximately 540 kilometers) [2]. From a financial point of view (taking into account the maximum tariff of 2.36CZK per kWh) fully recharging this battery would cost 177CZK which does not cover the expenses necessary to reach 100km with a combustion engine vehicle considering gasoline prices at about 32CZK per litre [5].

Another benefit of EVs for both present and future lies in local emissions reduction. As the air pollution in big cities increases and governments are trying to lower them in several ways, e.g. by restricting entrance for specific cars, higher taxes for older cars with higher emissions, or simply improving the public transport, EVs would allow people to drive as freely as now. However, electricity production related emissions are not taken into account. Only a small amount of countries in the whole world produces its electricity in nuclear power plants by more than 50%[3]. The rest of the production is mostyl covered by fossil fuel power plants and a smaller part from renewable resources. As result, the pollution does not disappear with the E-mobility, it is just shifted to the locations of power plants.

The most critical part of an EV is the battery. For example, Volkswagen guarantees a minimum capacity of 70 percent for eight years or 160,000 kilometers' [4]. Another parameter for the lifetime is the number of charging cycles. The battery is also the most expensive part of the vehicle and can be replaced in case of need. On the other hand, the production of a battery is not environment friendly. Moreover, the battery can only be used in specific temperature ranges and has to be protected from external impacts as there is a high risk for the battery to burst into flames when an EV crashes.

To make E-mobility even more attractive for the public, the charging process has to undergo several improvements. EVs are able to consume a large amount of power; thus, the power network has to be able to supply both EVs (in numbers getting close to amount of cars with combustion engines) and other infrastructures. At this moment, electric vehicles can be recharged mostly at specified grid connection points. Because almost the whole world is now electrified, bringing the charging points closer to EV drivers does not require much additional effort. Another advantage is that having a charger in a garage will not require to drive to a public charging station which could be occupied.

Improvement of the charging process and bringing the chargers closer to drivers are the most easily-achievable ones from the previously mentioned points. In other words, the goal is to get the charging point to private places such as garages, appartments and houses. Since the EV is capable of tripping the circuit-breakers due to large power consumption, the charging has to be controlled together with the other home appliances. As in the last years also a Home Energy Management systems are being installed in order to save energy and money of homeowners, handling of the charging process can be carried out by these devices as a new feature.

Part I

Environment description

Chapter 2

Environment

2.1 Introduction

Before the development of the algorithms, the environment for charging the EVs has to be defined. This chapter shortly describes the idea of Home Energy Management Systems (HEMS), which makes the whole idea of home charging possible without much further effort. Furthemore, single elements that need to be taken into account for the development including the charging process for the EV, and finally the whole setup transformed into a Simulink model with several restrictions and simplification are elaborated.

2.2 A brief introduction to Home Energy Management Systems

The potential of E-mobility depends on the possibility of placing chargers at public places such as parking lots, business and shopping centres or at private houses or garages under apartments. The commonality of all the mentioned places is that parked vehicles are mostly left there for several hours and they can be recharged without the need to drive to a recharging station. However a large number of EVs can cause the grid connection point circuit-breaker to trip because of the overload. It can happen when one or more devices are switched on in the respective house or the building and the consumption exceeds the fuse's (circuit-breaker's) threshold value. This should be avoided as most of the household appliances cannot be controlled or turned off at every moment. For example, boiling water with a kettle or the start of a dishwasher should not trip the fuse when an EV is recharging.

The problem of consumption control requires a more advanced solution which should be able to react upon unpredictable consumption, calculate and communicate the available charging power for the vehicle based on its requests or/and actual consumption. A HEMS can provide a solution to home charging.

2.2.1 Purpose of HEMS

The original purpose of HEMS is to help the user lower his/her energy consumption. Motivation for purchasing is both economical and ecological. A study carried out by Joule Assets Europe and VaasaETT [6] focuses on energetic and financial savings when using a HEMS. The paper states that using HEMS would have a payback period from one to three years and would create a flexible energy equal to production of at least two coal/gas power plants.

Achieving these results is possible by optimization of consumption. This is done by installing a control unit (also called 'Customer Energy Management' - CEM[7]) capable of monitoring and controlling the power distribution using few basic functions. The first and most important of them is measuring overall power usage. Based on information provided by the HEMS the user himself can lower the consumption just by realising how much energy some of home appliances are consuming and, if there is no need or specific reason to run them, simply pay more attention to switching these devices off. However, a more advanced approach requires connection of these home appliances to the central unit.

2.2.2 Consumption optimization

When some of the home appliances are connected to the CEM, the user can specify end times for the devices' operations (e.g. when a dishwasher should have his cycle done). The CEM then can plan the consumption in several different ways as the user can have specific demands; it creates dynamic consumption. Some of the used strategies are mentioned below.

Critical peak pricing

Critical peak pricing is an effort to cut demand for a set number of hours when critical peaks are expected [6]. These peaks appear at irregular intervals and, as discovered in [6], mostly during summer or winter due to heating and air conditioning. As a result the peaks are shifted/eliminated and maximum demand is lowered without the overall consumption being impacted.

Real time pricing

Unlike critical peak pricing, which moves the consumption from peaks of demand, real time pricing focuses on shifting the consumption to intervals where the power is generated mostly from renewable resources [6]. That brings a difference in pricing and as stated in [6], the customer will notice the differences in costs, which is caused because of electricity tariffs changes through the day and night, within three to five years [6].

2.2.3 Photovoltaic panels

Not only the HEMS can adjust energy supply based on the electricity provider and peaks in consumption, but the user can install photovoltaic panels (PV) and/or a battery inside the house. This enables the CEM to plan the house's consumption based on weather forecasts and PV's history to times when the PV system produces enough power. Or, if no consumption is planned, store it inside a battery for later usage.

Another optional function of the HEMS is called feed-in. If the power network is prepared for this and the user wants to participate, unused power from the PV system can supply the power network while obtaining bonuses from the energy provider as people using this feature can help to cover peaks in energy demand.

2.3 Used elements

The EV environment consists of several different elements. These are the grid connection point with the fuse/circuit-breaker, where the whole house is connected to the power network and where the whole house consumption is measured on each phase, the CEM unit, current sensors and an Electric Vehicle Supply Equipment (EVSE) which the CEM is able to control while charging an EV. Other devices or power consumers are not described here as their consumption is considered as unpredictable and uncontrollable for the purpose of this work.

The figure 2.1 shows how a house with an installed HEMS could look like. It describes an almost fully controllable house with both the PV system and a battery with a possibility of planning the power supply to the EVs.

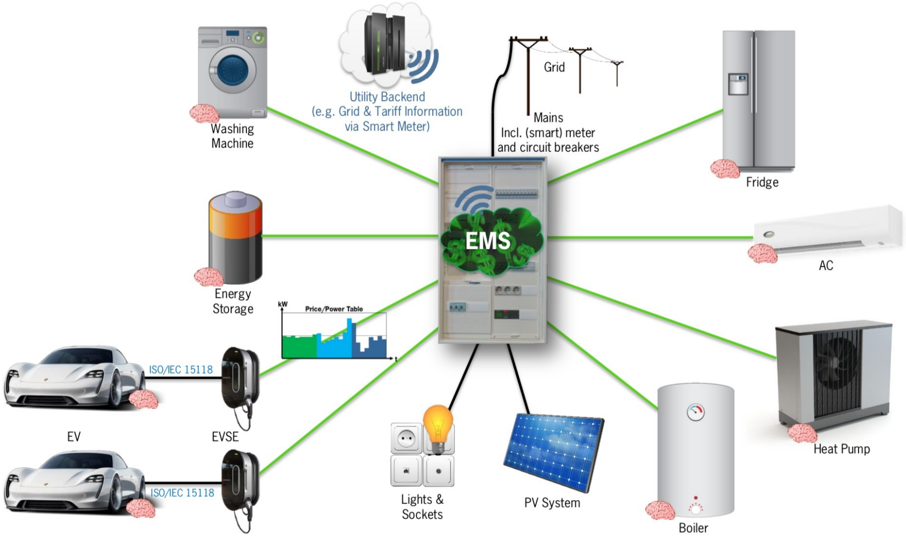

Figure 2.1: Scheme of the environment with other controllable home appliances (figure taken from [8] and modified)

2.3.1 Fuse type B

Every building has circuit-breakers installed at its grid connection point. Miniature circuit-breakers protect electric installations against overloads and short circuits [9] as the possible heat might damage the power network installation. As can be seen in the figure 2.2, a slow overload lasting for too long trips the fuse as well as a sudden high consumption.

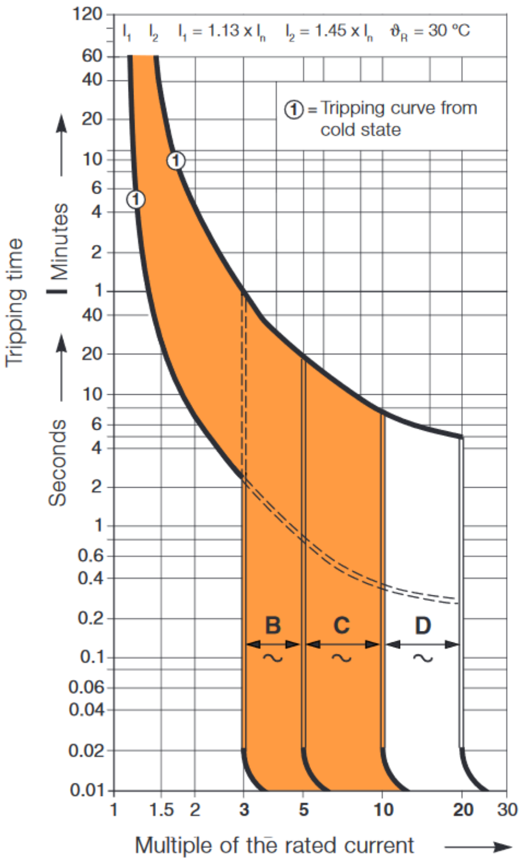

Figure 2.2: Circuit-breaker tripping characteristic [9]

There are three basic types of fuses used. The difference lies in the tripping current and time. The fuse type B has the strictest criteria, therefore it has been selected as the reference for the thesis. Disregarding possible inaccuracy caused by heating, some values of interest are: a) double the threshold value leaving six seconds to lower the consumption to/under the threshold, b) overloading by half of the threshold value which leaves about twenty seconds and c) thirteen percent overload which gives the control an hour to lower the consumption. Finally, reaching three times and more of the threshold leads to immediate tripping.

2.3.2 CEM

The CEM unit has a crucial role in controlling the house consumption. It processes all current measurements from the grid connection point, then evaluates and creates plans for the consumption of controllable devices. Moreover it stores information about tariff prices, threshold value for the fuses and serves as an interface for the user and the rest of the HEMS.

The CEM controls devices by sending three upper consumption limits because the power network has three phases[1]. The limits are calculated and sent as current values in Ampere representing the maximum possible power as the voltage in the network remains constant.

The CEM runs with frequency of

$$f_{CEM} = 4\text{Hz}. \tag{2.1}$$

Controlling devices with a small consumption with the delay of maximum 250ms is acceptable - however when values rise, the time needed to send new limits when the total consumption is getting closer to threshold value can cause a temporary overload and in worst case a blackout. The risk increases with increased delays on input, resp. output as shown in paragraph 2.3.4.

2.3.3 Current sensors

To measure the current flowing through the grid or to any device where the current is measured, sensors are required. As the installation of the CEM should be easy and non-invasive to the environment (it is not necessary to cut or change paths of any of the wires), the most logical solution is using Hall's current sensors as they are contactless and do not require any adaption of the home power network.

Since the sensor works as a current transformer and there are neither transport delays nor data buffers, the measurement is available in the CEM continuously and immediately. After processing (multiplying the received value by a defined scaling factor), the actual current on the phase can be used for further calculations.

2.3.4 Electric vehicle supply equipment (EVSE) and the charging process

The EVSE serves as an interface between the EV and the power grid and has several functions including coordination of the charging process. The process is initiated when the driver arrives at the EVSE and plugs the vehicle in. Optionally several parameters can be set inside the EV whilst the other cannot. These are:

- target state of charge - optional

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[1] If the network has three phases, otherwise the number is different.

- distance the EV will be driven - optional
- departure time - optional
- battery state of health
- battery type & capacity
- charging possibilities

The driver can select the target state of charge (or the distance which the car should be able to drive) or the departure time. EV then creates a charging plan and sends it to the EVSE which 'translates' the request for the HEMS. If the plan is accepted by the CEM as feasible, the charging begins.

If the driver does not specify the desired distance/state of charge or departure time, the EV then charges with maximum possible power. The focus of control algorithms presented in this work is to prevent blackouts while maximizing the power usage during unplanned charging by adjusting or stopping the charging even when unpredicted loads create a risk of a blackout.

Originally alternating current (AC) was used for recharging the vehicle. However, according to [10] AC stations were only able to supply the EV with about 1.4kW resulting into twelve hours of recharge time for a 16kWh completely discharged battery. Today, even though AC chargers reached higher powers with higher voltage and current, direct current (DC) is used for home charging as well as for fast charging stations.

Several requirements in order to preserve the battery lifetime are defining the process constraints. First of them is the minimum charging current - when obtaining current limits from the HEMS, the charging will not start until the limit value crosses this minimum value, and the charging will stop when the limit falls under it vice versa. This requirement is linked tightly in the CEM unit with two others - avoiding oscillations (as the limit can descend under the specific value) resulting into turning the charging on and off in the beginning phase, and turning the charging process off only when it is inevitable. For the purpose of the thesis a charger with minimum charging current of

$$I = 6\text{A} \tag{2.2}$$

was used.

The EVSE used in this work introduces an issue with respect to the complete system. It is capable of communicating with the CEM unit (receive limits, send information about actual power usage) but the output is sent once per second as a result of averaging from the last sample output. Moreover a buffer on the limit receiver causes a delay of an additional one second. Both delays on output and input are the main focus of this thesis.

2.4 Modeling the environment

The next part is dedicated to the model of the previously described elements. Simulink was chosen as the program for modelling and running simulations of the whole setup where several simplifactions were made as the main purpose of this work is to develop control algorithms. It is very important to state that the whole control together with the model was designed as a single phase instead of a classical three-phased power network. As common to the mentioned EEBus protocol, the communication exchanges only current values expecting a constant 230V.

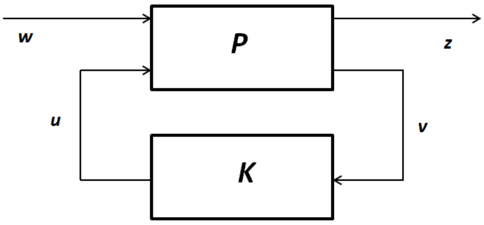

Figure 2.3: Generalized control problem formulation [11]

2.4.1 Generalized control problem

The generalized control problem was used as a template and modified to hold all important features of the real-life system. As can be seen in figure 2.3, the system consists of two main subsystems. The subsystem $\boldsymbol{P}$ represents the EVSEs with connected EVs all toghether with home appliances. It holds five EVSE models which were used as a minimum amount capable of tripping the fuse (see part 2.4.3).

The second subsystem represents a HEMS controller where input values are measurements from the system and output $\boldsymbol{u}$ is composed of limits for each EVSE. In this work the controller $\boldsymbol{K}$ is the CEM unit with stored algorithms and a switch which determines the algorithm to be used.

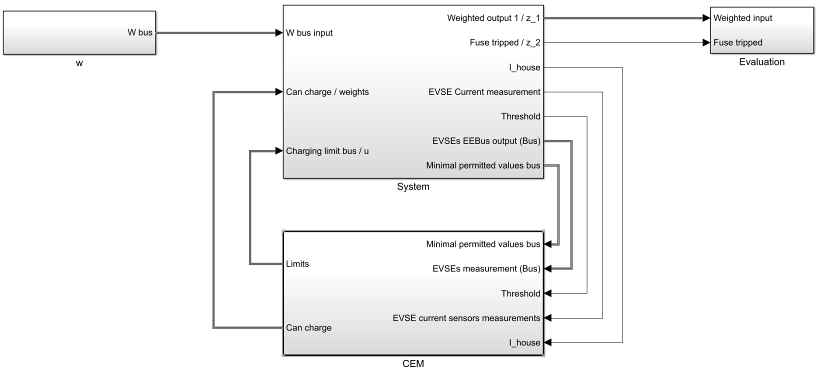

Figure 2.4: Simulink implementation of the generalized control problem for the thesis

2.4.2 Signals in the system

The system contains four different signals. Each one has its own definition as described below.

Signal w

Signal $\boldsymbol{w}$ is defined in [11] as weighted exogenous inputs. It can contain noises, disturbances, but also references. In other words, this signal represents everything coming from outside of the environment that cannot be controlled by the algorithm. In this case the signal is a bus-type signal which contains the threshold of the fuse, uncontrollable house consumption, minimum charging values for each EVSE and charging demand. The first two simplifications are done here - the charging demand for the EV can be known in advance and might differ in time; however the simulations were run with references given as single steps from zero to a given value at certain time. The same applies to the house consumption, which in reality differs in time and evinces dynamic behaviour.

Signal z

The definition in [11] describes the $\boldsymbol{z}$ signal as a weighted exogenous output or as a normalized control output. It is not defined what this signal should be by default. As for the charging control design the differences between charging demand and obtained limit were chosen weighted by one (if the vehicle can be charged) or zero (if the charging is not possible or if there is no demand) and summed. Second signal shows whether the circuit-breaker was tripped or not where only 'true' (1)/'false' (0) values appear.

Signal $\boldsymbol{u}$

The signal $\boldsymbol{u}$ only contains the upper consumption limits for the EVSEs, where each one gets its own value, generally different from the other EVSEs. As the simulation operates with 5 models, the signal $\boldsymbol{u}$ is a bus signal composed of 5 limit values.

Signal $\boldsymbol{v}$

The last signal to be described in the system is the measured output coming from the system to the controller. The contents of the bus signal $\boldsymbol{v}$ are threshold value (which could be stored inside the CEM because the threshold is constant for each case), the overall grid current consumption and EVSEs measurement communicated toghether with minimum allowed charging values through the communication protocol.

2.4.3 Model of the EVSE

Having defined the generalized control system together with the signals it contains, the next step is the EVSE. Modelling the charger can be complicated as for example shown in [12], it needs several controllers itself with filters in order to convert AC current and voltage to DC and provide stable power. The model developed and used in this thesis works with a single-phase DC network as the goal is to distribute power to the vehicles.

As seen in the figure 2.5, disregarding the output labeled *Scope out*, which serves the process of evaluation, three other outputs can be found. Output No. 1 sends the EEBus measurements. The blocks *Zero-order hold* in combination with *Unit delay* are one of several simplifications in the EVSE model. The averaging over one second is simplified and the EVSE model outputs values sampled with frequency

$$f_{EVSE} = 1\text{Hz}. \tag{2.3}$$

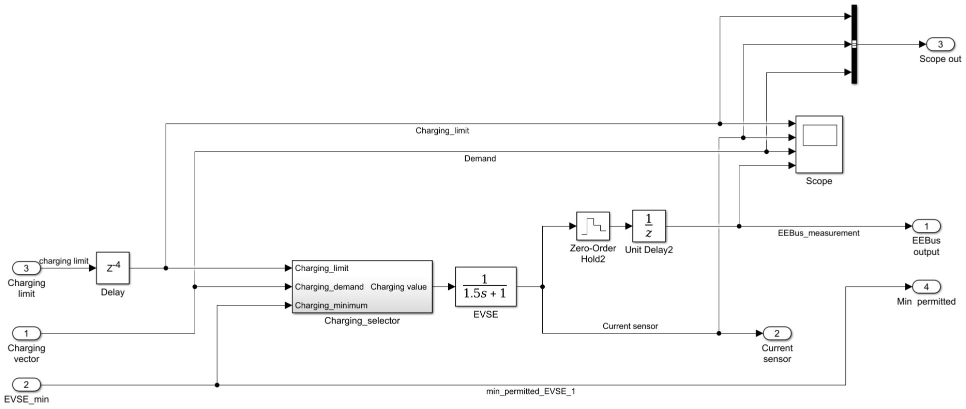

Figure 2.5: Simulink implementation: model of the EVSE

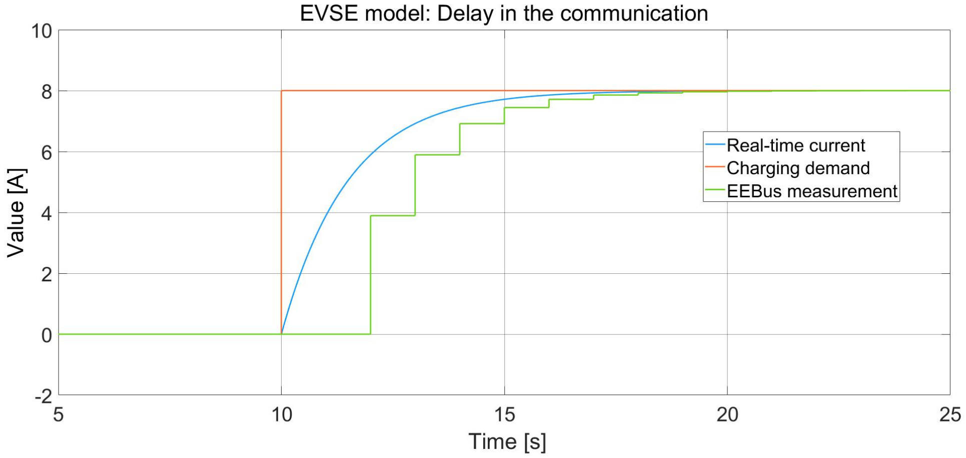

Figure 2.6: An example showing the delay in the communication on the EVSE output

Supposing the rest of the path being ideal, no other delay in the measurement communication appears. Figure 2.6 shows both the EEBus protocol delayed measurements and the real-time current consumption.

Output No. 2 labeled *Current sensor* sends real-time current consumption. This measurement is not processed separately, but is summed with the rest of the consumption and sent to the CEM as the grid consumption.

The EVSE core, labeled *EVSE* in the model, simulates the current flowing to the EV. The charger model is simplified to only a first order system with time constant

$$\tau = 1.5s, \tag{2.4}$$

which meets the assignment requirements. Equation

$$I(s) = \frac{I_{lim}}{\tau s + 1} = \frac{I_{lim}}{1.5s + 1}, \tag{2.5}$$

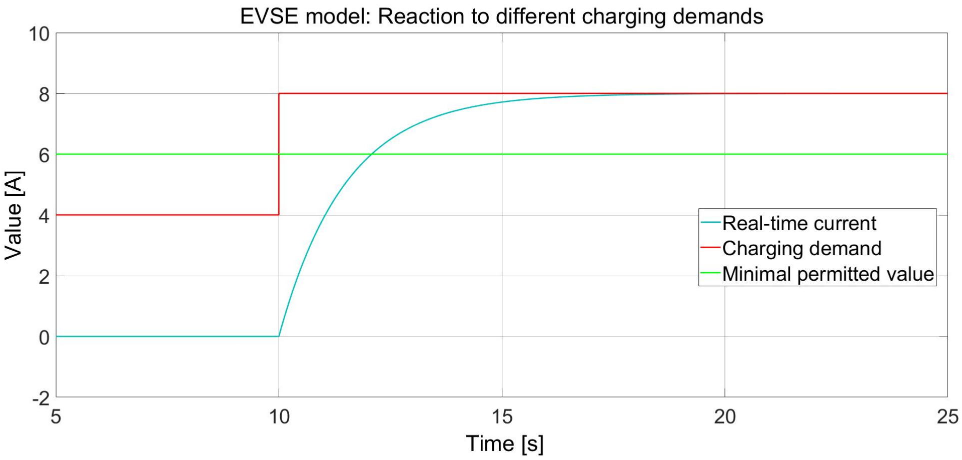

Figure 2.7: Response of the EVSE to charging demand; step from 4A to 6A with no threshold limitation

defining the first order system, can be transformed using inverted Laplace transform into equation

$$I(t) = I_{lim}(1 - e^{-\frac{t}{\tau}}) = I_{lim}(1 - e^{-\frac{t}{1.5}}) \tag{2.6}$$

showing the real-time consumption. I_{lim} in both equations 2.5 and 2.6 represents the current consumption limit.

Another signal connected to the EEBus protocol is passed through the whole system and comes from the $\boldsymbol{w}$ input: The minimum charging value. It remains constant through the whole simulation and the EVSE does not start charging until the limit passes the minimum value as can be seen in figure 2.7, where the charging current is represented by *Real-time current* goes up at the moment when the demand exceeds this value.

Figure 2.8 shows the reason why a more careful approach is necessary. As implementation of the algorithms with more detailed description including the deriving of the equation 3.3 is in the next part, the simulation was controlled by a signal calculated on a very basic equation given by [13] as

$$I_{lim} = Threshold - I_{grid} + I_{EVSE}, \tag{2.7}$$

where threshold is given by the fuse, I_{grid} is the total grid consumption and I_{EVSE} is obtained from the EVSE via the communication protocol. As figure 2.8 shows, there is a two second long delay (one second because of the sampling rate on the output, one second on the input due to internal data buffer) before the EVSE receives a command to adjust its consumption.

This paragraph shows how many EVSEs are able to cause the circuit-breaker to trip if only the equation 3.3 was used as the control signal while considering N EVs receiveing a global consumption limit equal to the threshold value, not charging at the beginning. This situation can appear for example after a configuration inside the CEM is done and the whole system restarts. Based on the equation 3.3 - nothing is flowing through the grid and EVSEs

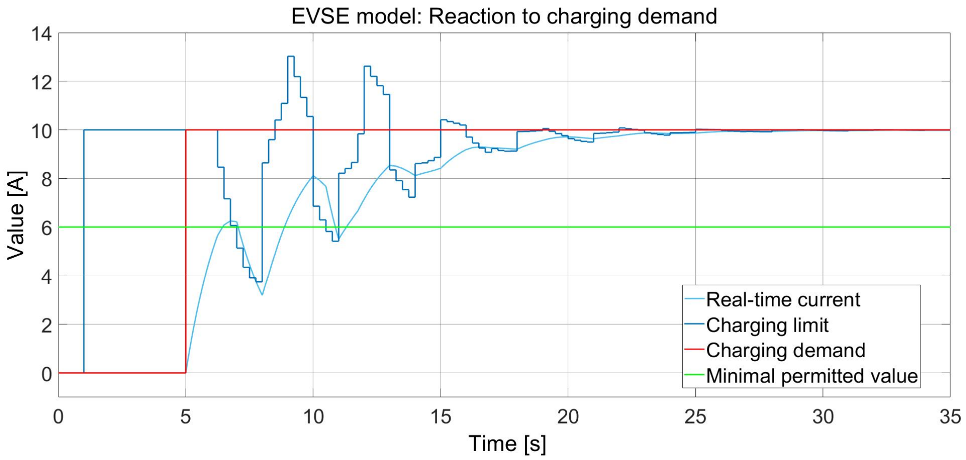

Figure 2.8: Response of the EVSE to charging demand; step from 0A to 10A; threshold = 10A

are not consuming anything, so the equation changes to only

$$I_{lim} = Threshold. \tag{2.8}$$

During the time period of 2 seconds the consumption rises to

$$I(2) = Threshold \cdot (1 - e^{-\frac{2}{1.5}}) = 0.736 \cdot Threshold \tag{2.9}$$

for each EVSE. Aiming to obtain the number N defining the least number of EVSEs to trip the fuse, the grid consumption for N chargers would be

$$I_{grid} = N \cdot I(2) = 0.736 \cdot N \cdot Threshold. \tag{2.10}$$

From 2.3.1 it is known that with the strictest rule the fuse trips when the consumption reaches 300% of the threshold. N is then calculated as

$$N = \lceil \frac{3 \cdot Threshold}{0.736 \cdot Threshold} \rceil = \lceil \frac{3}{0.736} \rceil = \lceil 4.07 \rceil = 5. \tag{2.11}$$

In other words, following the ideal model a simultaneous start of charging process for five EVs is capable of tripping the fuse, thus the model gives an opportunity to charge five vehicles as a sufficient number for the purpose of stability testing.

2.4.4 Modeling the circuit-breaker

To help faster evaluating of the control mechanism, a simplified model of the circuit-breaker was implemented. Based on figure 2.2, the table 2.1 shows several significant times which were used to create the model. Each row

Overshoot [%]	Tripping time [s]
13	3 600
25	360
40	60
50	20
75	10
100	6
200	0

Table 2.1: Tripping time based on overshoot over the threshold value

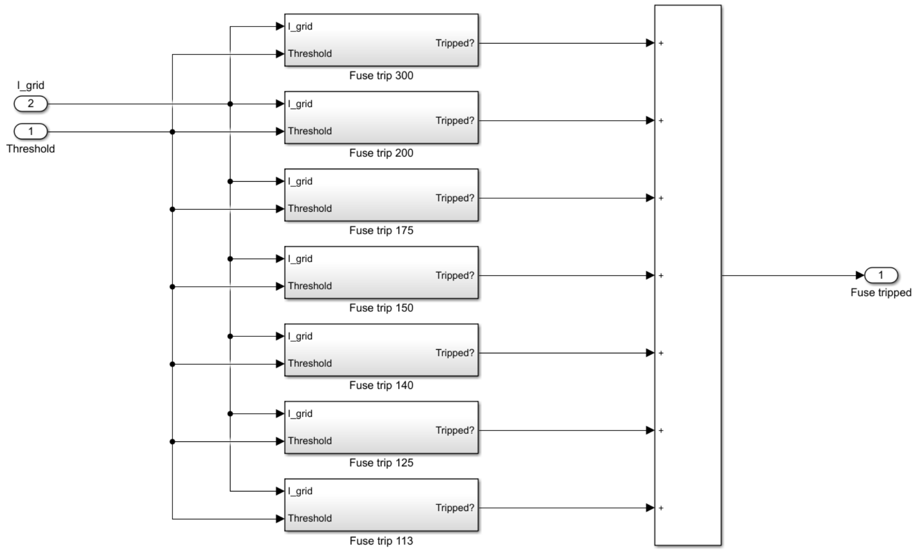

Figure 2.9: Simulink implementation of a circuit-breaker

from the table represents a subsystem in the whole fuse model as shown in 2.9. The implementation neglects any heat effects and treats the fuse as a switch where each subsystem behaves as a timer. As it can be seen in the figure 2.10, the threshold is multiplied by two constants - upper and lower boundaries. If the current measurement from the grid point lies within the interval specified by these boundaries, a logical value ’true’ (represented by number 1) is being integrated over time. The integrator block adds ’1’ for each second for which the grid consumption exceeds the threshold. Because the fuse should have no memory, the integrator (counter) reset is driven by a falling edge of the signal detecting leaving the lower boundary of this subsystem.

Going from top to bottom, the highest subsystem has the strictest conditions to fulfill. If any of the subsystems detect the fuse to be tripped, the simulation will not stop, but the output is non-zero. However if the higher subsystem’s condition is fulfilled, all other conditions are fulfilled as well.

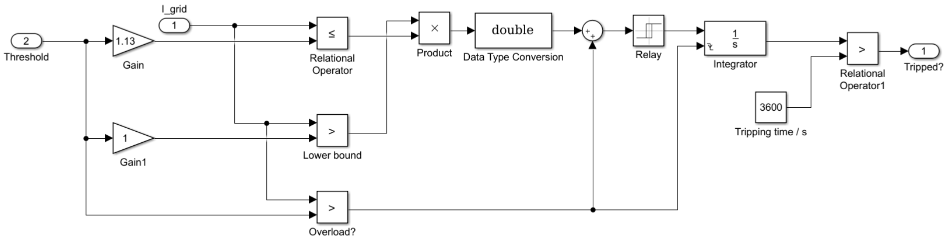

Figure 2.10: Simulink implementation of circuit-breaker component; overshoot of 13% with tripping time 3600s

2.5 Other simplifications

This last part describes other simplifications which were made in the model as not everything could be substituted. Current sensors for example do not have to be simulated since the current consumption is sent directly as a signal. As already mentioned, the whole model behaves as a single-phase power network.

Since the EVSE model simulates only real-time consumption and communication delays, it has no ability of further planning with regards to user's wishes.

To summarize all the simplifications and restrictions, the controller is designed to react only on real-time charging demand and consumption with no future planning or detailed vehicle information. Furthermore, the model supports only single-phased networks which eliminates possibility to delegate power from one phase to another. Another issue brought in by Simulink, which resembles an ideal environment, does not take into account the imperfection of the communication channel. For example, if two vehicles request charging at the exact same time, they will not start charging at the same time - Simulink however will provide them the limit simultaneously.

Part II

Algorithms & implementation

Chapter 3

Algorithms: Description and implementation

3.1 Requirements

The previous part has shown that implementing a controller for the home charging is inevitable. First of all a set of requirements to be followed has to be defined. This part contains description of the requirements with a short explanation why they have to be fullfilled.

Avoid tripping the fuse

The controller has to react to real-time changes in grid consumption, which is why home charging is of lower priority. This is also determined by the fact that most of the home appliances are not controllable by HEMS.

Avoid oscillations of the charging power

For preserving the lifetime and state of health of the EV's battery limits have to be distributed in a way that eliminates oscillations. The figure

2.8 in section 2.4.3 shows a problematic control using only a basic approach; this has to be avoided.

Termination of the charging only when it is necessary

The problem of unwanted charging process termination occurs due to usage of minimum permitted charging currents. If the limit drops below this value, the charging is terminated automatically. The issue lies in the used relays which switch based on whether the vehicle is being charged. Switching these shortens their lifetime and could result into increased expenses. The example shown in figure 2.8 shows the connection of this problem with the oscillation - the charging limit dropped two times under the minimum permitted value (at time t = 7s and t = 10.75s) meaning the relays being switched off and on again two more times than necessary. Repeating this every time while the vehicle is being recharged reduces the lifetime of relays to only a third of its original value.

Power usage maximization

The last requirement does not concern safety or lifetime, but efficiency. The goal is to maximize the power usage to reduce the charging time to minimum but still without overloading the grid or triping the circuit-breaker.

3.2 Description

Several approaches can be used for distributing power. The thesis focuses on two different algorithms: priority-based and balanced. Although papers [14] and [15] use algorithms that are based on planning with respect to real-time electricity tariffs, they brought up a few points which can be useful for developing a real-time unscheduled controller.

3.2.1 Priority-based algorithms

The first algorithm to be described is based on priorities. The device with the highest priority can consume everything it has planned, the device with lower priority receives the remaining ununsed power.

The following priority algorithms have the same implementation, they only differ in how the priority is assigned. A very natural approach is First-Come-First-Serve algorithm. People encounter it almost every day - waiting in a queue in a shop, traffic lights etc. The highest priority is assigned to the vehicle which requests the charging first. Every vehicle arriving after has to subordinate its charging demand to higher priorities.

The second featured and tested algorithm is based on a fixed priority list. The priorities are assigned by the user. An advantage of this approach is that the highest priority vehicle's (which is for example driven every day to work) owner will probably have the vehicle charged to desired states. On the other hand, the lower priority vehicle can be forced to terminate its charging process when the higher priority vehicle arrives with a demand not leaving any usable power to other vehicles.

The biggest advantage of these two priority-based algorithms is that they do not require any further specification from the user such as desired state of charge on departure or departure time. Other possible algorithms using priorities can be for example based on deadline (Eearliest Deadline First - EDF) or state of charge, both desired on departure or actual on arrival. Nevertheless, further testing and investigations are required as the EDF did not prove itself to be optimal, as discovered by [14].

Example of behaviour: First-Come-First-Served

For a better understanding the behaviour, an exemplary situation with two EVs where the minimum charging current is 6A as mentioned in equation 2.2 and a fuse with the threshold of 16A is being considered.

At the beginning no other home appliance is turned on. The first vehicle arrives and obtains a limit equal to the threshold - 16A - but charges with only 10A. After some time, the second EV arrives with the same plan of 10A. However, it can only consume 6A. At this moment the first EV, which still, as it has the highest priority, can raise its consumption, starts consuming 12A for a short period of time. Because only 4A are left on the grid and the minimum value for both chargers is 6A, the second charger has to stop. After the first EV's current consumption descends to 10A again, the lower priority one starts charging again. Afterwards an unknown device with consumption of 7A is turned on - to ensure the blackout protection, the CEM terminates the charging for lower priority EV and the higher priority receives a new limit to follow, which is 9A.

Example of behaviour: Priority list

Consider the same setup as in the example above - two EVs, both with a demand of 10A for the whole time, circuit-breaker's threshold current is 16A. The only difference is that their priorities are set by default.

The first vehicle to come is now the lower priority one and starts charging with its request of 10A. When the higher priority EV arrives, it obtains a limit which is equal to threshold again. Although being the first one to be charged, the lower priority vehicle has to reduce its consumption to 6A. It would also be the first one to be cut off again if the higher priority EV raises its charging power or if another device is turned on.

3.2.2 Balanced algorithm

The balanced algorithm considers all the vehicles connected to the grid equal. It aims to give everyone the same power limit. If any of the vehicles does not use all the provided current, the rest should be processed and offered to other EVs in order to maximize utilization.

The advantage lies in treating all vehicles in the same way - everyone has an opportunity to charge the same amount of energy. On the other side, if a vehicle creates its plan and a new one arrives, the current limits are recalculated and the plan might be recalculated as well which could cause the charging to be terminated temporarily until a new plan is ready.

As both types of algorithms were firstly developed and implemented without the minimum charging current, the development of minimum charging values support for the balanced approach was not successful. Several ideas for the control with connected issues are mentioned in the summary.

Example of behaviour: Balanced algorithm

Again, the same setup as for the First-Come-First-Server and priority list is used. The difference, as mentioned above, lies in not having the priorities. Also, the charging is not cancelled if the limit drops under 6A for any of the vehicles.

The beginning remains the same as well - the first vehicle receives a limit of 16A as there is nothing else consuming power. When the second vehicle is plugged in, the limit is recalculated based on equation

$$I_{limit} = \frac{I_{available}}{2} = \frac{16}{2} = 8A. \tag{3.1}$$

Both vehicles can only use 8A for charging now. If a device consuming 5A is started, the limit for both vehicles changes to

$$I_{limit} = \frac{16-5}{2} = 5.5A. \tag{3.2}$$

3.3 Theoretical background

The next part describes the equations and approach that were used for developing the control. Both algorithms are based on the same equation and both are sending their limits gradually, as can be seen in figures 3.1 and 3.3.

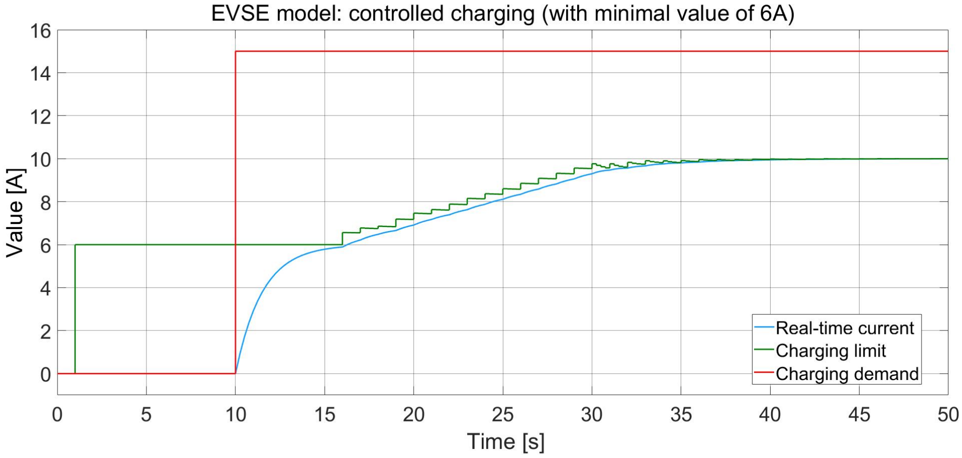

Figure 3.1: Controlled charging: Demand (15A) exceeding the threshold (10A) while slowly raising the charging limit ($K = 0.1$)

3.3.1 Common base

The basic problem is calculating the current available for charging. As specified in [13], the equation to start from is

$$I_{available} = I_{Threshold} - I_{grid} + \sum_{i=1}^{N} I_{EVSE_i}, \tag{3.3}$$

where $I_{available}$ defines the current which can be used for charging, $I_{Threshold}$ is the threshold value of used circuit-breaker, I_{grid} is the overall consumption received from grid measurements and the sum of I_{EVSE} defines the electrical current usage for charging which is sent by EVSEs. The CEM obtains this with a one second delay.

Specifying the available current generally as

$$I_{available} = I_{Threshold} - I_{house}, \tag{3.4}$$

the current consumed by uncontrollable/other devices, represented by I_{house}, has to be calculated using the Kirchhoff's law for current. Knowing that all the current flowing through the grid connection point is consumed either by the house or the EVSEs, the grid consumption equals to

$$I_{grid} = I_{house} + \sum_{i=1}^{N} I_{EVSE_i}. \tag{3.5}$$

Now the I_{house} can be substituted by

$$I_{house} = I_{grid} - \sum_{i=1}^{N} I_{EVSE_i} \tag{3.6}$$

in the equation 3.3.

3.3.2 Priority-based approach

The idea used for the priority-based algorithms lies in separating calculations of limits and checking whether the charging is possible. Splitting the solution into two parts gives a possibility to reduce the charging limits smoothly when overload occurs and guarrantees fastest possible reactions when the charging should be terminated because of insufficient power. Also, as the limits calculating part always sends at least minimum values for chargers, any EVSE can start charging at any moment if it is allowed to start.

First, the process determinating the possibility of charging is described. The algorithm only uses real-time grid measurements and compares them with the threshold value. However it does not terminate the charging with every overload occurence as the controller can prevent tripping the fuse with lowering the consumption limit. The turn-off point is the defined as

$$I_{Turn-off} : -I_{Threshold} + I_{min} > I_{Threshold} - I_{grid} \tag{3.7}$$

where the I_{min} is defined in equation 2.2. The state 'on' has different value which is equal to I_{min}. This is valid for the highest priority EVSE.

Every lower priority EVSEs has to respect the consumption of higher priority ones. To explain the behaviour and prepare the modification, an example considering two EVSEs and fuse's threshold of 16A is provided. The first one (with higher priority) is charging 9A, the second one 7A. Now, if another device consuming 2A is turned on and the control is following the condition 3.7 with no modifications, none of the chargers will be turned off. Substituting the values in the condition would yield

$$-I_{Threshold} + I_{min} = -16 + 6 = -10A \tag{3.8}$$

and

$$\begin{aligned} I_{Threshold} - I_{grid} = I_{Threshold} - (I_{EVSE_1} + I_{EVSE_2} + I_{house}) = \\ = 16 - (9 + 7 + 2) = -2A. \end{aligned} \tag{3.9}$$

The second charger should be stopped now, however with outputting limit of 6A, not lowering the first charger with consumption of 9A and having the 2A consumption from house, the sum is 17A and circuit-breaker will eventually be tripped. The correct way should be turning the second charger off as its limit (5A) does not satisfy the minimum value condition.

To terminate the process, the priorities have to be taken into account. In other words, the current used by the first EVSE cannot be considered as available for the lower priority vehicles. Therefore measurements obtained from higher priorities have to be subtracted. The condition 3.7 after modifying will become

$$I_{Turn-off_i} : -I_{Threshold} + I_{min} > I_{Threshold} - I_{grid} - \sum_{j=1}^{M} I_{EVSE_j} \tag{3.10}$$

where M is a number of chargers of higher priority than the charger i. Using this condition does not affect the highest priority charger but will cancel the charging of the lower priority vehicles as shown in figure 3.2. Regarding the example, the modified condition in the moment of starting the 2A device looks like

$$I_{Threshold} - I_{grid} - \sum_{j=1}^{M} I_{EVSE_j} = 16 - (9 + 7 + 2) - 9 = 16 - 18 - 9 = -11A. \tag{3.11}$$

The condition 3.7 is now fulfilled and the second charger cannot charge.

Second part of the priority-based charging only focuses on computing the limit. As shown in paragraph 2.4.3, it is unsafe to allocate and provide all the available power to all connected chargers. To give every connected EV an opportunity to start charging, the minimum value is offered in the beginning. When the CEM gets the current within a certain range, it starts to return the obtained measurements plus a fraction of the available current computed as in equation 3.3. The only difference here is that the i index labels sum of measurements coming from EVSEs with lower priority and the current one. From the point of the lower priority chargers, the higher ones are acting as other uncontrollable home devices. The runup speed is based on the fraction

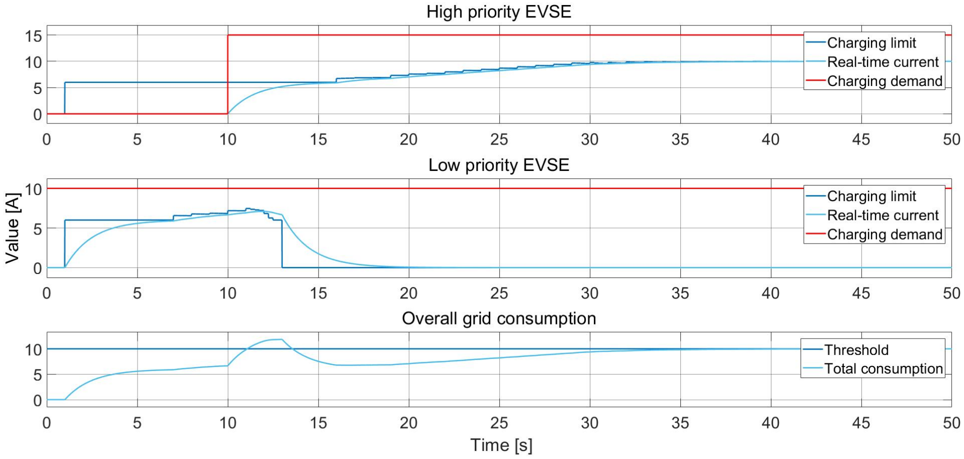

Figure 3.2: Controlled charging: Low priority EVSE stopped when higher priority EVSE starts charging. Algorithm: Priority list, minimum value active; test case ID: PRIO_03

of the available current. The final equation for the charger limit is then

$$I_{lim_{EVSE_i}} = I_{EVSE_i} + K \cdot (I_{Threshold} - I_{grid} + \sum_{j=1}^{M} I_{EVSE_j}) \tag{3.12}$$

where j stands for lower priority EVSEs and K is the fraction of the current limitation which follows

$$K \in (0, 1\rangle \,. \tag{3.13}$$

The controller also has to keep the values of the limit within a certain range. The lower boundary is already given, the upper one can be the threshold value or, in case of recharging more vehicles or having another consumption, the available current given as

$$I_{available} = I_{Threshold} - I_{grid} + \sum_{j=1}^{M} I_{EVSE_j} \,. \tag{3.14}$$

The last part of the algorithm focuses on a more precise calculation of the available current. As the demand of the vehicle remains unknown, the last part reserves power by virtually modifying the real grid consumption. It forces other chargers to lower their consumption by lowering the available current. This is done with regard to a simple fact that when the EV starts its charging, it is obvious that at least the minimum charging value will be consumed. Until the incoming measurement confirms reaching of this value, the CEM behaves as if the charger provided the minimum value all the time. The virtual modification is simply done by subtracting the obtained measurement and adding the minimum permitted value of the charger. After obtaining the minimum value, the CEM can then no longer predict the demand, so it again uses the real obtained measurement.

3.3.3 Balanced algorithm

In comparison to the priority-based approach, the balanced charging one has several features in common. The base of the algorithm is again the equation 3.3, now without any modification as the limit is not driven by any priorities. The only difference is that the limit for each EVSE is computed as

$$I_{lim} = \frac{I_{available}}{N} = \frac{I_{Threshold} - I_{grid} + \sum_{i=1}^{N} I_{EVSE_i}}{N} \tag{3.15}$$

where N is the number of active chargers. Omitting the minimum permitted values there is no need to check whether the charging is possible and the limits can be sent throughout the whole charging session.

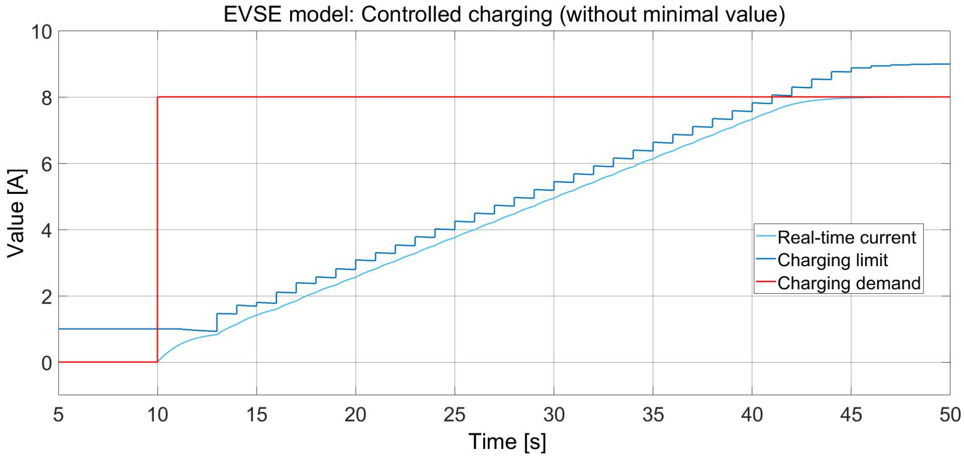

Figure 3.3: Controlled charging: Demand below threshold, distribution of current for an EVSE without minimum permitted value

To prevent oscillations and possible overload, the raw limit from equation 3.15 gets processed and set as the upper bound for the control. The output for the EVSE is then composed from the obtained measurement and a fraction of the available current. The equation for this is

$$I_{lim_{EVSE_i}} = I_{EVSE_i} + K \cdot \frac{I_{Threshold} - I_{grid} + \sum_{i=1}^{N} I_{EVSE_i}}{N}. \tag{3.16}$$

The parameter K again follows the condition 3.13.

The second part of the balanced charging control is redistributing the unused current. If a vehicle is being charged with value below the limit (even while reaching its demand or the given limitation), the unused current calculated as

$$I_{unused_i} = \frac{I_{available}}{N} - I_{EVSE_i}. \tag{3.17}$$

This current could be redistributed to other vehicles in order to maximize consumption. The idea is to sum all ununsed current and eliminate chargers providing it. As a result, a new equation can be written as

$$I_{extra} = \frac{\sum_{i=1}^{N} I_{unused_i}}{N - M} \tag{3.18}$$

where N is the number of EVSEs and M is the number of EVSEs charging below the limit. This value is provided as an extension for the upper bound, which now becomes

$$I_{upper\_limit} = \frac{I_{available}}{N} + \frac{\sum_{i=1}^{N} I_{unused_i}}{N - M}. \tag{3.19}$$

The overall unused current has to be saturated - other EVSEs are still obtaining limits which allow them to raise the consumption. If the system contained three EVSEs for example, where two vehicles were charging with a small amount of power, the third one could be consuming everything what is left available on the grid. Suppose

$$K \in (0, 1\rangle \tag{3.20}$$

and two low power EVs are being charged in a way which gives them opportunity to obtain limits as specified in 3.16 without any saturation. With regards to equation 2.9, which shows that the consumption reaches 73.6 % of the given limit before the CEM can react, if the two low-power chargers decided (with regards to their internal plan) to charge within the full obtained limit, the consumption will grow to

$$I_{growth} = 0.736 \cdot (N - 1) \cdot K \cdot \frac{I_{available}}{N}. \tag{3.21}$$

For simplification, $I_{available}$ is considered to be equal to the threshold. The mentioned equation cannot trip the fuse immediately (all the factors - K, $\frac{N-1}{N}$ are lower than one), but it can cause significant overload. With a sudden house consumption, tripping the fuse might be inevitable. As this cannot be prevented, the potential overload can at least be minimized.

For the minimization, the part responsible for redistribution has to know how much power is sent via limits. Then it has a specification how much can the sum of limits grow over the threshold. The current used for redistribution now only fills the gap.

3.4 Implementation

Simulink was used for implementation without any functions transfered from code. Both approaches [1] are stored inside the CEM unit block. The

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[1] The First-Come-First-Serve does not have its own implementation as it differs just by assigning priorities.

figure 3.4 shows algorithms blocks and a switch controlled by a variable *algo*, which can be set from a Matlab script together with the rest of variables (minimum charging values, threshold etc.). Setting the frequency of the controller is done through the subsystem settings and is not realised inside the model.

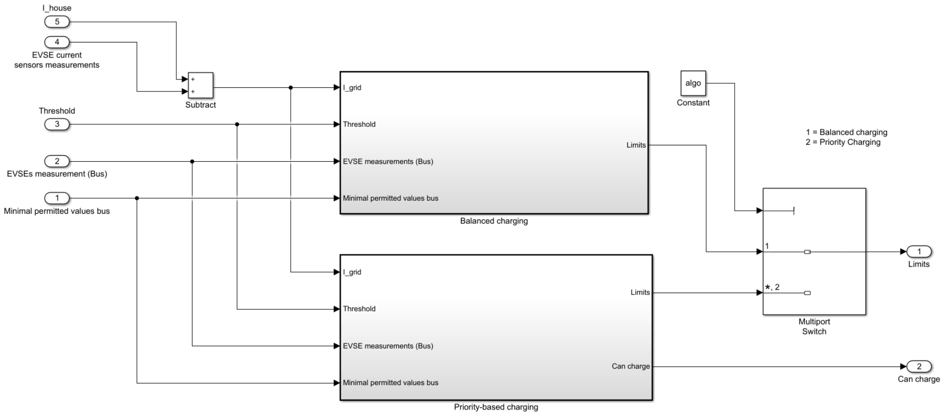

Figure 3.4: Simulink implementation: Routing of signals inside the CEM unit

3.4.1 Priority-based algorithms

Both First-Come-First-Serve and Priority list have the same implementation, the difference only lies in assigning the priorities. In the implementation, the priorities remain fixed following rule where the lowest index number has the highest priority. With increasing the index number, the priority descends.

As described in the theoretical part, the implementation is separated into two subsystems. The condition 3.7 is realised with *Relay* which allows to place the hysteresis according to different turning points. Calculations are separated in their own subsystem where the grid consumption is preprocessed with reserving the current for higher priorities together with the EEBus measurements. The output afterwards receives all signals and based on the measurements and available current the limit is saturated (if necessary) and sent to the EVSE. The whole Simulink scheme can be found in the appendix D.

3.4.2 Balanced charging

As the balanced charging does not follow the minimum charging current rule, there is no need for checking and cancelling the output.

The balanced charging block holds three basic parts. The basic block calculates available current and divides it by N active chargers. First ouput prepares the N for redistributing unused power, second sends the result of equation 3.15. Afterwards the limit is processed, a fraction is added to the received measurement and returned to the EVSE while the difference between the limit and obtained current measurement is sent via closed-loop controller and added back as a saturation for the limit-outputting subsystem. For the implementation see appendix D.

Chapter 4

Testing the implementation

To define whether the developped algorithm is working properly, a set of test cases has to be defined. Because Simulink is going hand in hand with Matlab, a script capable of running another $.m$ file with the test cases inside the model was created. Tests cover several basic demands and simulations which could appear in real situation.

4.1 Test cases

Each test case should cover at least one requirement placed on the control. Abilities which were tested were:

- stability - whether algorithm does not cause overload itself by sending the limits
- performance - if the algorithm behaves properly for every EVSE in the simulation
- reaction speed - when overload is detected, can the controller prevent tripping the circuit-breaker
- effectivity - whether the consumption is maximized.

Each approach has several tests cases connected going from one or two EVSEs to test whether the algorithms behave as expected in basic situations to all 5 EVSEs operating with unexpected consumption coming from the house.

At first each approach has to fulfill a demand from one EVSE - let it charge its desired power, saturate it on the threshold or calculate the available current properly when another device starts consuming power. Testing with two vehicles is supposed to show if lower priority consumption does not affect the higher priority and if the higher one is able to raise its demand, again without overload. For the balaned charging connection of another EV should trigger recalculation of limits and lowering the EV which was already being charged. As for the last, performance test with all five EVSEs running simulated a situation when, for some reason, a restart of the CEM was necessary and all the EVSEs were discovered with their charging demand at once [1]. The whole list of test cases with results and notes can be found in appendix B.

For the testing, the value of parameter K was set to

$$K = 0.1 \tag{4.1}$$

as no requirement for the runup speed is set. The K can be tuned to achieve the final demand faster but with a risk of oscillations.

4.2 Testing results

As for the results, the implementation succeeded in twenty out of twenty-five test cases. In four test cases the simulation was interrupted by the assertion block - the fuse was tripped. For the priority based algorithms the blackout was caused by a house consumption equal to the threshold value. Even though the CEM sent limits equal to zero immediately, the power consumption was not lowered in time due to the EVSEs' internal buffer, which causes the delay of one second on limit receipt.

The other three failed tests were testing the implementation of the balanced algorithm. The house power consumption was over fifty percent of the threshold in all three cases. An example is shown in the figure 4.1. The reason for failure is same for all of them: When the overload is detected, the CEM immediately lowers the limits. EVSEs receive a new limit, lower their consumption and send new measurements. The problem relates to delay in measurement communication, because whilst the grid consumption is falling, the CEM is receiving the original values from the EVSEs. Based on the equation 3.15, the CEM behaves as if the other consumption has decreased. The limits are rised again until the new set of measurements is obtained and

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[1] This situation does not reflect the real world scenarios as, due to non-ideal environment, EVSEs would connect at the exactly same time.

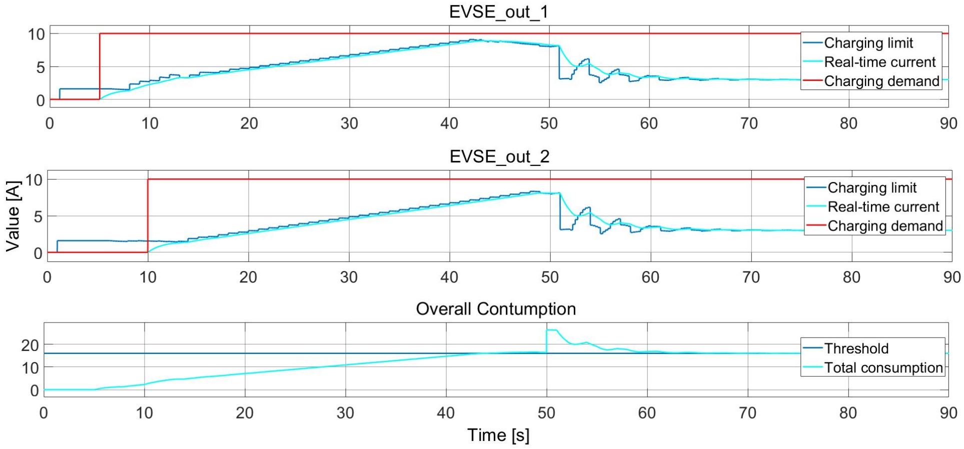

Figure 4.1: Controlled charging: Two EVSEs, house consumption lowers available current. Balanced algorithm, no minimum permitted value

limits are lowered again. Due to this oscillation, the control cannot lower the charging power in time which leads to a blackout.

The last test's result is evaluated as partial success. It is connected to the redistribution of unused current. If one's demand was exactly matching the equation 3.15, one was charging under the limits and one could charge more, the half of it would be used, but the second half offered to the EVSE charging on limit would remain unused.

Chapter 5

Conclusion

The main goal of this thesis was to develop algorithms for allocating power (via computing current consumption for each EVSE) to make the charging more effective. The first part introduced the home energy management system which allows to monitor and control the overall house energy consumption in order to minimize running costs or/and be more gentle to the environment. The optimization follows several basic scenarios such as reducing the peaks or switching to the solar panels, if installed.

Afterwards the description of environment was included with several issues connected to the problem of power control. The environment has been transformed into a Simulink model with several simplifications to match the generalized control problem. After describing the problem definition with requirements ideas for implementation determined the solution.

5.1 Implementation summary

The implementation focused on real-time consumption control to prevent blackout with respect to communication delays. First, the equations for specifying the limits were defined and afterwards transformed to Simulink block schemes with possibility of running with Matlab to help running different test cases.

The basic idea of both algorithms uses the EVSE's own measurement enlarged by a fraction of the current available for charging. As the available current is calculated and used as a saturation, in case of overload EVs obtain lower limits immediately. The advantage lies in avoiding oscillations by slowly raising the limits and going down very fast (in worst case turning off the charging immediately), on the other hand the charging is slowed down in the beginning. However the disadvantage is disputable as the runup is slowed in a matter of seconds while the whole charging could take several hours. Also further tuning with modifying the constant fraction could be done.

The final part of the implementation contains test cases definitions with explanation for designing them in a way they have been designed. Based on results of testing, both algorithms can be considered as successful, however the balanced charging needs several improvements in order to provide better results. Both algorithms did not send values exceeding the threshold and both were able to prevent blackouts. However four tests ended as a failure. The one in the set designed for priority based algorithms is caused by the delay and cannot be prevented without changing the model so that it reflects the real-life appliances in a more detailed way, the environment (for example optimization of the communication to eliminate delays) or the algorithm which in this case would not comply with the requirement of maximizing the power consumption. The other three tests are connected to the balanced algorithm and failed due to limit oscillations which lead to a blackout. These three tests would probably succeed with a better handling of the limit output (as mentioned in part 5.2.2) or with using the minimum charging current rule: All the final limits would drop under the 6A value, so at least one charger would be immediately switched off. Also one test case ended as a partial success due to issue with current redistribution. With regards to the four failed tests, the control implementation can be considered as successful assuming proper modelling of house appliances or using the minimum charging current would prevent the blackout.

5.2 Possible improvements

Needless to say, the whole model together with the algorithms cover just a basic overview of the whole problem. This last part gives suggestions how both could be expanded.

5.2.1 Model improvements

As the model represents a necessary minimum for algorithm development, the behaviour of algorithms is connected with the ideal environment. From the environmental point of view, the house consumption should be improved as in real life it is not an ideal step. Also all transient effects are omitted. Because the charging limits mainly change due to changes of unexpected grid consumption, proper modelling of house appliances might destabilize the control.

Another issue is lack of information from the EV. The simplified environment does not know anything about both desired and actual battery state of charge. Having this information could bring up a solution with planning the charging and avoiding blackout as well.

Last but not least the environment could be expanded to a regular three-phase power network. Having a regular model with EVs which are supporting asymmetric charging (a different power values are used on each phase, e.g. phase one and two could be using 7A while the third one only 5A) the problem can be solved by simply moving the power consumption to another phase.

5.2.2 Suggestions for control algorithms

The control offers a large field of possible improvements. The main target should be the runup speed. Faster runup can be obtained with adding larger fractions of the available power or with implementing a more sophisticated control mechanism. A proposal for the priority based charging would be raising the limits one by one. Connected with that, the controller could send the full available power for the first EVSE and recalculate only in case of overload. When the measurements reaches a stable value or after a specific time window, the controller could fix the limit for an EVSE and move one step lower in the priority list. At the end it would move back to the first one and offer more power, if available. More specific requirements would be needed as the described approach would leave low priority EVs to start charging and after specific time they would be disconnected again.

The balanced charging approach definitely needs more specifications. The biggest issue arises when there is not enough power to charge two EVs simultaneously even with their minimum (e.g. with threshold value of 10A and two EVSEs communicating 6A as the minimum charging current). Following the absence of priorities, the most logical (but least practical) would be not to charge at all. To avoid this, the First-Come-First-Serve should be an extension for the real-time control. For each EVSE which discovers an EV, an admittance test should be done - if the grid could handle charging at least the required minimum, all limits would have to undergo recalculations, otherwise the newcomer would not start charging. All in all the balanced approach can be taken from many different views - the control could go for having the same final state of charge after specific time, or letting each EV to be charged for a specific time. However all these modifications can be taken as a different way to set priorities for individual chargers.

Finally, the issue connected to fast drops of the limit could be handled in a better way. A very basic suggestion for improvement would include a switch which, after an overload was detected, would send the limits calculated immediately after the overload is detected. New limits might be distributed after the blackout is successfully prevented and all the chargers' consumption match the limit which they are obtaining.

Appendices

Appendix A

Project specification

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

BACHELOR‘S THESIS ASSIGNMENT

I. Personal and study details

Student's name:	**Valerián Jakub**	Personal ID number:	**457238**
Faculty / Institute:	**Faculty of Electrical Engineering**		
Department / Institute:	**Department of Control Engineering**		
Study program:	**Cybernetics and Robotics**		
Branch of study:	**Systems and Control**		

II. Bachelor’s thesis details

Bachelor’s thesis title in English:

Bachelor’s thesis title in Czech:

Algoritmy pro zpětnovazební alokaci výkonu pro nabíjení několika elektrických vozidel

Guidelines:

The goal of the project is to come up with algorithms for allocating a power (setting a maximum current) for several electric vehicles at a charging station such that the total power available at the station is fully used but not exceeded. It must be assumed that at least some (if not all) vehicles cannot communicate their charging requirements (the less so their charging plans over some time horizons) to the charging station, hence the control algorithms must process their true (measured) consumption and adjust the allocation of power (maximum current) accordingly in real time. Nonnegligible communication delays between the cars and the charging station must be accounted for. Algorithms should allow several patterns: first come first served, assigned prirority based, balanced (or proportional or 1/n). The algorithms should be excessively tested in simulations in Simulink but some data from measurements might be provided by a collaborating industrial partner.

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[3] L. Zhang and Y. Li, “Optimal Management for Parking-Lot Electric Vehicle Charging by Two-Stage Approximate Dynamic Programming,” IEEE Transactions on Smart Grid, vol. 8, no. 4, pp. 1722–1730, Jul. 2017.

Name and workplace of bachelor’s thesis supervisor:

doc. Ing. Zdeněk Hurák, Ph.D., Department of Control Engineering, FEE

Name and workplace of second bachelor’s thesis supervisor or consultant:

Date of bachelor’s thesis assignment: **15.02.2019** Deadline for bachelor thesis submission: **24.05.2019**

Assignment valid until:
by the end of summer semester 2019/2020

doc. Ing. Zdeněk Hurák, Ph.D. Supervisor’s signature	prof. Ing. Michael Šebek, DrSc. Head of department’s signature	prof. Ing. Pavel Ripka, CSc. Dean’s signature

III. Assignment receipt

The student acknowledges that the bachelor’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor’s thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt

Student’s signature

Appendix B

Test report

Test specification & protocol

Date 21.05.2019

Test criteria	Criteria description
PASS	Test outcome is as excepted.
PARTIAL	Test outcome is only partly achieved.
FAIL	Test has failed.
NOT TESTED	Test has not been carried out.

Test ID	Test Name	Test description	Test prerequisites	Expected Outcome	Result	Comment / Obstacles
FCFS_01	Single low power EV	An EV tries to charge with a demand that is lower than the available current on the main fuse.	Charging demand is fixed throughout charging time.	No overload on the main fuse, charging demand is met in appropriate time	PASS	
FCFS_02	Single high power EV	An EV tries to charge with a demand that is higher than the available current on the main fuse.	Charging demand is fixed throughout charging time.	No overload on the main fuse, charging demand is following the sent limits.	PASS	
FCFS_03	Single low power EV, house consumption	An EV tries to charge with a demand lower than the current available on main fuse. Other consumption is detected which should leave enough current to continue charging.	Charging demand is fixed throughout charging time.	Charging current is lowered without tripping the fuse.	PASS	The run up of the charging did not allow the current to be raised to the demand within 20 seconds (then the other consumptin starts).
FCFS_04	Single low power EV, house consumption	An EV tries to charge with a demand lower than the current available on main fuse. Other consumption is detected which should leave terminate the charging process.	Charging demand is fixed throughout charging time.	Charging is terminated without tripping the fuse.	PASS	The issue from case FCFS_03 was eliminated by setting the time difference to 30 seconds.
FCFS_05	Two high power EVs	An EV tries to charge with a demand that leaves less than the minimum possible consumption for the second EV.	Charging demand is fixed throughout charging time.	First EV does not change its charging current, second one does not start charging.	PASS	
FCFS_06	Two low power EVs	An EV tries to charge with a demand that leaves less than the minimum possible consumption for the second EV.	Charging demand is fixed throughout charging time.	First EV does not change its charging current, second one does not start charging.	PASS	
FCFS_07	Two low power EVs, house consumption	First EV starts charging, then the second one starts. After some time house consumption is detected which should lower the second EVs' charging current without terminating the charging.	Charging demand is fixed throughout charging time.	First EV charges its demand the whole time, second EV is lowered. The fuse is not tripped.	FAIL	When the house consumption reach the threshold value, the controller is not able to lower the charging power in time limit due to the one second delay.
FCFS_08	Two low power EVs, house consumption	First EV starts charging, then the second one starts. After some time house consumption is detected which should terminate the charging process of the second EV and lower the first one.	Charging demand is fixed throughout charging time.	First EV's charging current is lowered with other consumption, second EV has its charging terminated. The fuse is not tripped.	PASS	
FCFS_09	Multiple high power EVs, same time start (stability test)	All EVs start the charging in the same time. A fallback should prevent overload while several of them should be able to charge within their demand.	Charging demand is fixed throughout charging time.	Depending on the threshold and values set, several EVs should be able to charge while the rest is not able to start the charging	PASS	

Test specification & protocol

Date	21.05.2019

Test criteria	Criteria description
PASS	Test outcome is as excepted.
PARTIAL	Test outcome is only partly achieved.
FAIL	Test has failed.
NOT TESTED	Test has not been carried out.

Test ID	Test Name	Test description	Test prerequisites	Expected Outcome	Result	Comment / Obstacles
PRIO_01	Two low power EVs	Higher priority EV starts the charging, then the lower priority starts as it should have enough current left.	Charging demand is fixed throughout charging time.	Both EVs are charging while no overload is achieved.	PASS	
PRIO_02	Two low power EVs	Lower priority starts charging, then the higher priority lowers the consumption of the lower one achieving its demand	Charging demand is fixed throughout charging time.	Both EVs are charging while no/minimum overload is achieved. If overload appears, the fuse should not be tripped.	PASS	
PRIO_03	Two high power EVs	Lower priority starts charging, then the higher priority starts charging which should terminate the charging process of the lower priority EV.	Charging demand is fixed throughout charging time.	Charging of the second EV should be terminated.	PASS	
PRIO_04	Three low power EVs	The EVs should start in a pattern 2 - 3 - 1, where the lowest number represents the highest priority. All EVs should be able to charge at least their minimum possible current.	Charging demand is fixed throughout charging time.	All EVs should be able to charge without achieving overload leading to tripping the fuse.	PASS	
PRIO_05	Two high power EVs, house consumption	The lower priority EV starts charging first, then the higer priority. The charging of the lower priority EV should be terminated, then the house consumption should cause the same for the higher priority EV.	Charging demand is fixed throughout charging time.	As a result both EVs should not be able to charge while the process should be terminated without causing the fuse to be tripped.	PASS	

Test specification & protocol

Date	21.05.2019

Test criteria	Criteria description
PASS	Test outcome is as excepted.
PARTIAL	Test outcome is only partly achieved.
FAIL	Test has failed.
NOT TESTED	Test has not been carried out.

Test ID	Test Name	Test description	Test prerequisites	Expected Outcome	Result	Comment / Obstacles
BALANCED_01	Low power EV	An EV with demand below the threshold starts charging.	Charging demand is fixed throughout charging time.	EV reaches its charging demand.	PASS	
BALANCED_02	High power EV	An EV starts charging with demand higher than the threshold.	Charging demand is fixed throughout charging time.	EV consumes current equal to threshold.	PASS	
BALANCED_03	Low power EV, house consumption	An EV starts charging with demand below the threshold. The house consumption step starts several seconds after the EV and should not influence the EV's current limit.	Charging demand is fixed throughout charging time.	EV reaches its demand and it is not lowered through the whole time.	PASS	
BALANCED_04	High power EV, house consumption	An EV starts charging with demand over the threshold. Then the house starts consuming.	Charging demand is fixed throughout charging time.	EV is lowered from the threshold to consumption corresponding with the house.	PASS	
BALANCED_05	Two low power EVs	Both EVs start charging at random times; total demand is lower or equal to threshold.	Charging demand is fixed throughout charging time.	Both EVs get on the charging demand level.	PASS	
BALANCED_06	Two high power EVs	Both EVs start charging with demand higher than half of the threshold.	Charging demand is fixed throughout charging time.	Both EVs get the same charging limit and reach it.	PASS	
BALANCED_07	Two EVs	One EV is charging under the half of the threshold, second charges more.	Charging demand is fixed throughout charging time.	Both EVs are charging with their demand and/or the consumption is equal, if the total demand is equal or higher than the threshold.	PASS	
BALANCED_08	Two high power EVs with house consumption	Two EVs start charging with consumption above threshold. House consumption starts at certain value and lowers itself.	Charging demand is fixed throughout charging time.	Both EVs start at same value, after lowering the house consumption the charging values should increase.	FAIL	Oscillations which appear during lowering the power after the house consumption arises caused the blackout.
BALANCED_09	Two high power EVs with house consumption	Both EVs are charging, one below the common limit, second over this limit. The house then starts consuming.	Charging demand is fixed throughout charging time.	First, the energy should be distributed completely. After the house consumption, it should be lowered for both EVs, but only if the limit drops below the low power EV.	FAIL	Oscillations which appear during lowering the power after the house consumption arises caused the blackout.
BALANCED_10	Five EVs (stability test)	Five EVs start charging at pseudorandom values, where the overall energy distribution is checked - at least one with a plan providing unused power, one above the common limit and one exactly on limit. The sum of plan should be equal to threshold value.	Charging demand is fixed throughout charging time.	All EVs reach their charging demand.	PARTIAL	Not all EVSEs reached their charging demand, which should be possible.
BALANCED_11	Five high EVs with house consumption (stability test)	Five EVs start charging at random values. Then the house consumption appears.	Charging demand is fixed throughout charging time.	No overload is achieved while the runup, blackout is protected when the house consumption appears.	FAIL	Oscillations which appear during lowering the power after the house consumption arises caused the blackout.

Appendix C

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Appendix D

CD

Content of the CD:

- configuration.m
- test_cases.m
- lib.slx
- model.slx
- test_spec_bt_jv.xlsx
- README.txt