Swedish Electromobility Centre | REPORT

Power conversion challenges with an all-electric land transport system

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Project title: Power conversion challenges with an all-electric land transport system

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Partners: Lund University, AB Volvo, Scania, Volvo Cars, Vattenfall

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Contents

Sammanfattning

Projektet är temaforskares projekt för tema “elmaskiner och drivsystem” under SEC-fas 3. “Power Conversion Challenges with an All-Electric Land Transport System” fokuserar på gränssnittet mellan elbilen och energikällan, som i de flesta fall är det elektriska kraftnätet. Baserat på resultaten från intervjuer med SEC-industripartnerna valdes tre ämnen:

- Kostnadsjämförelse av olika laddningssystemskonfigurationer: kostnadsmodeller har utvecklats och används för att bedöma samhällskostnaden för att elektrifiera den svenska flottan under olika hypotetiska scenarier.

- Hantering av chassipotential med konduktiva elvägar: Elektriska modeller av båda fordonen och infrastrukturen har skapats för konduktiva ERS, och potentiella felscenarier har analyserats. Dessutom har påverkan av olika systemparametrar i den övergripande säkerheten studerats.

- Påverkan av en hög effekt och mycket dynamisk belastning på ett svagt kraftnät. Effekten av elektromobilitetsrelaterade kraftbelastningar i det befintliga nätet ska analyseras, och nätstödmätningar kommer att föreslås vid behov (pågående arbete).

Även om projektets omfattning kan tyckas vara för bred i början, är tanken att börja utforska dessa områden, bygga upp den nödvändiga kompetensen inom Sveriges Elektromobilitets Center och initiera forskningsverksamhet som kan leda till nya projekt i framtiden.

Summary

This project is the Theme Researcher project for Electrical Machines and Drives during SEC Phase 3. “Power Conversion Challenges with an All-Electric Land Transport System” focuses on the interface between the electric vehicle and the energy source, which in most cases is the electric utility grid. Based on the results from a round of interviews with SEC industrial partners, three topics were selected:

- Cost comparison of different charging system configurations: the necessary cost models have been developed and used to assess the societal cost of electrifying the Swedish fleet under different hypothetical scenarios.

- Management of chassis potential with a conductive dynamic charging solutions: electric models of the vehicle and the infrastructure have been created for the case of conductive ERS, and potential fault scenarios have been analysed, studying the influence of different system parameters in the overall safety.

- Impact of a high power, highly dynamic load on a weak power grid. The impact of electromobility related power loads in the existing grid will be analysed, and grid-support measurements will be proposed when needed (this part is currently in progress).

Although the scope of the project may seem too broad at first, the idea of the project is to start exploring these areas, building up the necessary competence within the Swedish Electromobility Centre and initiating research activities that could lead to new projects in the future.

Background

When trying to shape an all-electric land transport system, it becomes clear that there are a number of challenges yet to overcome. Some of these challenges are of a purely practical and applied nature: e.g. the design of a certain component, the implementation of a particular communication protocol, while others are more strategical or even philosophical, being related in some cases to social sciences and economics: e.g. deciding whether to use an AC or DC connection for battery charging, finding the optimal balance between the different charging modes and infrastructure, creating an attractive business case for the different stakeholders, etc. Some of these aspects have been gradually set by the market itself: for example, most electric vehicle manufacturers nowadays are using a high power DC connection to charge their batteries, even if they were using AC before, as it is the case with the Tesla Model S. Some other of these challenges is however far from being solved, and further research is needed in order to make the right decisions.

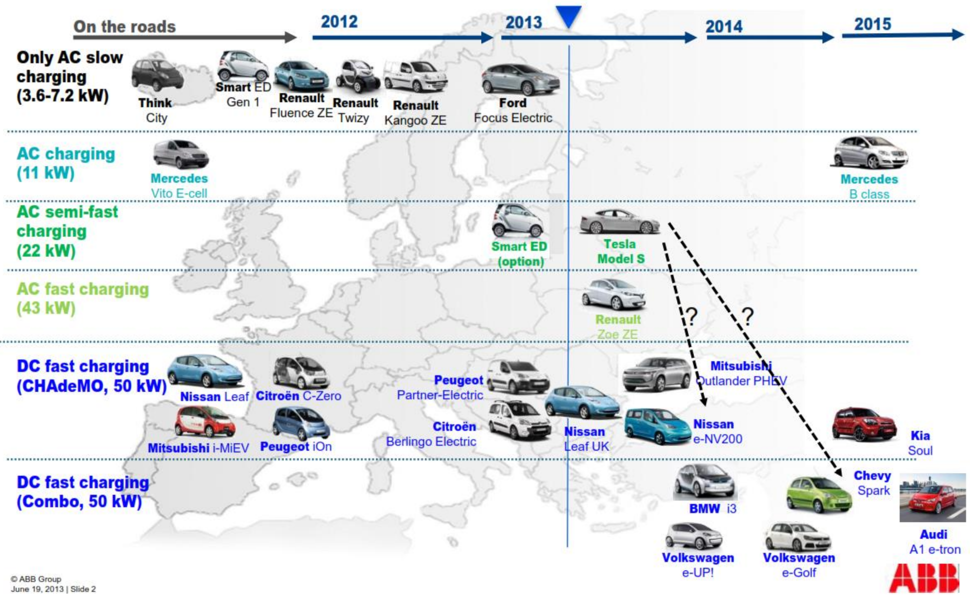


Figure 1: Evolution of static charging systems for EVs (source: ABB group)

As a preparation for this project, a 4-month pre-study was conducted during which the main industrial partners in the Swedish Electromobility Centre (formerly the Swedish Hybrid and Electric Vehicle Centre - SHC) were interviewed in order to find which of these unaddressed challenges were of interest for them. Although the subject of power transfer and conversion in electric land transportation systems is much broader, the time frame of this project does not allow covering it all, and therefore the project is limited to the following topics based on the answers received:

- **Cost assessment of different drive- and charging-system configurations:** a sensitivity analysis of the cost of different alternatives, based on detailed cost models developed at LTH, comparing AC vs. DC charging, on-board vs. off-board installation, static vs. opportunity vs. dynamic mode, etc.
- **Chassis potential management with a conductive dynamic charging solution:** although fast static charging systems have made electric cars much more attractive, reducing charging times to less than one hour, full electrification of heavy duty vehicles will not be possible without dynamic charging solutions. Charging while driving however introduces new safety challenges that need to be

considered. Since the majority of the dynamic charging test sites developed in Sweden are of conductive type, this project aims to model the high voltage circuit and its coupling to the chassis and other structural parts of the vehicle for such solutions. Moreover, monitoring methods for chassis potential and insulation impedance will also be developed.

- **Analyse the impact of a high power, highly dynamic load on a weak grid:** grid models will be developed to assess the impact of the expected loads. When needed, methods to support the grid will be proposed.

At the beginning of the project, the aforementioned research topics were to a large extent unexplored, since most of the focus has been on driving the vehicles rather than charging them. However, during the course of the project, some of these topics (especially the cost assessment and the potential impact on the power grid) have received much attention, and there are currently a number of national and international research projects are ongoing.

Moreover, synergies between this project and some of the aforementioned activities have emerged. One particularly relevant example is the collaboration with the SEC project IDEAS, in which multi-agent transport simulations are used to estimate the impact that charging infrastructure deployment has on traffic patterns. The results from IDEAS give an estimation of the usage of the different charging equipment, the power delivered to the vehicles over time, which can be used as an input to the grid impact studies proposed in this project.

General project description

The project is effectively divided into four sub-projects, addressing each of the topics mentioned above, plus creating a compilation of relevant EU projects on EV charging. Each of the sub-projects will be approached individually, although the outcome of anyone of them can be useful for the rest. The different sub-project are described in detail below, together with the main research approach intended.

1 - Cost assessment of different system configurations

Charging electric vehicles can be done in many ways: low power charging at home overnight, at somewhat higher power for a few hours in a parking lot, at a fast-charging station along the motorway during a lunch break, or charging while driving on a dedicated charging lane [1]. Each of these alternatives has their own pros and cons, and needs certain equipment to be installed either on- or off-board the vehicle. While some of these charging methods, especially the lower power ones, have been extensively proven already in commercial applications, others are still undergoing substantial development. The objective of this part of the project is to create a number of scenarios, in which the different charging modes are combined in different proportions, and compare them in terms of performance, applicability and cost.

To achieve that, several stages were proposed in the initial project proposal:

- Perform a state-of-the-art review of all commercial and prototype-stage charging solutions available. Compile and convey to SHC the results from several EU projects such as Fabric, Unplugged, EV-connect, FastInCharge, ZeEUS, Green eMotion, and some national projects like Fastned in the Netherlands, Elmo in Estonia, and Electric Boulevards in the UK. [2 – 10].
- Write a report compiling the most relevant results from the previous literature review.

- Adapt the detailed cost models developed at LTH initially just for hybrid and electric powertrains to assess the cost of the different charging solutions. [11]
- Propose different drive- and charging-system scenarios and compare them in terms of performance, applicability and cost.

2 - Chassis potential management with a conductive dynamic charging solution

The most promising conductive dynamic charging solutions at the moment do not provide a solid electrical earth connection for chassis potential limitation. The fact that the vehicle is in movement while charging from a high voltage source makes it extremely difficult to ensure a reliable earth connection for such systems. Maintaining the chassis potential close to earth is paramount for safety reasons when the vehicle is circulating at low speed in urban areas and can get in contact with pedestrians, or in case of accidents to prevent the vehicle occupants from suffering an electric shock.

Currently, a number of solutions have been proposed based on a PEM (Protective Earth Minus) connection rather than a PEN (Protective Earth Neutral) connection. The objective of this sub-project is to analyse the different protection alternatives and find out methods to ensure that the chassis potential is always kept at a safe level.

The most important stages are:

- Develop an overall electrical model of the powertrain and the connection to the charging infrastructure in order to estimate the chassis potential under different operation conditions.
- Assess the suitability and performance of the different protective connection possibilities (PEM, PEN, etc) using the previous model.
- Propose chassis potential monitoring methods and evaluate their performance using the previous model and experimental measurements in test prototype when applicable.

3 - Analyse the impact of a high power, highly dynamic load on a weak grid

With the increasing number of electric vehicles, the load on the electricity grid will be also increased. In some cases, a completely new infrastructure may be deployed, e.g. if a major road becomes electrified, but in other cases it may be more advantageous to use the existing infrastructure to supply the power needed by the vehicles -e.g. substituting the existing diesel buses for electric ones and use opportunity charging at the bus stops. These loads are usually high power, even up to some megawatts, applied for short periods of time, and in some cases, the grid may be too weak to withstand these high power and highly dynamic loads. The objective of this sub-project is to develop the necessary tools to assess the capability of the grid at a certain location to cope with a certain load (high power, highly dynamic as an EV charging hub) and propose solutions in case the electric infrastructure needs to be upgraded.

The most important stages are:

- Review existing literature from previous research projects (mostly EU funded projects as mentioned in the first sub-project) and create a simulation model of a local grid with a representative load.
- Assess the grid behaviour when subjected to different loads, varying in power level and duty cycle.
- Develop methods to support the grid and evaluate their performance for the different types of load.
- Seek cooperation with electric power system research groups.

Results

Note: A combination of slightly optimistic time planning and unexpected, but positively surprising relevance of the first two sub-projects (cost assessment and chassis potential) led to the need for a 9-month time extension for the project, granted by the Swedish Electromobility Centre under the application *"Power conversion challenges with an all-electric land transport system – continuation"* (Oct 2018 – June 2019). However, due to lack of research staff in related projects, the final date for the continuation phase has been postponed until December 2019. A final version of this report with all the results from the third sub-project will be delivered then.

1) Cost assessment of different system configurations

In this subproject, the cost models developed at LTH have been used to compare the cost of electrifying the complete Swedish automotive fleet, assuming different future scenarios.

As any analysis of large and complex systems, this cost comparison is based on a number of assumptions, the most important of which are summarised below:

- The Swedish vehicle fleet remains the same, consisting roughly of 5 million passenger cars (GCWR below 3.5 ton), 14 thousand urban buses, 20 thousand distribution trucks (GCWR between 3.5 and 16 ton) and 65 thousand long-haul trucks and coaches (GCWR above 16 ton).
- The main energy storage on-board the vehicles consists of Li-ion batteries. The cost of these batteries is assumed to be 100 €/kWh at pack level, which is well below the market values of 2017, but which seems a reasonable value in a few years' time according to some of the future predictions in the literature and even more so, to the real battery cost evolution published by Bloomberg. [12-14].
- The cost of the electromobility related equipment on-board the vehicles (electrical machine(s), traction inverter(s), on-board charger, ERS interface if required, etc.) has been calculated in detail, including the costs corresponding to the manufacturing processes involved (facilities, tools and wages) and the effect of production volumes. Since the objective of the analysis is to compare the societal cost of the different scenarios, profit and overhead costs are not taken into account. The details of these cost models are found in two PhD theses carried out at LTH by Gabriel Domingues [15] and Pontus Fyhr [16].
- If Electric Road Systems (ERS) are deployed, it is assumed that for each road segment to be electrified only half of its distance will be equipped with ERS infrastructure. This is represented by the parameter $k_{ERS} = 0.5$, and it is the result of a somewhat rough optimisation process balancing the cost of the installed batteries on-board the vehicles with the cost of the ERS infrastructure deployed (see Figure 2). If too little ERS is installed, all the energy transfer between the infrastructure and the vehicle should be concentrated in a short time and therefore at high power rate. This, in turn, would impose restrictions on the battery size, since charging at too high C-rate will cause fast degradation of the battery. On the other hand, if most of the road length is electrified, the vehicles could obtain the energy they need directly from the ERS and a very small battery would be required.

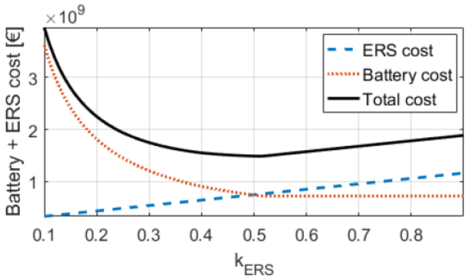


Figure 2: Balance between the cost of batteries and infrastructure as a function of k_{ERS}

- In order to calculate the annualised societal cost, different depreciation times have been considered: 10 years for the on-board components and 15 years for the infrastructure. Besides, a rate of 3% per year is considered both for the ERS maintenance (in those scenarios where ERS is present) and for the interest on the investment.
- When transitioning from combustion to electric vehicles, a number of components on-board the vehicles are no longer valid. In this case, the removal of the internal combustion engine, the transmission (gear-box) and the fuel tank has been considered.
- The prices of fossil fuel and electricity are based on the price in Sweden at the time of the study (1.4 €/litre and 0.09 €/kWh respectively). 20% VAT is deduced from both prices since the study considers only the societal cost.

Five scenarios have been considered and the corresponding costs of electrifying the whole Swedish fleet are compared using the proposed models:

1. All vehicles except long-haulers have enough battery capacity installed to operate for a full day. Long-haulers have enough battery for running a 4 hour shift and then the tractor can be exchanged by a fully charged one, in a pony-express fashion.
2. Overhead Electric Road Systems (ERS) are installed in all European and national roads (about 15 000 km) so that the battery capacity installed on long-haulers can be drastically reduced.
3. In addition to overhead ERS, opportunity charging is provided in the cities, so that the battery capacity installed in urban buses and distribution trucks can also be reduced. Only passenger cars remain with
4. The overhead ERS in scenario 3 is now replaced by inductive ERS installed on the ground.
5. The inductive ERS is replaced by conductive ground-based ERS.

The results of the cost comparison are shown in Figure 3.

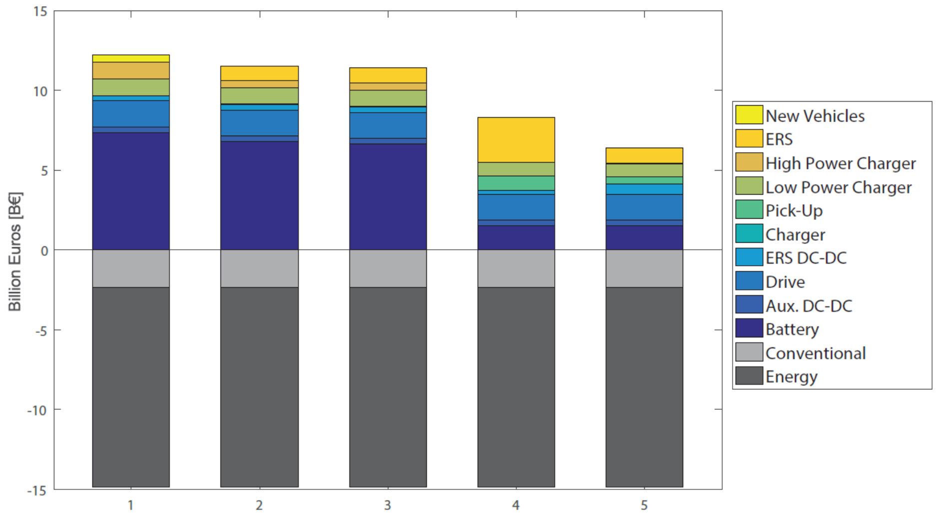
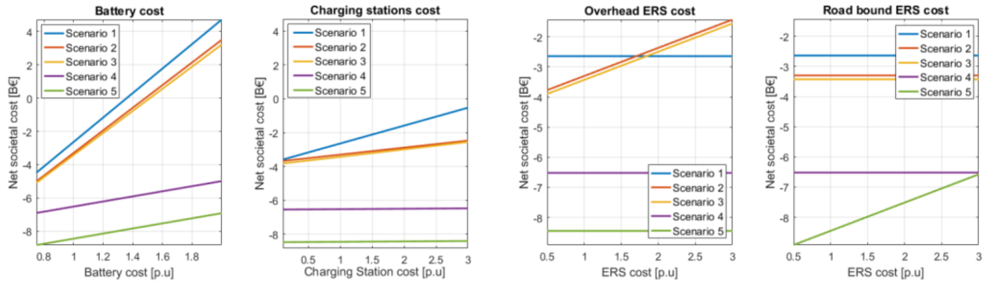


Figure 3: Societal cost comparison of electrifying all road transport in Sweden for 5 different scenarios

Several conclusions can be drawn when looking at the results presented in Figure 3. First and foremost, with the remarkably low cost per kWh assumed for the Li-ion batteries, all presented scenarios result in a net saving for society, with the positive part of each chart (costs) being smaller than the negative one (savings). Secondly, it is quite clear that the batteries installed on-board the vehicles (mostly passenger cars, which are the most numerous vehicle category) is the main cost driver for the system. Reducing the battery capacity installed in passenger cars (moving from scenario 3 to scenario 4) has the largest impact on the total societal cost.

A sensitivity analysis showing the net societal cost/saving when varying the assumed battery cost (see Figure 4, a) shows that scenarios 1 to 3, in which the battery represents a significant fraction of the total cost, are quite sensitive to the assumed €/kWh figure, and the cost of transport electrification becomes higher than the expected savings for battery costs over 135 €/kWh for scenario 1, and 150 €/kWh for scenarios 2 and 3. Conversely, scenarios 4 and 5, in which passenger cars can use the ERS hence the total installed battery capacity in the system is significantly lower, are much less sensitive to the battery cost, remaining beneficial for society under the whole range considered. In order to stress the importance of the battery cost over other assumptions also related to a system largely relying on large batteries, a sensitivity analysis is conducted on the cost of the fast-charging stations network (see Figure 4, b). The initial assumption in scenario 1 is that, since charging time is on average approximately 5 times longer than refueling, in order to cope with the peak demand for example during holidays or long weekends, the number of fast-charging points is estimated to be 5 times the number of fuel pumps available in Sweden: currently 2600 major service stations, only those with a shop/restaurant considered, with an average of 8 fuel pumps in each station. This is of course a very coarse assumption that can be extensively disputed. However, when looking at the sensitivity study results in the plot of Figure 4, b, it is obvious that the impact of the fast-charging infrastructure cost is much less than that of the estimated battery cost. It is worth noticing that the scale in the x-axis is in p.u., representing either an increase/decrease of the number of fast-charging points available, their power rating or their cost, as well as the wider range considered in this case. When looking at the overall picture, it is clear that scenarios 4 and 5 are the most advantageous, and that this advantage relies basically in the lower total battery capacity installed, which overcomes the additional infrastructure investment for the ERS. Moreover, in the battery cost sensitivity analysis presented before it can be seen that the battery cost should become much lower than 75 €/kWh for the any of the first three scenarios to be comparable to scenario 5 - the one with conductive ERS. This is also partly due to the specific fleet composition in Sweden: over 5 million Light Duty Vehicles (mostly passenger cars) compared to only 65 thousand long-haul vehicles. Nonetheless, in order to understand the influence of the assumed ERS technology cost in the results, additional sensitivity analyses are run on the estimated cost of both conductive ERS technologies: overhead and road-bound. The results are presented in Figure 4 c and d.



(a) (b) (c) (d)

Figure 4: Sensitivity analysis for the following parameters: a) battery cost, b) fast charging staion cost, c) overhead ERS installation cost, d) roadbound ERS installation cost.

All 5 scenarios presented previously consider a hypothetical final situation in which all vehicles are electrified and all European and national roads are equipped with ERS (in the corresponding scenarios). However, if this ever happens, it will be through a rather slow and complex transition process, in which both the electric vehicles and the necessary charging infrastructure will be deployed gradually. In order to identify which roads will be most suitable for electrification, a new cost figure is introduced: the electromobility equivalent energy cost. This new cost figure is defined as the sum of the following costs incurred when 1 kWh is spent on transport:

- the cost of 1 kWh of electric energy
- the cost related to the depreciation of the electromobility related components (electric powertrains onboard the different vehicles) depreciated with the total energy converted by those vehicles
- the cost related to the depreciation of the ERS and the static fast-charging infrastructure (when present), depreciated with the total energy supplied to the system over the considered time frame

The electromobility equivalent energy cost is illustrated in Figure 5.

Figure 5: Illustration of the electromobility equivalent energy cost.

Estimating the cost of fast-charging stations is somewhat complicated, since there are several aspects to it that are difficult to model such as the price of the real-estate, groundwork if needed, etc. However, the electrical equipment needed as well as the connection to the power grid are fairly well defined, and the cost of those can be estimated in 350 €/kW. Very much more complicated is the estimation of the cost of ERS infrastructure, as this is a relatively new application only implemented at pilot test sites so far. Some experience can be gathered from similar systems such as trams, trolley buses and even railways; however new challenges arise related to the combination of higher speeds, wider range of vehicles using it, variable position of the vehicles relative to the road and the use of rubber tyres. Based on the information obtained from the pilot sites already available, the cost of the ERS is estimated as:

$$C_{ERS} = k_0 P_{ERS} + k_1 L_{ERS} + k_2 k_{ERS} L_{ERS} N_{lanes}$$

The previous expression estimates the cost of the ERS infrastructure for a specific section of the road of length L_{ERS} split in three separate terms:

1. *Power term*: the first term is directly proportional to the maximum hourly-averaged power that the ERS needs to deliver, assumed to be 2.5 times higher than the average power to account for the variations of the traffic volume throughout the day. Being proportional to the amount of traffic in that particular section of the road, this term accounts for the transformers and rectifying stations feeding power to the road. The proportional constant is set to k_0 = 300 k€/MW.
2. *Distribution term:* the second term is directly proportional to the total length of the road section that is electrified, accounting for the cabling that runs along the road, supplying electricity from the feeding points to the rectifying stations. The proportional constant is set to k_1 = 150 k€/km.
3. *Roadbound hardware term:* the last term accounts for the actual modules of electric road installed and all the accessory components needed such as witches, breakers, protection circuitry as well as the installation work on the road. This term is proportional to the electrified length (which does not need to be the full length of the road) represented by k_{ERS} L_{ERS} and the number of lanes that are electrified (N_{lanes}). The proportional constant is set to k_2 = 500 k€/km.

In order to assess the suitability or the profitability (from a societal point of view) of electrifying a certain road segment, different combinations of traffic volumes of Light-Duty Vehicles (LDV, mostly passenger cars) and Heavy-Duty Vehicles (HDV, mostly long-haul trucks) are considered, under 3 different scenarios. For comparison, the cost of the fossil fuel needed to replace 1 kWh of electricity invested in transport, assuming 1.4 €/liter (- 20% VAT), 10 kWh/liter, and average powertrain efficiencies of 25% for combustion and 78 % / 79% for electric LDV and HDV respectively, is ≈ 0.35 €/kWh.

1) <u>ERS based on overhead lines only for HDV, LDV remain on fossil fuels.</u>

HDV are more suited to lead the introduction of ERS since they drive over well defined routes most of the time, their driving patterns are more predictable, and their electrification is difficult otherwise. Since LDV do not benefit from the ERS and use fossil fuels instead, they do not play a role in the cost calculations. From the results in Figure 6it is clear that those roads with a flow of more than 900 trucks per day (and direction) will benefit from the deployment of overhead ERS – given that all those vehicles are electric and are capable of using the ERS infrastructure.

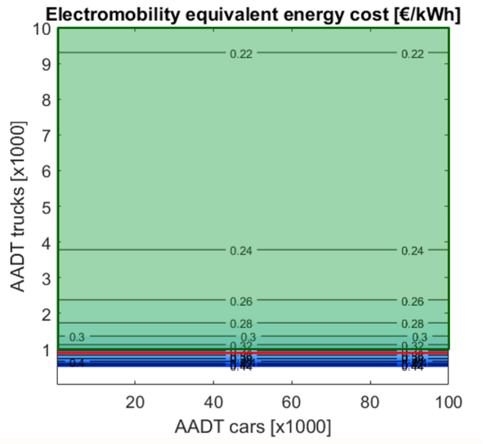


Figure 6: Electromobility equivalent energy cost for overhead lines for HDV, LDV remain on fossil fuels.

2) <u>ERS based on overhead lines only for HDV, LDV become battery electric vehicles.</u>

In this scenario, all LDV from the previous scenario become battery electric vehicles. Since they cannot access the overhead ERS, fast-charging stations need to be deployed, and the battery installed on-board passenger cars is relatively large (72 kWh).

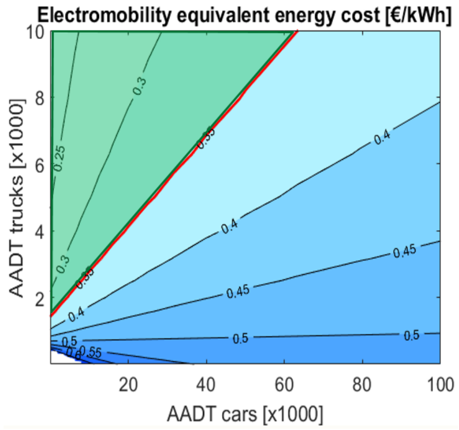


Figure 7: Electromobility equivalent energy cost for overhead ERS for HDV, LDV become battery electric vehicles.

When looking at the results, it is interesting to note how, for any any combination of $AADT_{Trucks}$ and $AADT_{Cars}$, increasing the volume of trucks in the road results in a lower cost. Conversely, if $AADT_{Trucks} > 700$ increasing the volume of cars always results in a higher cost. The reason for this is that, since batteries are an expensive component only installed in cars in this scenario, and taking into account that the degree of utilisation for cars is much lower than for trucks, the cost of the electromobility related components on-board the vehicles depreciated with the total energy converted becomes higher, the higher the number of cars.

3) <u>Roadbound ERS available for both HDV and LDV</u>

Since LDV are also benefitting from the ERS installation, the battery onboard passenger cars can be substantially reduced. The results of the cost calculations are shown in Figure 8.

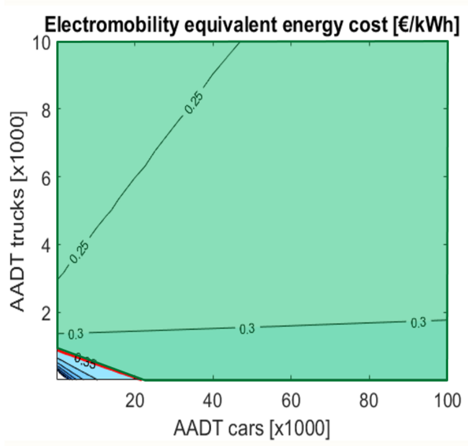


Figure 8: Electromobility equivalent energy cost for roadbound ERS available for both HDV and LDV.

A few interesting remarks are worth making when looking at the results. First, the overall electromobility equivalent energy cost is significantly lower than in the previous scenario, in which LDV relied on large batteries. Since the cost of both overhead and roadbound solutions is modelled in the same way, the difference in the electromobility equivalent energy cost between the two scenarios is almost negligible for low car traffic volumes ($AADT_{Cars}$). Nevertheless, when the number of cars increases, the combination of overhead ERS and batteries considered in the second scenario makes the system more expensive, therefore, as shown by the results in Figure 7 and Figure 8, the higher the $AADT_{Cars}$, the more advantageous it becomes to move the ERS infrastructure from overhead lines to a road-bound solution. Moreover, as in the previous scenario, once a minimum number of trucks is exceeded (in this case $AADT_{Trucks} > 1300$) increasing the volume of cars results in a higher cost, even though both vehicle types share now the ERS infrastructure, and neither large batteries nor fast-charging infrastructure is required. The reason for this is again the higher utilisation ratio of trucks compared to cars, and the conclusion drawn is simply that the more a vehicle is used, the cheaper the cost per kWh becomes.

Further details about the assumptions made in the different simulations as well as more results and discussions can be found in the papers published within the project (see section Papers and Publications below).

2) Cost assessment of different system configurations

In this subproject, the safety issues related to not having a solid protective earth connection when supplying a vehicle from a conductive ERS are analysed.

When running on a conductive ERS, the vehicle is supplied with electricity using some kind of sliding contacts ("pick-ups") that move relative to the power supply lines allowing the vehicle to connect/disconnect at any time, none of the proposed solutions can guarantee that a solid protective earth connection exists at all times while the vehicle is connected to the power supply. This in turn implies that, unlike what happens in trams and railways, the body of the vehicle cannot be connected to earth at all times, so potential dangerous situations in which an insulation fault results in an energised vehicle body must be avoided.

The first step is to model the electric power system in a vehicle in order to assess the effect of potential insulation faults. In a vehicle suited for conductive ERS operation there are three independent electrical domains – see Figure 9. In normal operation conditions, these domains are isolated from one another: I) one domain coupled to the high voltage traction battery (like in normal BEVs), with a high impedance (commonly referred to as "floating") both with respect to the vehicle's chassis and to the ERS power supply; II) one domain coupled to the low voltage (usually 12 or 24 V) system; and III) one coupled to the ERS power supply, thus with a low impedance to its ground/earth potential.

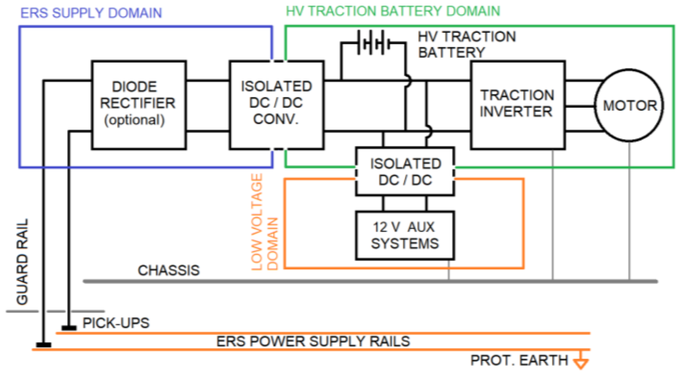


Figure 9: Power system diagram for a conductive ERS suitable vehicle.

Compared to a conventional Battery Electric Vehicle (BEV), the ERS power supply domain is added on-board in order to use the conductive ERS. It consists of the contact devices ("pick-ups") interfacing the ERS and collecting the current from the ERS power supply lines, a rectifier (if needed) which is usually single-quadrant, to rectify the currents from the ERS, and an isolated DC-DC converter to transfer the energy to the HV traction battery domain. In most solutions, the pick-ups are mounted in a metallic sub-frame that is also electrically floating with respect to everything else, acting as a guard-rail for electric safety purposes.

The ERS can supply the vehicle acting as either an unregulated DC voltage source or a variable/AC source. In the Elonroad solution (the one modelled since it was accessible for experimental testing and validation) the vehicle is connected to short segments that, as the vehicle moves, are alternatively connected to an unregulated DC voltage level (typically 600 V) or a low potential close to the earth potential, resulting in a square wave voltage signal at the pick-ups. The pick-ups provide at least three contact points reaching three consecutive power segments of 1 meter each, every second of which is always at a near zero voltage while the rest are commutated between +600 V and zero. Due mostly to the parasitic capacitances in the system, some of this square wave voltage (at the input to the rectifier) is coupled to the vehicle chassis and body, which could potentially affect the performance of any chassis potential monitoring device used. The chassis of the vehicle is, under normal conditions, also floating with respect to the external ERS power supply earth, only coupled through the parasitic resistance and capacitance of the tires and asphalt. However, since the ERS power supply is earthed, there is a risk that an insulation fault in this part of the electric system provides a low impedance path to the vehicle chassis, creating a hazard for people outside the vehicle that could get in touch with the energised parts.

The model is built using the open software LTSpice. Figure 10 shows a screenshot of the developed model. In order to simulate the effect of a human body in touch with the chassis of the vehicle, a resistor of 2.5 kΩ is placed between the vehicle chassis and earth. This value depends on a number of factors: contact surface area, humidity conditions, type of shoes that the person is wearing (if any), etc. However, 2.5 kΩ seems a reasonable value for this analysis, corresponding to very conservative assumptions from a safety point of view (e.g. a bare foot person standing on an earthed plate touching the vehicle with the whole hand). Since a relatively low value of the resistance is assumed, the touch current is used to evaluate the potential hazard in the different cases.

Based on the charts published by the International Electrotechnical Comission (ITC) [17 - 18] presenting different thresholds for perception, pain and heart affection, the average RMS value of the touch current over 100 ms is used, and the safety limit is set to 5 mA.

Since the model will be validated against experimental tests in Elonroad's pilot test site in Örtofta (Skåne), the most relevant parameters have been directly measured from the test site. The exact values used can be consulted in the published papers within the project (see section Papers and Publications). The experimental test setup consists of a purposely built trailer equipped with three pick-ups installed on a sub-frame as explained before. The current from the pick-ups is rectified and consumed in a rack of industrial heaters mounted on the trailer, as seen in Figure 11.

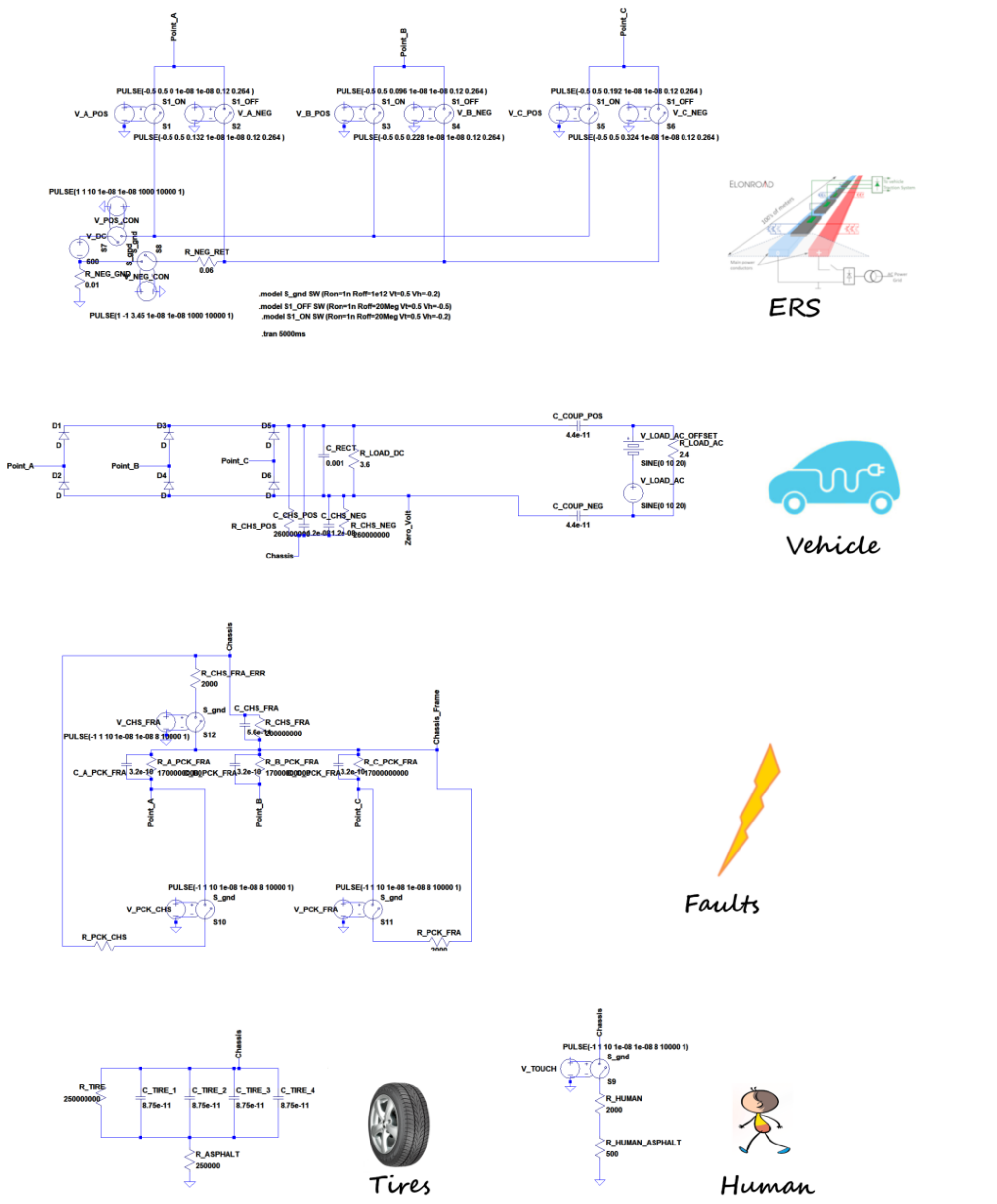


Figure 10: LTSpice model of the ERS, the vehicle, and the human body.

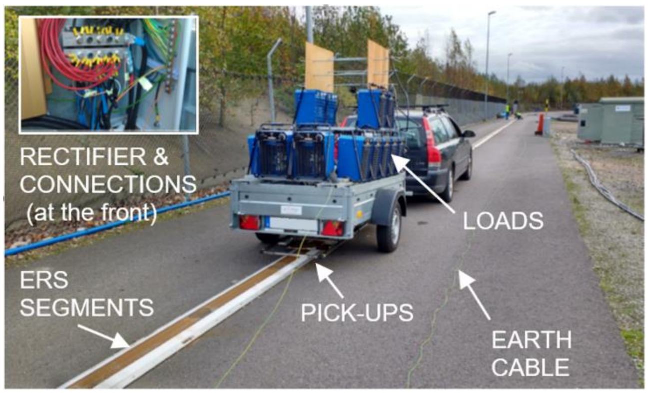


Figure 11: Experimental setup at the Elonroad pilot test site.

As an example, the simulation results and corresponding experimental validation results are shown in Figure 12 - Figure 16 for three representative operation cases:

1) Normal operation: a vehicle in normal operation (no insulation faults or any other kind of anomalies assumed) is simulated. The vehicle is driving over a conductive ERS at 30 km/h and just before t = 2 seconds a nearby person gets in touch with the vehicle and remains in touch for the rest of the simulation. This is quite an unlikely event for a vehicle moving at that speed, but it helps to understand the simulation results better. Two values are considered for the resistance of the asphalt layer, only affecting the current path through the tires, since the touch current goes through a "human" path, modelled by a 2.5 kΩ resistor between chassis and ground as previously stated.

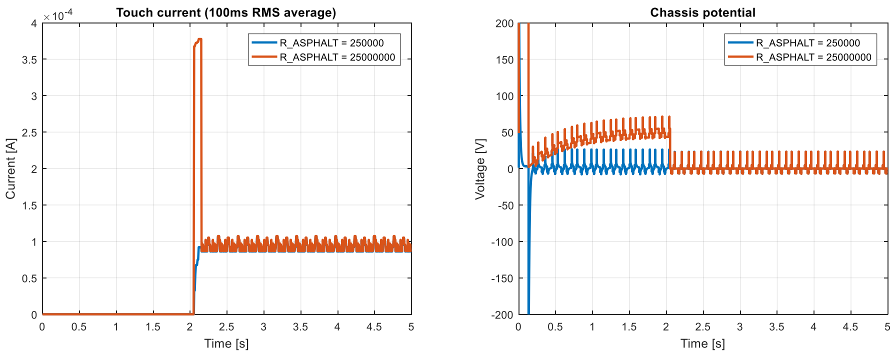


Figure 12: Touch current (100ms RMS average) (left) and chassis potential (right) during normal operation

The initial pulse at high asphalt impedance is due to the charge/discharge sequence of the parasitic capacitances in the system through the human body. Also, a higher asphalt resistance results in a higher touch current, because the return path through the tires and the asphalt has a higher resistivity and therefore more current flows through the easy path: the human body. Looking at the right plot, we can see that once the model has settled after the initialisation transient, the chassis potential stays within reasonable levels. Once the human gets in touch with the chassis, a lower resistance path to earth is established and therefore the chassis potential is lowered.

2) Loss of connection of the ERS negative rail: if, during operation, the vehicle losses connection to the lower potential rail, the voltage at the negative terminal of the dc-link just after the input rectifier will become the same as that of the positive terminal (typically 600 V in the Elonroad system). Due to the parasitic capacitances and resistances, this might be reflected on the chassis' potential. If a touch event happens just after the loss of connection (when the chassis potential is highest), a hazardous situation may happen.

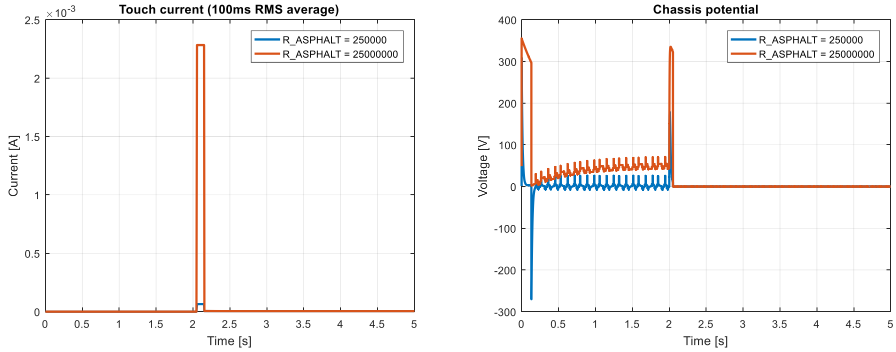


Figure 13: Touch current (100ms RMS average) (left) and chassis potential (right) during loss of connection of the ERS negative rail

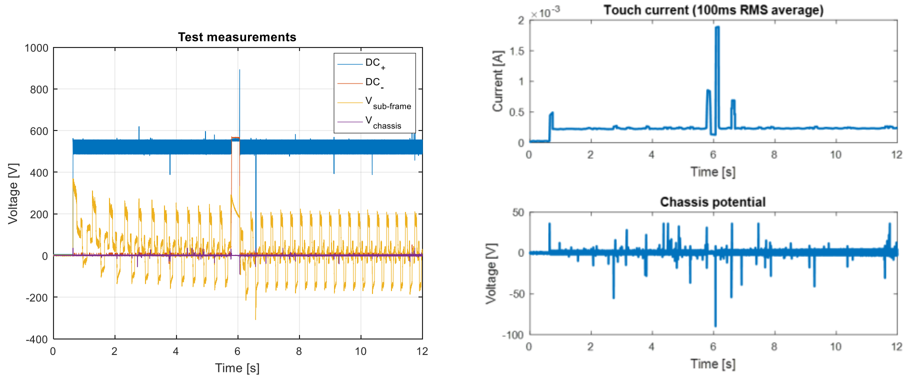


Figure 14: Measured voltages referred to earth (left), touch current RMS value over 100 ms (right, top) and chassis potential (right, bottom) under a loss of connection to the negative rail

As it can be seen in both the simulated and the experimental results, in the unlikely event that a person in the vehicle surroundings touched the chassis just after a loss of connection to the ERS negative (low potential) rail, the touch currents will be significantly higher than in the normal operation case, although the maximum value of 5 mA is not exceeded. These results suggest that a loss of connection to the negative ERS rail should be detected by the vehicle and safety measures taken in order to limit the chassis potential in that case.

3) Insulation fault in the ERS power supply domain: In this case, an insulation fault is introduced between one of the pick-ups and the vehicle's chassis. It is worth noticing that this is an extremely unlikely event, since the mechanical design of the system with the guard-rail should prevent this from happening at all. Nevertheless, it is studied since this poses one of the most potentially dangerous situations for conductive ERS vehicles.

The simulated insulation fault resistance is selected to 2.5 kΩ (equal to the human body resistance) which is much higher than the value that could be expected if an alien metal object would cause such fault. From the simulation results already it is clear that, despite the relatively high fault resistance value chosen, the touch current is much higher than the safety value of 5 mA. This is to be expected nonetheless, since this is an extreme fault situation. In such cases, a safety system must be in place and, by either sensing the exceptionally high chassis potential – even before the touch event, or the leakage current through the body, detect the fault and bring the chassis potential to a safe value, preventing any accidents.

The experimental measurements, although with a much higher fault resistance for practical implementation reasons, show essentially the same behaviour.

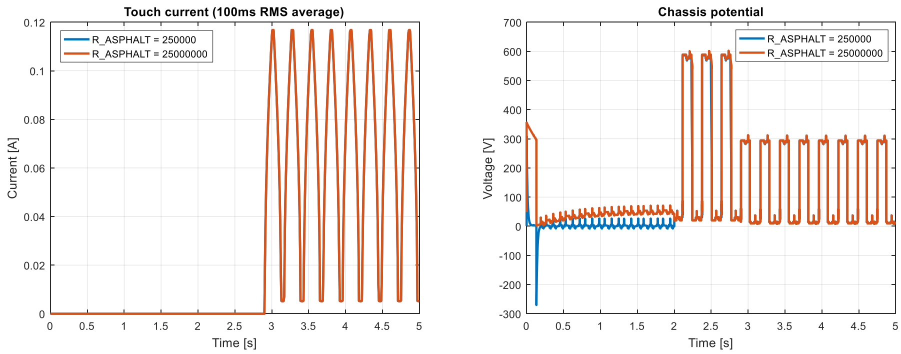


Figure 15: Touch current (100 ms RMS average) (left) and chassis potential (right) under pick-up to chassis insulation fault (at t = 2s) and touch event (at t = 2.90s)

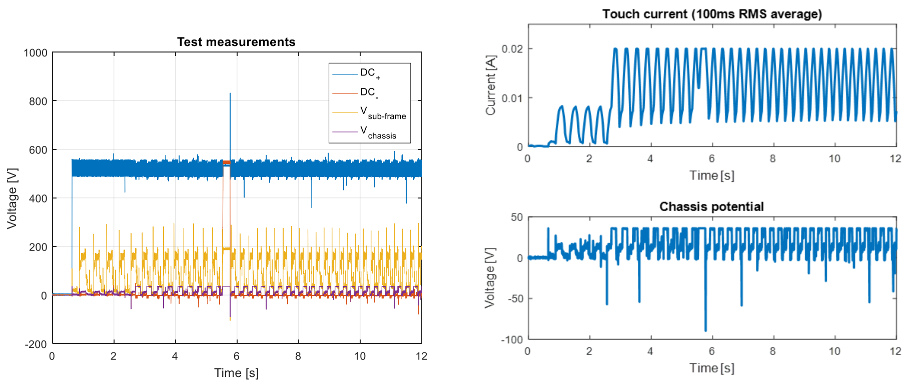


Figure 16: Measured voltages referred to earth (left), touch current RMS value over 100 ms (right, top) and chassis potential (right, bottom) under a pick-up to chassis insulation fault.

Several additional cases using the Elonroad ERS model are included in the published articles within the project, considering e.g. the effect of the salt – snow mix on the roads during wintertime.

Additionally, as a result of the discussions with Honda, an ERS with floating power supply has also been simulated. This time the model resembles the Honda solution, thus it represents a more conventional system with two separate contact rails, positive and negative, rather than consecutive short segments. Figure 17 shows the schematic for such a system, in which neither of the power supply potentials is referred to earth.

Looking at the diagram, it is obvious that a single insulation fault will not create a hazardous situation. Actually, two insulation faults in opposite electrical potentials are needed in order to create danger: e.g. if the positive rail at the power supply becomes ground, the second fault on the vehicle side must connect the negative pole in the system to the chassis, in order to establish a hazardous potential difference between chassis and earth.

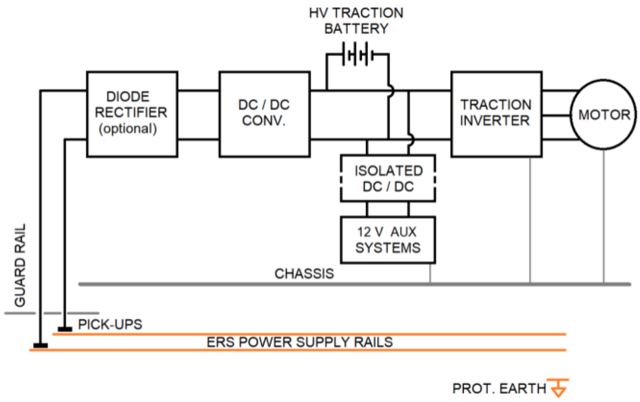


Figure 17: Power system diagram for an ERS suitable vehicle. Note that the ERS power supply is not related to earth.

Figure 18 shows the same fault as Figure 15 but for an ERS with a floating supply. An insulation fault between the positive contact on the current pick-up and the vehicle chassis happens at t = 2 s, and a nearby pedestrian touches the chassis 0.5 ms after that, and remains in touch with it for the rest of the simulation. It is clear that, in this case, the maximum current of 5 mA is not reached.

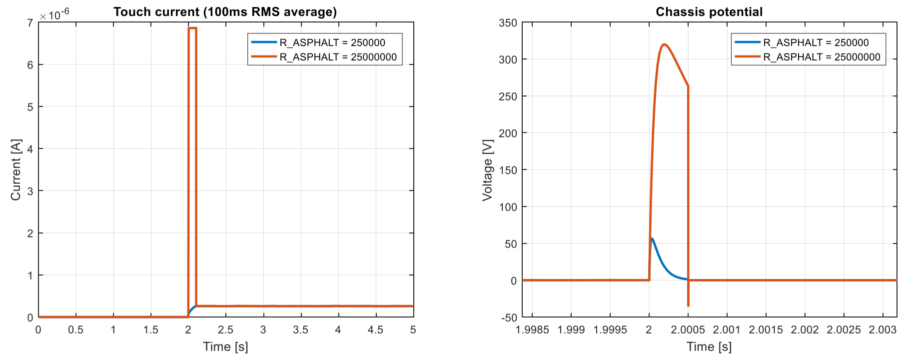


Figure 18: Touch current (100 ms RMS average) (left) and chassis potential (right) under pick-up to chassis insulation fault (at t = 2s) and touch event (at t = 2.0005s)

If a second insulation fault is introduced in the right place, a hazardous touch current can be expected. Figure 19 adds a second fault on the infrastructure side. In this case, a hazardous potential difference is established between the chassis and earth, and a touch event results in too high currents through the human.

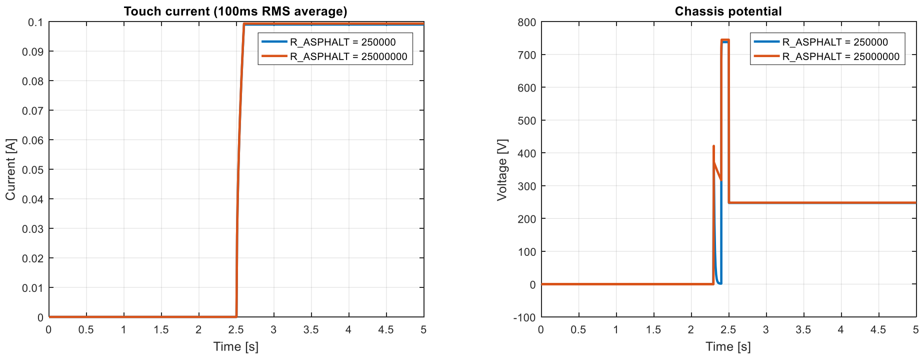


Figure 19: Touch current (100 ms RMS average) (left) and chassis potential (right) under pick-up to chassis insulation fault (at t = 2.3s), ERS negative rail to earth fault (at t = 2.4s) and touch event (at t = 2.5s)

3) Analyse the impact of a high power, highly dynamic load on a weak grid

As mentioned at the beginning of the Results section, this subproject is currently being carried out, and will be reported in December 2019.

Utilization of results

The results obtained from the different sub-projects have been extensively presented at several conferences and workshops, both in Sweden and abroad. The most relevant ones are:

- Oral presentation "Cost analysis of potential scenarios for electric drive and charging systems" at the Energirelaterad Fordonsforskning Conference organised by the Swedish Energy Agency in Gothenburg, 2017.
- Oral presentation "Societal cost of electrifying all Danish road transport" at the 30th International Electric Vehicle Symposium and Expo (EVS), in Stuttgart, Germany, 2017.
- Oral presentation "Electric Roads: reducing the societal cost of automotive electrification" at the 2017 IEEE International Transport Electrification Conference and Expo (ITEC 2017) in Chicago, USA, 2017
- Oral presentation "Electric Roads: the importance of sharing the infrastructure among different vehicle types" at the 2017 IEEE International Transport Electrification Conference and Expo Asia-Pacific (ITEC 2017 AP) in Harbin, China, 2017
- Organisation of a Special Session on Electric Road Systems at the 2017 IEEE International Transport Electrification Conference and Expo Asia-Pacific (ITEC 2017 AP) in Harbin, China, 2017
- Oral presentation "Chassis potential measurement and limitation in conductive ERS supplied vehicles" at the 2nd Electric Road Systems Conference, Stockholm, Sweden, 2018
- Oral presentation "Electric safety challenges with a conductive ERS" at the 31st International Electric Vehicle Symposium and Expo (EVS), in Kobe, Japan, 2018 (recognised with the Young Investigator Award)
- Oral presentation "Electric safety assessment in conductive ERS: grounded vs. ungrounded systems", at the 3rd Electric Road Systems Conference, Frankfurt am Main, Germany, 2019
- Organisation of a 3 hour Workshop on "Differentiative factors on Electric Road Systems: State-of-the-art technology review" at the 5th International conference E-Mobility Charging Infrastructure Europe 2020, organised by IQPC in Berlin, Germany, 2019
- Organisation of a 3 hour Workshop on "Electric Road Systems – Providing EVs with unlimited range" at the 2019 IEEE International Transport Electrification Conference and Expo (ITEC 2019) in Detroit, USA, 2019

Moreover, the results have been shared with the Research and Innovation Platform on Electric Road Systems.

During the project, several collaborations have originated. Some of them have already led to new projects, and some other are active and may result in new activities. As an example:

- A collaboration with the Technical University in Berlin (TUB) resulted in the project IDEAS (financed by SEC) which has recently finished (June 2019). Nonetheless, the results obtained from this collaboration have been deemed as very interesting by several SEC partners, and thus collaboration between SEC and will continue in the future.
- A collaboration with Honda Motor Company in Japan. Honda has developed their own ERS and are very interested in the work done within this project regarding electric safety. While this collaboration has not yet materialised in a new project, there is an open communication channel with Honda, which hopefully will lead to further cooperation.

Targets

The proposed project is in line with the Roadmap for the Electrical Machines and Drives theme, aiming to broaden the existing knowledge on both static and dynamic **charging solutions**, to reach a better understanding of the transition period towards a fully electrified transport system. This project aims to continue **widening the thematic area scope**, including the **electric utility grid impact** of a high power, highly dynamic load such as that arising from electric vehicles charging and operation, as initiated in the precedent Thematic Researcher Project in Electrical Machines and Drives.

Regarding specific Swedish Electromobility Centre's goals, this project addresses:

1) **Main Swedish Electromobility Centre's goal – International exchange:** since the project aims to look into the utility grid impact, which is a new topic within this thematic area, the project needs to continue the collaboration with the Energy and Power Group in the University of Oxford, as well as City University in London, both with ample experience in non-conventional power systems and grid modelling. Additionally, new collaborations with Technical University in Berlin and Honda Motor Company have been established, and researchers from both institutions have been visiting us in Sweden.
2) **Benefits for the industry:** the topics addressed within this project continuation emerged from the discussions between the researchers and SEC industrial partners. Therefore they represent relevant challenges that SEC industrial partners are facing or foresee they will face in the near future. In addition, the topic of grid impact of EV charging is of high interest to Vattenfall, who recently joined the Centre as a full member.
3) **Scientific challenges:** the project research focus is very much in line with the topics suggested in the Horizon 2020 call, particularly GV-08-2017 – Electrified urban commercial vehicles integration with fast charging infrastructure. Based on this, and on the numerous European projects from previous calls conducted in the field, it is clear that the project goals are current and relevant for the international community, both scientific and industrial-wise.
4) **Dissemination of knowledge and results:** the results obtained have been presented at suitable occasions, both at national and international conferences and journals. In addition, the research originated in the project has been shared with the existing Research & Innovation Platform on Electric Roads.
5) **Collaboration with other centres and internationalisation:** as stated before, the project relies on a collaboration with the Energy and Power Group, University of

Oxford, as well as the City University in London, UK. The results obtained could also be of interest for the Energy Technology Research Group at Chalmers, Gothenburg, with which a collaboration is already ongoing.

6) **Develop further competence:** the proposed project does not include a new PhD training. However, it aims to widen the scope of the Electrical Machines and Drives thematic area by including the electricity grid impact analysis of an increasing electric transport system. This, in turn, is expected to lead to involvement of PhD students in subsequent research projects.

Industry contribution

AB Volvo, Volvo Construction Equipment and Vattenfall contributed with valuable information and input data mostly at the beginning of the project.

Collaboration

Besides SEC partners, the project has built on an existing collaboration with experienced researchers from the University of Oxford (UK) and City University of London (UK), especially for the grid impact subproject.

A collaboration with TU Berlin, created within the project, has led to the SEC funded project IDEAS. The results from this new project can be used as input data for both the cost and grid impact analysis presented.

Moreover, the ERS developed by Honda presents an essential difference with all others developed in Sweden in that it is "floating" with respect to earth. Based on inputs from Honda, this type of power supply has also been simulated, and a future collaboration to conduct experimental measurements at Honda's pilot site may be possible.

Last, the project results have been shared with the Research and Innovation Platform on Electric Roads, a project financed by the Swedish Energy Agency and managed by RISE.

Dissemination of knowledge

For a complete list of events in which the project results have been presented please refer to Section "Utilization of Results"

Papers and publications

Several papers have been published within the project. Additionally, the results have been presented in numerous conferences / workshops that did not result in a published article (see Section "Utilization of Results").

Fyhr, P, Domingues, G, Andersson, M, Márquez-Fernández, FJ, Bängtsson, H & Alaküla, M, Electric roads: Reducing the societal cost of automotive electrification, 2017 IEEE Transportation and Electrification Conference and Expo, ITEC 2017, Chicago, United States, 2017/06/22.

Márquez-Fernández, FJ, Domingues-Olavarría, G, Lindgren, L & Alaküla, M, Electric roads: The importance of sharing the infrastructure among different vehicle types, 2017 IEEE Transportation Electrification Conference and Expo, Asia-Pacific, ITEC Asia-Pacific 2017, Harbin, China, 2017/08/07.

Domingues-Olavarría, G, Márquez-Fernández, FJ, Fyhr, P, Reinap, A & Alaküla, M 2017, Societal cost of electrifying all Danish road transport, EVS 2017 - 30th International Electric Vehicle Symposium and Exhibition 2017, Stuttgart, Germany, 2017.

Domingues-Olavarría, G, Márquez-Fernández, FJ, Fyhr, P, Reinap, A & Alaküla, M, Electric roads: Analyzing the societal cost of electrifying all Danish road transport, World Electric Vehicle Journal, vol. 9, no. 1, 9, 2018.

Márquez-Fernández, FJ , Schuch, S, Lindgren, L & Alaküla M, Electric safety challenges with a conductive ERS, EVS 2018 - 31st International Electric Vehicle Symposium and Exhibition 2018, Kobe, Japan, 2018 (recognised with the Young Investigator Award)

Márquez-Fernández, FJ , Schuch, S, Lindgren, L & Alaküla M, Electric safety challenges with a conductive ERS – chassis potential modelling and measurement, World Electric Vehicle Journal, vol. 10, no. 2, 30, 2019.

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