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Industrial Electrical Engineering and Automation

Chassis Potential Detection and Limitation with Conductive Electric Supply

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Preface

This report is the final part of my studies for a master's degree in Engineering Physics at the Faculty of Engineering (LTH) in Lund. I began my studies after leaving my hometown Mjölby in August 2010. It has been a great journey so far and I certainly hope it will remain so in the future.

I want to thank my supervisor Mats Alaküla for all help and for giving me the opportunity to work on this project. I also want to thank Lars Lindgren for comments on various topics, Getachew Darge for helping me in the laboratory and Carina Lindström for assisting me with all administrative matters. Finally, I want to thank my family and friends for all support.

Abstract

The automotive industry is in for significant changes in the years to come. With the acknowledgment of greenhouse gases as a major contribution to global temperature rise, energy usage sees a transition in favor of renewable sources. Adding the uncertainty of whether a peak-oil production is reached or not, fossil fuels are no longer considered reliable. In the wake of this, new candidates emerge as alternatives to the existing car fleet technology. Standards and regulations are continuously being updated to ensure safety and reliability, but it is ultimately up to the technology itself to adopt if it is to survive.

This project focus on personnel safety issues that arise from electric vehicle charging. Specifically, some new concepts of battery charging infringe on the possibility to use a safety ground connection to reduce the risk of electric shock. The project intent is to find an alternative solution for such concepts by means of active detection and limitation of the chassis potential.

The report shows promising results. Sensors mounted on the vehicle body can be used to collect a good ground reference without an actual safety ground connection. An on-board current source can then be used to make the chassis potential follow the reference. However, unresolved issues remain that needs to be addressed. These include a less insulated voltage class B system, a.c. signals that could potentially propagate to the electric chassis and uncertain resistivity values for plausible fault types. These should be evaluated in future work as well as constructing a physical model of the system.

Nomenclature

Symbols

i	current
v	voltage
g	switch state
s	signal
C	capacitance
V	electric potential
R	resistance
A, B, C	contact points

Indexes

X_1, X_2	chassis-to-pickup, positive and negative lead
X_p, X_n	chassis-to-battery, positive and negative lead
X_r, X_0	rail potentials, positive and negative (0 V)
X_h	through or across a human body
X_t	tyres
X_ref	reference value for chassis or current source
X_feed	feed current or compensation current
X_ch	chassis
X_ctrl	control
X_skin, X_body	human body characteristics, skin and internal body
X_a, X_b, X_c	rail-to-sensor contact points

Abbreviations

BEV	battery electric vehicle
BMS	battery management system
BOEV	battery-only electric vehicle
ECU	electric control unit
EMC	electromagnetic compatibility

ERS	Electric Road System
EV	electric vehicle
FCEV	fuel cell electric vehicle
HEV	hybrid electric vehicle
ICEV	internal combustion engine vehicle
PHEV	plugin hybrid electric vehicle
RCD	residual current device
REEV	range-extended electric vehicle
a.c.	alternating current
d.c.	direct current
rms	root mean square

Most symbols and terms are shown here. A symbol or term not shown is either self-explanatory, non-important or explained close to where is was used.

Contents

Chapter 1

Introduction

The idea of electrified transportation extends back to the beginning of the nineteenth century, following the invention of the electric motor. Electric vehicles (EV's) were introduced in the 1850's, and by the 1900's they constituted a significant share of the leisure car market, notably in the United States [1, p. 2]. However, EV's were typically expensive and short-ranged and could not compete with the emerging internal combustion engine technologies.

In the late twentieth century, a growing awareness of global warming spread across the globe. Fossil fuels were recognised as a dirty and insecure source of energy, and the demand for cleaner and more environmentally friendly sources was evident. Consequently, electric vehicles became popular again. As of early 2015, there were roughly 740,000 electric cars on the road worldwide, of which about 320,000 were registered in 2014 [2].

This master thesis project focus on a grounding system interface for EV's conductively connected to an earth grounded electric supply, where a sturdy low-ohmic connection from vehicle chassis to ground can not be established. An example of when this is relevant is the Slide-in ERS project [3]; a project based on the concept of conductive continuous power transfer from road to vehicle during propulsion. In it, the physical contact between vehicle and power supply slides on two rails that are connected to ground and an elevated potential, respectively. Due to irregularities in the road and possibly soiled rail sections, such a contact could never guarantee a low-ohmic connection. Thus, it does not suffice as grounding in today's standards and regulations.

1.1 Scope and Constraints

An alternative to the conventional safety ground connection is evaluated by means of simulations and experiments. It resembles an on-board system that actively monitors and controls the chassis potential. Important components are sensors that define a good ground reference, a current source that limits the chassis potential to a desired level and a control unit used for fault monitoring and current regulation. A full explanation of the system is given in chapter 3. The project involves identification of relevant standards on personnel safety, generation and simulation of a system model, and experiments to verify the findings.

The work was carried out at the department of Industrial Electrical Engineering and Automation at the Faculty of Engineering (LTH) at Lund Universiy. It was limited to only include single fault scenarios with the ambition to test a conceptual design rather than generating a complete safety system.

1.1.1 Redendum

Due to a tight time schedule, the experiments were not finished in time. For this reason, work regarding the physical model of the system has been excluded from the report and instead added in Appendix C.

1.2 Outline

An overview of relevant safety aspects regarding both electric vehicles and the human body can be found in chapter 2. This is followed by a description of the system model in chapter 3, an illustration of the simulation process in chapter 4, the project results in chapter 5, discussion in chapter 6 and, lastly, conclusions and future work in chapter 7. Symbols for relevant electric components are depicted in Appendix A, simulation blocks of minor importance in Appendix B and the experimental work in Appendix C.

Chapter 2

Theory

This chapter's topic is grid-connected electric systems and the risk they pose to human bodies. An introductory description of an electric vehicle is first given. This includes important safety features and standards. Next section is on battery charging methods with examples of conventional solutions and how safety measures are implemented. The last section covers electrical properties of the human body and its reaction to electric shock.

2.1 The Electric Vehicle

In this report, an electric vehicle (EV) is defined as an electric car, bus or truck if nothing else is mentioned. Conventionally, the phrase also includes other vehicles that convert electricity to motive power, such as trams, trains and trolleybuses. They are discussed in short but are not the focus of this project. Furthermore, a variety of electric vehicles with varying system configurations exist. Examples are hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), battery-only electric vehicles (BOEVs), range-extended electric vehicles (REEVs) and fuel cell electric vehicles (FCEVs). To avoid confusion and the need of describing similar configurations several times, only the BOEV will be explained more throughly.

2.1.1 Battery-only electric vehicle

Also referred to as an all-electric vehicle, the BOEV relies solely on an electric motor for propulsion. Compared to an internal combustion engine vehicle (ICEV), the advantages are plenty, e.g. high electric machine efficiency, low levels of emission, lower noise, smoother operation and the possibility to implement regenerative braking [1, p. 492]. Although the other technologies mentioned above have similar advantages, the all-electric vehicle is better suited as a reference for this project. Namely, its fuel is all-electric.

The main components of a BOEV's powertrain are illustrated in Figure 2.1. A battery pack, made up of several batteries such as lead-acid or lithium-ion [1, p. 497], constitutes the main source or energy. The other source is the auxiliary battery. Although essential for low-voltage applications such as lighting systems and radio, the auxiliary battery will not be discussed in this report. Its low-voltage characteristics does not make it a safety risk.

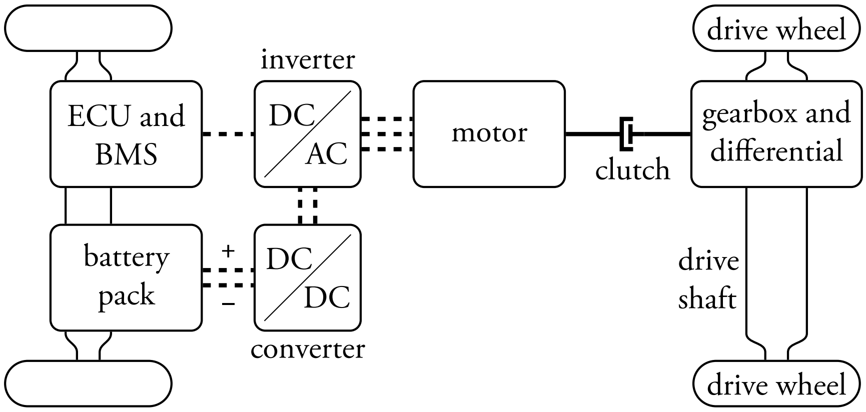


Figure 2.1: Typical powertrain of an all-electric vehicle.

Continuing on from the battery pack, a converter may be used to step up the battery voltage to more suitable levels. The voltage is then fed to an inverter that changes the direct current (d.c.) to three-phase alternating current (a.c.) that powers the motor. Of course, this is only done if the vehicle is powered by a three-phase a.c. motor. If a d.c. motor is used, there is instead need for an additional converter. However, the most common form of electric machines in EV's today are a.c. motors. Common types are permanent magnet motors, induction machines and switched reluctance motors [1, p. 8].

The electronic control unit (ECU) is the main control unit and regulates the motor power consumption based on signals from pedals and different sensors in the vehicle. It also controls the direction of power flow. When accelerating, power flows from the motor to the drive shaft. When braking, power flows in the opposite direction and recharges the battery pack. Battery recharging is monitored and regulated by the battery management system (BMS) to ensure safe operation.

Power transfer from motor to wheels is accomplished by the drivetrain. Several configurations are possible. The major components are a clutch, a gearbox, a differential, a drive shaft and drive wheels [1, p. 495 – 496]. This is true for most automobiles including non-electric vehicles. The workings are as follows: A clutch is used to engage or disengage the transmission of torque from motor to wheels, for example when changing gears. The ratio of torque to angular velocity is controlled with a gearbox that connects to a differential. The differential distributes the angular velocity so that

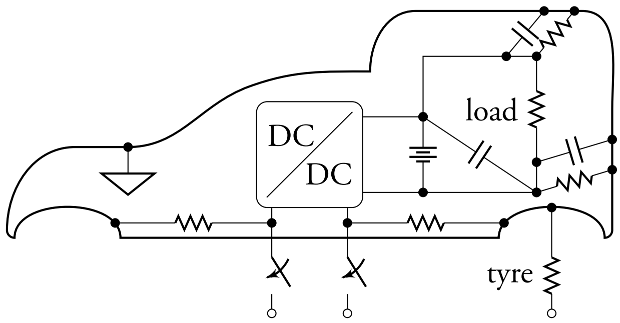


Figure 2.2: Electrical properties of an EV. Capacitors represent stray capacitances and resistors without label represent insulation resistances. Note that the d.c./d.c. converter shown here is supplied as part of the charging system and not the same as in Figure 2.1.

the drive wheels can rotate at different speeds. This is very useful when turning the vehicle. Finally, the drive wheels convert the transmitted energy to surface friction on the road and the vehicle is propelled forward.

A simplified model of an EV's electrical properties is shown in Figure 2.2. The powertrain is reduced to only include the traction battery, the inverter and the motor. However, since the motor and inverter are modelled as a resistive load, there are actually only two components shown. Other features are insulation, stray capacitances and tyres. The figure also includes connections for battery charging and a d.c./d.c. converter that isolates the on-board circuity from the external power source. Battery charging will be explained in section 2.2. Another feature, perhaps the most important regarding the scope of this thesis, is the common ground reference also known as the electric chassis.

2.1.2 The ground reference

All electric systems need a clear electric potential reference from which voltages are defined. Stationary systems are therefore in contact with a sturdy low-ohmic conductor thoroughly connected to the utility grid ground potential. In everyday language, this is simply referred to as ground. The ground connection prevents voltages generated in e.g. a power plant to elevate above earth's potential.

A system without a ground accumulates charge over time. When the charge reaches dangerously high levels, discharges from system to ground can occur. An example of this is lightning strikes during a lightning storm. Here, potential differences between high altitudes and the earth ionises the air and creates a conductive path. Extraordinary large amounts of charges flow through the air over an extremely short time. Since similar discharges to ground are not wanted in electric systems, a ground connection is used to prevent it from happening.

In mobile applications, a connection to earth is not always easy to establish. Instead, something called a floating ground is used as a well-defined reference for all involved electric systems. In EV's, the floating ground is the electric chassis and constitutes a metal frame. It is normally the same as the negative lead of the auxiliary battery. Although good enough as potential reference, the chassis alone does not make a good ground. A connection to earth is also necessary. Therefore, vehicle tyres are made slightly conductive to dissipate possible static charges [4].

2.1.3 Safety specifications

There are two different electric systems in an EV: the voltage class A system and the voltage class B system. Voltage class A and B refers to the voltage level and are defined in [5] as

Voltage class A - classification of an electric component or circuit with a maximum working voltage of less than 30 V a.c. (rms) or 60 V d.c.

Voltage class B - classification of an electric component or circuit with a maximum working voltage between than 30 V a.c. (rms) and 1000 V a.c. (rms) or between 60 V d.c. and 1500 V d.c.

A circuit powered by the auxiliary battery is thus categorised as voltage class A and the traction circuitry previously described as voltage class B. Due to the higher voltage in class B circuits, safety criteria are stricter as compared to class A. Some of them are listed below:

Capacitive couplings For d.c. body currents caused by discharge of capacitive couplings between a voltage class B potential and electric chassis when touching d.c. class B voltage, one of the following options shall be fulfilled:

- energy of the total capacitive between any energized voltage class B live part and the electric chassis shall be <0.2 J at its maximum working voltage; total capacitance should be calculated based on designed values of related parts and components;
- alternative mechanical or electrical measures for d.c. voltage class B electric circuit, as explained below.

Alternative electrical or mechanical measures include the following:

- double or reinfoced insulation instead of basic insulation;
- one or more layers of insulation, barriers and/or enclosures in addition to the basic protection;
- rigid barriers/enclosures with sufficient mechanical robustness and durability, over the vehicle service life.

De-energisation The voltage class B electric circuit in question may be de-energised as a protection measure. The monitoring of faults within the circuit or the detection of events may be used to trigger the de-energisation. One of the following conditions shall be met for the de-energised circuit.

- The voltage shall be reduced to less than 30 V a.c. (rms) for a.c. and 60 V d.c. (rms) for d.c. circuits.
- The total stored energy in the system shall be <0.2 J.

Isolation resistance requirements The minimum isolation resistance shall be at least 100 Ω/V for d.c. circuits and at least 500 Ω/V for a.c. circuits. The reference shall be the maximum working voltage.

Requirements for vehicle power inlet The vehicle power inlet shall comply with at least one of the following requirements:

- de-energise the circuit within 1 s;
- de-energise in a time specified by the manufacturer and IPXXB.

The vehicle power inlet intended to be conductively connected to the grid shall have a terminal for connecting the vehicle electric chassis to the ground of the grid. The isolation resistance at the vehicle power inlet, which includes circuits conductively connected to the grid during charging, shall be at least 1 MΩ when the charge coupler is disconnected.

2.1.4 Example of fault monitoring

An implementation of the monitoring of faults mentioned above is shown in Figure 2.3. Supposedly, this is the solution implemented in Volvo cars. Due to lack of written references, a similar system can be found in [6]. The implementation involves physical resistors of 375 kΩ connected from chassis to each lead of the battery. The reference uses larger and nonuniform values, but all resistances that fulfill the isolation resistance requirements for a.c. circuits are valid. The criterion is

$$\frac{R}{v} \geq 500\,\Omega/\mathrm{V} \tag{2.1}$$

from section 2.1.3. With a working voltage of 600 V, the minimum allowed resistance is 300 kΩ. It is even arguable that the criterion on d.c. circuits should be used, in which case the minimum resistance is much less. Moreover, capacitors are connected across the resistors. Note that these are not physical capacitors but rather stray capacitances. They usually result from Y capacitors, used for electromagnetic compatibility (EMC) reasons, or parasitic capacitive couplings [5, p. 6]. Each stray capacitance has a value of 0.6 μF, equaling a stored energy roughly the same as in [6].

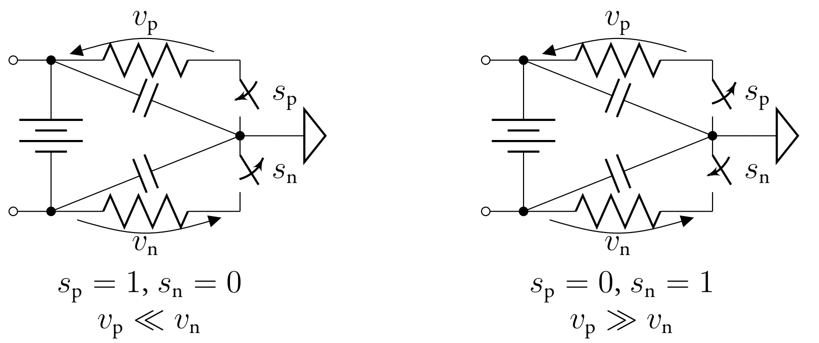


Figure 2.3: Schematics of monitoring system. An open switch is represented with 0 and a closed switch with 1.

Two switches, each connected in series with one of the resistors, are controlled with 0.25 Hz signals. The frequency can be kept rather low since a fault between battery lead and chassis does not normally result in a personnel safety issue. The two signals are phase-shifted 180° so that one is always open when the other is closed. When the switches' states change every half period, electric charges flow through the closed switch. Any stored energy in the capacitance is emptied and the voltage goes to zero. Since no charge can flow through the other switch, the voltage across it builds up which stores energy in the capacitance. As time passes, the voltages changes periodically as seen in Figure 2.4.

In the event of a fault from either battery lead to chassis, or a changed stray capacitance value, the voltage output change accordingly. If too large a fault or too high a capacitance value, a contactor (a type of switch) in series with the battery opens to prevent dangerous currents to flow.

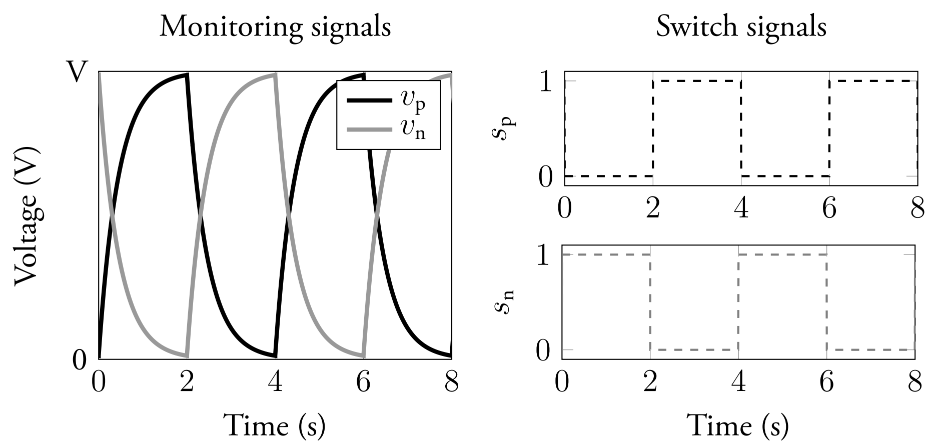


Figure 2.4: Typical signals in a fault-free monitoring system.

2.2 Charging the Battery

Energy can neither be destroyed nor created; it can only be converted into another form. Therefore, as the electric machine and drivetrain of an EV converts electric energy to kinetic energy, the stored energy inside the battery is depleted. To replenish it, a connection between power grid and EV is established. There are several ways this can be done, some of which are explained here. Prior to this, however, an introduction to power transmission and the need for safety ground is given.

2.2.1 The grid

The grid connects power plants and other electricity producers with the end consumers. In Sweden, the grid can be divided into the national grid at 220–400 kV, the regional network at 40–130 kV and the local network at 0.4–20 kV [7, p. 13]. The different grid levels are separated with so called substations that transform one voltage to another. Since the Swedish grid carry a.c. (50 Hz), the transformation is done with transformers.

An important feature of transformers is that they constitute a galvanic isolation between two systems. It means that an electron current can not flow from one of the systems to the other. This is due to the very nature of electromagnetic induction; the underlying phenomenon on which the transformer relies. When a current flows into a transformer's primary side, the first thing to happen is the conversion of electric energy to magnetic energy. The energy then continues through an iron core to the secondary side, where it is converted back to electric energy again. No electron current flows inside the core itself, meaning that electrons flowing into the transformer on one side also flows out on the same side.

A direct consequence of this is that the dissipation of charges between two systems no longer is possible. From a safety perspective, this means that both systems must have separate ground connections in order to be protected from discharges to ground, as explained in section 2.1.2. This is illustrated in Figure 2.5.

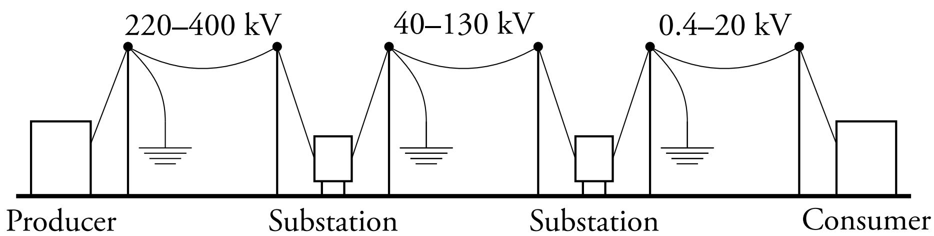


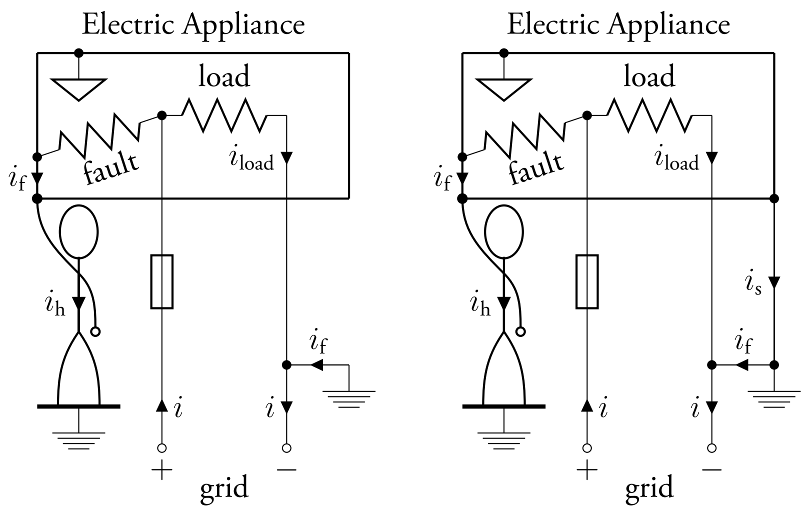
Figure 2.5: Swedish grid.

2.2.2 Safety ground

As previously explained, a ground is established in most electric systems. It is used to uniquely define voltages and to prevent charges to accumulate in a system so that no dangerous discharges can occur. However, this results in another issue: if an object touches the ground reference and a grounded electric system simultaneously, the object forms a closed circuit from system to ground through which current can flow. This is known as a leakage current and is not desired. Under bad circumstances, such a current can be very large and potentially cause damage to the object. By introducing a safety ground, this can be avoided.

An example is illustrated in Figure 2.6. The object is a human and the system constitutes a grounded grid that powers an electric appliance. The appliance is modelled as a resistor, which draws a current i_{load} from the grid, and a metal casing. All powered system parts are insulated and can therefore not be touched during normal operation. However, the insulation which separates the system from the casing has failed. This is symbolised as the leakage current i_{f} through a fault resistor. In the left figure (Figure 2.6a), there is no safety ground. This simply means that the metal casing is not connected to ground. Therefore, the current that flows through the fault continues through the human to ground and back to the grid. The value of the current i_{h} depends on several factors such as grid voltage, fault resistance and the electrical properties of the human. In a case were the fault resistance is small and the human is soaked in water, i_{h} would be dangerously high.

Additionally, there is one more protective component that needs to be mentioned: the fuse. It is depicted as a box with a line through it and prevents large currents to



(a) Without safety ground. **(b)** With safety ground.

Figure 2.6: Illustration of a safety ground connection.

flow. A fuse is rated to trip at a specified amperage, meaning that the fuse still conducts if the current is too low. Typical currents that are dangerous to a human body are not enough to make most fuses trip, rendering the fuse rather worthless in said scenario.

As opposed to the left figure, the right one (Figure 2.6b) does have a safety ground. Here, the fault current splits into two parts: the current i_h from before and another current, i_s. The safety ground is depicted as a simple line since it is typically low-ohmic, so most (if not all) leakage current i_f would go straight to ground instead of first taking the path through the human. Note that the actual current through the human is not significantly reduced as compared to the previous scenario. The safety lies in the extremely large total current i, which will trip the fuse and brake the circuit.

As a last remark, very often there are other safety features in addition to the safety ground. An example is the residual-current device (RCD) installed in most households. It is a device that monitors the net current flow between household and grid. In normal operation, no current can flow anywhere except where it is supposed to and the net current is very close to zero. However, in the event of a fault, a new path for the current is introduced, resulting in a net flow that differs from zero. This is detected by the RCD, which disconnects the household from the grid.

The RCD is a significant device in some areas of technology. In this project, though, it is not very important.

2.2.3 Plug-in connectors

Conventional methods for charging of electric car batteries involve plug-in connectors designed for higher voltage and amperage than ordinary wall sockets. There are several designs available on the market, although the more common ones are:

SAE J1772 Designed for up to 32 A one-phase a.c. currents. It is not likely to play a significant role in the future, at least not in Europe [8, p. 17]. Referred to as a type 1 implementation.

Mennekes Also known as a type 2 connector. It manages currents of 70 A one-phase or 63 A three-phase a.c. [8, p 18]. It is one of the two current standards in Europe.

Combo 2 The other standard in Europe. It combines two different kinds of contacts and can therefore be used for both a.c. and d.c. charging. A.c. charging speed is typically slower than d.c. [8, p 19].

CHAdeMO A Japanese solution based on d.c. charging. Maximum voltage is 500 V and maximum current is 120 A [8, p. 18 – 19].

The connectors are depicted in Figure 2.7. They may be different in appearance and pin setup, but they all have a way of dealing with protection against electric shock. The

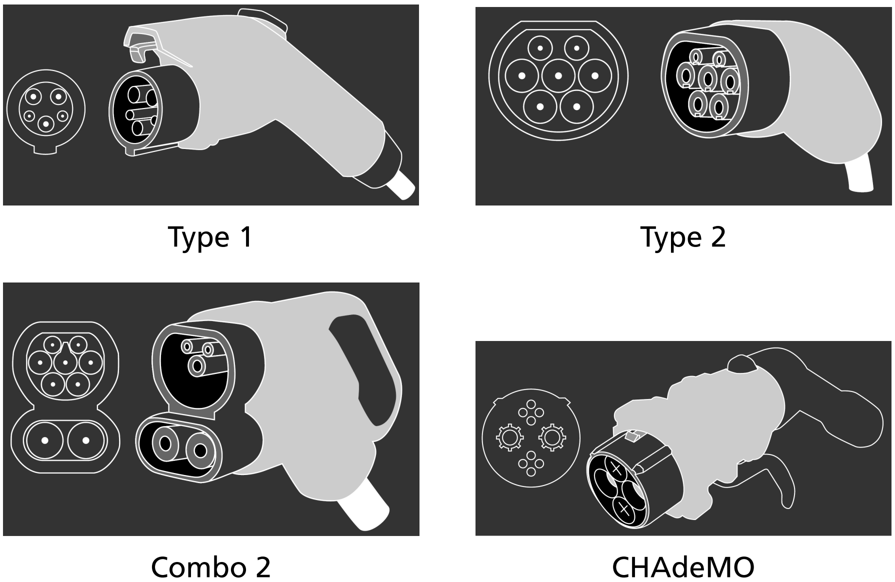


Figure 2.7: Plug-in connectors.[1]

type 1, type 2 and Combo 2 use safety ground connections [9], whereas CHAdeMO make use of transformers to galvanically isolate the connector from the grid [10].

2.2.4 Trolleybuses

Trolleybuses are electric buses powered via two overhead power lines typically under a d.c. voltage of 600–750 V [11]. Their appearance differ significantly from other buses in that trolleys are mounted on the roofs. The driver can manually attached or detached the trolleys to and from the lines, making it possible to make small detours from the lines as long as on-board batteries are in place. However, this is not always the case, and many trolleybuses are fixed to a predefined route much like a train or a tram. Today, there are more than 40,000 trolleybuses in service worldwide, of which about three quarters are located in eastern Europe. [11, p. 469]

Like most road vehicles, trolleybuses operate on rubber tyres. Thus, there is no simple way to establish a safety ground. The solution to this problem is called double or triple insulation [11, p. 472], which in short means stricter insulation criteria for trolleybuses as compared to e.g. plug-in electric vehicles. For instance, the resistance requirement between body and high voltage circuits is minimum 5 MΩ and between body and positive lead of low voltage circuits minimum 1 MΩ [12, p. 124]. Extra insulation adds weight to the vehicle, and although it may be fine for larger vehicles such as buses, it may be undesired in smaller cars.

[1] Electric Vehicle Institute. *Plug-In Around the EV World*. Retrieved September 2, 2015 from `http://www.ev-institute.com/images/Plug_World_map_v5.pdf`.

2.2.5 Slide-in Electric Road System

In 2014, Volvo GTT published a report on a charging system that powers EV's conductively via powered rail sections on the ground [3]. The system is called Slide-in Electric Road System (ERS) and is similar to the concept used in this project. It is designed for highway use as one of two plausible alternatives currently being evaluated. The other alternative is based on induction but will not be discussed here.

Two conductive rails are placed side by side on the road, as seen in Figure 2.8. One of the rails is divided into shorter sections whereas the other is continuous. The shorter sections constitute the positive lead and can individually be powered to 750 V [3, p. 33]. Initially, though, all sections are at ground potential V_0. Power boxes placed along the road act as the interface between grid and rails and converts the grid voltage to lower levels. A connector or pickup is mounted on the vehicle underbody to be used for rail connection when desired.

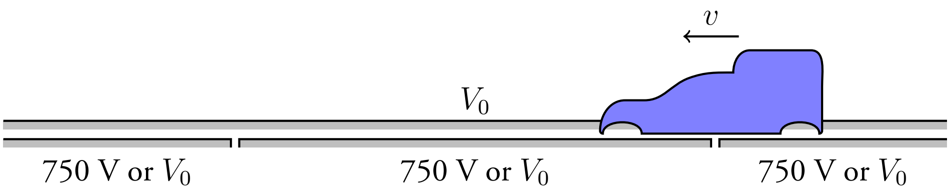


Figure 2.8: Illustration of the ERS.

When a vehicle-to-rail connection is established, a sensor system determines the position of the car and powers the corresponding section. Since the rails are much longer than the car, most of the powered section is exposed. This means a personnel safety risk and precautions must be taken accordingly. As a safety measure, the length of the sections were chosen to the distance a vehicle travels every second at a speed of 60 km/h. A time interval of one second was chosen to be the reaction time of a human standing in front of a driving car. In other words, if pedestrians were to touch a section while it is powered, they would get hit by the car that activated it. Therefore, the exposed parts of a powered rail section does not mean any additional safety risk. Note that this is only true if a car travels at least 60 km/h, why the system is designed to not be activated if a car travels slower than that.

Although the project is quite extensive, a safety ground connection has not been considered in the report. In the event of an electric fault, there is nothing that controls the chassis potential. One way to solve this is to assume similar criteria on insulation as in trolleybus technology. However, cars are much smaller than buses and would suffer more from the increased weight and volume. Therefore, solutions such as the one presented in this report could be interesting, the details of which are explained in section 3.

2.3 Electricity and the Human Body

An object in contact with two different electric potentials draws a current based on the object's conductive properties. The higher the conductivity, the higher the current flow. Although high currents are wanted in some electrical machines, it is not desired in the human body tissue. If too high, a human can suffer from burns, shock and even death.

In electric safety calculations, the human body is typically distinguished as a series connection of the skin and internal body. This is shown in Figure 2.9. Here, a capacitance C_{skin} in parallel with a resistance R_{skin} models the skin, whereas a sole resistor R_{body} models the internal body. The total current i_{h} is referred to as the touch current, a recurring term throughout this document. Furthermore, A and B represent contact points.

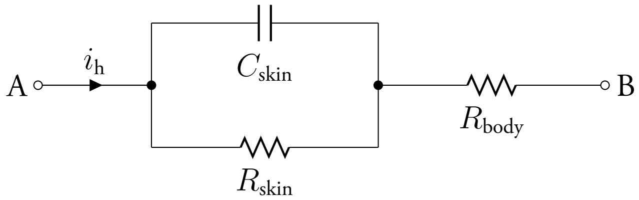


Figure 2.9: Simple model of a human body.

Typical values for the resistances and capacitance are R_{body} = 500 Ω, R_{skin} = 1500 Ω and C_{skin} = 0.66 μF [13]. These values represents a scenario in which the human body's conductivity is greatly increased. Such a scenario is chosen to ensure a maximum possible current through the body. Normally, however, the skin resistance varies significantly with external conditions and can reach values greatly exceeding that in the model [14]. Some examples are shown in Table 2.1. Moreover, the internal body resistance is tissue dependent. Muscles tend to be characterised as low-ohmic and fat as high-ohmic.

Table 2.1: Resistances for certain skin conditions. Units in kΩ.

Condition	
Submersed in water	1.2–1.5
Sweat	2.5
Dry skin	10–40
Sole of foot	100–200
Heavily calloused palm	1,000–2,000

Of course, not all touch currents are dangerous. A large current may be very dangerous to the human body, whereas a small current may not even be noticeable. Touch currents are therefore often categorised after corresponding bodily reactions, as see in Table 2.2 [13]. Notice that the thresholds are roughly three to four times higher for d.c. than for a.c. The difference is due to the fact that a.c. alternates and d.c. does not.

Table 2.2: Important touch current thresholds.

Threshold	a.c. (mA)	d.c. (mA)
Tingling sensation	0.5	2
Strong muscular reaction	5–10	25
Ventricular fibrillation	40–100	140–200

An alternating current of 40–110 Hz can give rise to continuous muscle contractions [14], potentially preventing a person from releasing a current source if touched with a hand. This prolongs the duration of exposure to the electrical circuit, thus increasing the risk of permanent damage to the body. Often, the phrase *let-go current* is used when referring to the a.c. threshold for strong muscular reactions. A direct current, on the other hand, does not give rise to continuous contractions. Instead, d.c. tends to produce a single muscle spasm with the potential of sending a person flying. Although increasing the risk of blunt injury on impact, this actually decreases the exposure time.

Chapter 3

System Description

In this chapter, the system details are described. Plausible fault scenarios and safety requirements are incorporated in the first section along with an overview of the system schematic. This is follow by sections on the main system elements.

3.1 Schematic

The system schematic is illustrated in Figure 3.1. The system inputs are two potentials, V_r and V_0, supplied via powered rail sections in the road. These potentials are collected by low-conductance sensors and distinguished as high and ground potential. The ground potential V_gnd is then sent to a control unit along with the vehicle chassis potential V_ch. From these two values, a reference signal s_ref is generated and sent to an on-board current source, which feeds the chassis with a current i_feed. The result is a feedback system that monitors and limits the chassis potential.

If the rails fail to provide a good ground potential, the control unit signals the pickup to disconnect from the power supply P_supply. This also applies when there is a too elevated fault from chassis to either polarity of the powered rails.

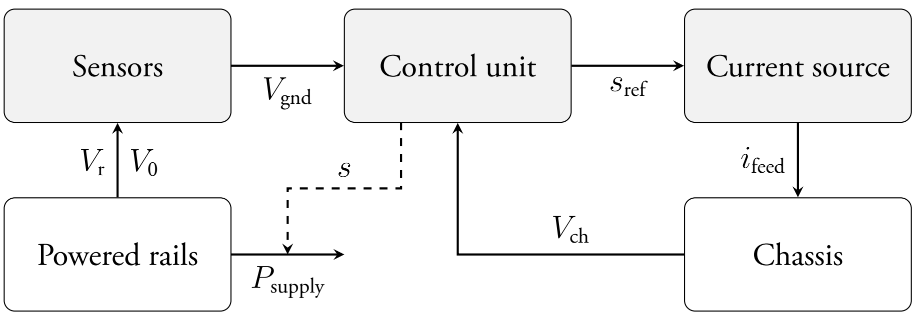


Figure 3.1: System schematic.

3.1.1 Assumptions and limitations

During normal operation, the chassis potential does not pose a threat to humans. A high resistance from chassis to V_r prevents an elevated touch current to flow. Therefore, a problem only exists when the resistance drops for some unwanted reason. This is known as a fault from chassis to V_r. On the other hand, a fault from chassis to V_0 is not really a threat to personnel safety since it would act as a ground connection. It is unwanted due to other reasons, though, but since this report is on the topic personnel safety, it will only be considered slightly.

Table 3.1: Plausible fault scenarios. Note that a lost pickup contact is not considered a fault, but rather normal operation.

Anomaly	Example scenarios
Fault from chassis to V_r or V_0	Insulation degradation, ice on pickup
Lost sensor contact	Soil or ice on rail

Plausible fault scenarios are shown in Table 3.1. Note that a single-fault scenario approach is used. This means that two or more simultaneous faults are considered impossible. This limits the generality of the result but greatly reduce the complexity of models. Furthermore, some single fault scenarios are excluded from the project. These include faults from chassis to the on-board voltage class B system, faults from chassis to the on-board class A system and component failures other than insulation degradation from pickup to chassis. Lastly, four system criteria was generated to help ensure personnel safety. They are found in Table 3.2.

Table 3.2: Safety criteria on system.

#	Safety criterion
1	The chassis potential V_{ch} must be kept at an acceptable level when the vehicle is connected to the grid.
2	A safety system must be able to handle arbitrarily large faults. Faults below a desired threshold resistance must be detected by the system.
3	The system must function under normal conditions, which includes road bumps and icy rails.
4	Sensors must be able to distinguish V_r from V_0 and pick the right potential as V_{gnd}. They must also distinguish a valid ground reference from a bad ground reference.

3.2 Rails

In this project, the rail model is based on a concept for continuous power transfer from road to vehicle in urban environments. Since more people reside near city streets than country highways, a greater need for pedestrian safety precaution is apparent as compared to the Slide-in project described in section 2.2.5. A concept designed for city use needs to be inherently safe and provide no means for pedestrians to come in contact with high voltage.

A solution, provided through the courtesy of Dan Zethraeus, is to use rail sections placed on the road in a dashed line pattern. This is illustrated in Figure 3.2. Every section is initially connected to ground V_0. When a vehicle connects to the rail, it starts to communicate with a positioning system that tries to determine the vehicle's position. When the position is established, the closest section to either of the contact points A, B or C is powered with a voltage V_r. Only every second section can be powered in this manner, thus always ensuring a closed circuit between V_r and V_0. Consequently, when a vehicle disconnects from the rail, the system stops powering the sections.

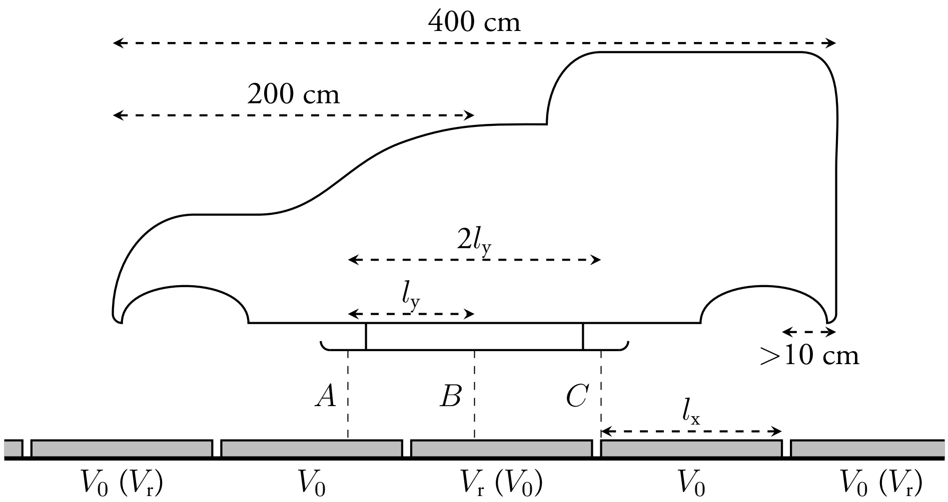


Figure 3.2: Rail and pickup dimensions.

The safety lies in the rail section sizing. In the illustration, each rail section length is l_x separated at a spacing of 5 cm. The current pickup consists of three point contacts on a metal slip mounted in the centre of the vehicle underbody. The point contacts are evenly spaced out over a distance of $2l_y$. Measured from the centre to either front or back, this yields a maximum of l_x+l_y rail in contact with the vehicle. Assuming a vehicle length of at least 4 m, the system can easily be dimensioned so that the vehicle body cover the powered sections at all time.

3.3 Sensors

An important feature of the sensors are very good contact with the rail. This means that the connection must not break due to road noise, road bumps or other vibrations that propagate to the vehicle. Therefore, the idea is to use multiple-contact sensors. The more contact points, the higher the probability of an unperturbed contact with the rail. Additionally, the sensors must be resilient and be unaffected by vehicle vibrations. Such multiple-contact elastic sensors closely resembles painting brushes, why they simply are referred to as brushes in this report. Since the brushes are not meant to conduct electricity, but rather sense the rail potential, the brush filaments can be kept thin. This makes them rather fragile. They were therefore placed behind the sturdier current pickups for protection against any formation of ice or soil that could cause damage. This is pictured in Figure 3.3.

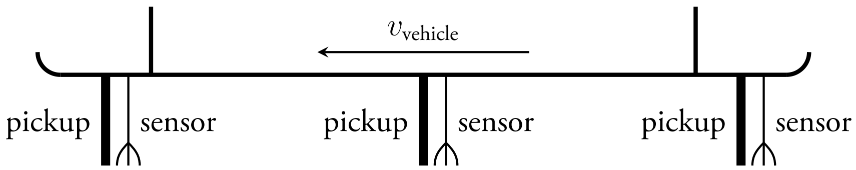


Figure 3.3: Sensors placed behind current pickups.

3.3.1 Rail-to-brush interface

A good contact can not be guaranteed at all times. Even if very fine filaments are used that do not lift from the rails, the contact will brake if something highly resistive comes between the rails and brushes. For instance, this could happen a cold winter day when ice form on the rail sections. Of course, if the pickup is designed to somehow remove the ice and snow with absolute certainty, this is not a problem. Most likely though, even well-designed brushes will lose contact with the rails from time to time. Therefore, such a scenario must be considered.

The interface between rail and brushes are depicted in Figure 3.4. Here, resistors represent the contact points. Resistance is low for a good connection and high for a bad.

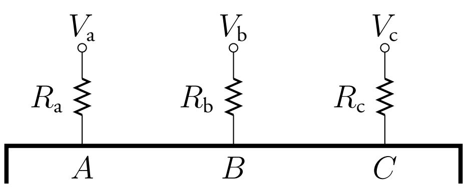


Figure 3.4: Electric connection from rail to brushes.

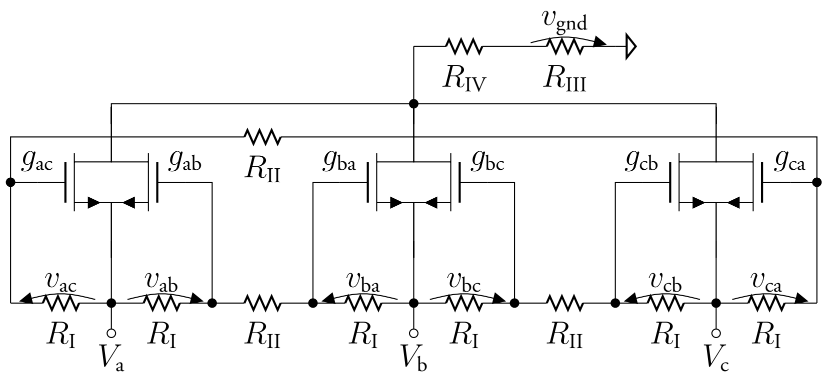


Figure 3.5: Sensor circuit. Finds V_0 and checks if it is well-defined.

3.3.2 Brush-to-chassis circuitry

When the rail potentials have been collected, regardless the connection quality from rail to brushes, three potentials are sent on-board the vehicle. The next step is to identify the potentials as either V_r or V_0, thereby chosing a ground reference V_{gnd}. One way to do so is to use the circuit in Figure 3.5, which in principle does the same thing as the circuit described in section 3.5.

The output of the circuit is explained with a truth table, see Table 3.3. High potentials and closed switches are represented with 1, whereas low potentials and open switches are represented with 0. For example, if $V_a = V_0$ and $V_b = V_C = V_r$, both switches at A are closed. If instead $V_a = V_b = V_0$ and $V_c = V_r$, one switch at A and one at B are closed. Note that for all possible inputs, there are always two switches closed, both connected to V_0. Thus, $V_{gnd} = V_0$ will always be the ground reference. Then again, this is only true in a fault-free scenario. Therefore, when faults are introduced to the matrix, the possible outputs must be reconsidered.

Table 3.3: Truth table for sensors. Fault-free scenario.

Input			**Output**					
V_a	V_b	V_c	g_{ac}	g_{ab}	g_{ba}	g_{bc}	g_{cb}	g_{ca}
0	1	1	1	1	0	0	0	0
0	0	1	1	0	0	1	0	0
1	0	1	0	0	1	1	0	0
1	0	0	0	0	1	0	0	1
1	1	0	0	0	0	0	1	1
0	1	0	0	1	0	0	1	0

Here, the only faults considered are weak or completely lost rail connections. Although dysfunctional switches or broken voltage sensors would indeed be problematic, it does not fall within the scope of this thesis to evaluate the need for redundancy. Furthermore, the single fault criteria approach is used. Hence, as previously described, a fault is represented by a non-zero value for either R_{a}, R_{b} or R_{c}. To determine its influence on V_{gnd}, the voltage across the arbitrary switch g_{xy} needs to be calculated. Here, x and y are placeholders for any of a, b or c. Mathematically, the voltage can be expressed as

$$v_{\mathrm{xy}} = \frac{R_{\mathrm{I}}}{2R_{\mathrm{I}} + R_{\mathrm{II}}} \left(V_{\mathrm{x}} - V_{\mathrm{y}}\right) . \tag{3.1}$$

This is actually the voltage (gate voltage) that controls g_{xy}. If it is higher than a certain threshold voltage, the switch is closed, otherwise the switch is open. Continuing from here, (3.1) is extended to a function of V_{r}–V_0, i.e.

$$v_{\mathrm{xy}} = \frac{R_{\mathrm{I}}}{2R_{\mathrm{I}} + R_{\mathrm{II}} + R_{\mathrm{x}} + R_{\mathrm{y}}} \left(V_{\mathrm{r}} - V_0\right) , \tag{3.2}$$

where it has been assumed that V_{x} is connected to V_{r} and V_{y} to V_0. For any non-zero (and positive) value of R_{x} or R_{y}, the gate voltage would be lower than in a fault-free scenario. The larger the fault, the less the voltage. Yet, since single fault scenarios are assumed, the two faults can not exist simultaneously. With $R_{\mathrm{y}} = 0$, (3.2) is simplified to

$$v_{\mathrm{xy}} = \frac{R_{\mathrm{I}}}{2R_{\mathrm{I}} + R_{\mathrm{II}} + R_{\mathrm{x}}} \left(V_{\mathrm{r}} - V_0\right) . \tag{3.3}$$

With an opposite rail potential polarity, (3.3) is instead expressed as

$$v_{\mathrm{xy}} = \frac{R_{\mathrm{I}}}{2R_{\mathrm{I}} + R_{\mathrm{II}} + R_{\mathrm{x}}} \left(V_0 - V_{\mathrm{r}}\right) . \tag{3.4}$$

It should be obvious that equal potentials lead to $v_{\mathrm{xy}} = 0$.

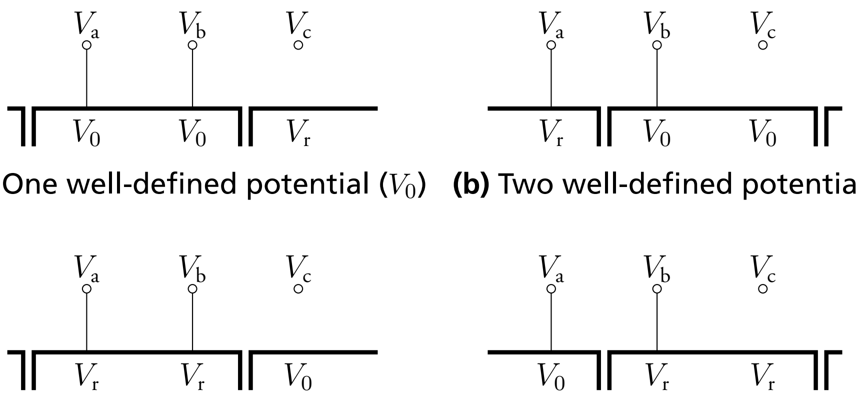
It is worth noting that (3.3) and (3.4) are approximations, although in this case extremely good ones. They are derived with the assumption that open switches have very large resistances. Since all non-zero values of v_{xy} require the input potentials to include both V_0 and V_{r}, switches connected to one of the potentials (V_{r}) will always be open. Furthermore, the fault is assumed to be either very large (open circuit) or close to zero (short circuit), resulting in the two possible outcomes

$$v_{\mathrm{xy}} = \frac{R_{\mathrm{I}}}{2R_{\mathrm{I}} + R_{\mathrm{II}}} \left(V_{\mathrm{r}} - V_0\right) \tag{3.5}$$

and

$$v_{\mathrm{xy}} = 0 \tag{3.6}$$

for zero and large values, respectively.



(a) One well-defined potential (V_0) **(b)** Two well-defined potentials

(c) One well-defined potential (V_r) **(d)** Two well-defined potentials

Figure 3.6: Considered fault scenarios between brushes and rail.

There are four possible single fault scenarios, as seen in Figure 3.6. Figure 3.6a and Figure 3.6c result in one well-defined potential, whereas Figure 3.6b and Figure 3.6d result in two well-defined potentials. For a truth table over these scenarios, see Table 3.4. Note that the floating potential V_c is determined from V_a and V_b. It can therefore amount to ½. This is not enough to close a switch, though, as long as the gate threshold is set accordingly. Also note that a brush positioned in a rail section gap has a floating potential as well. Such a scenario is therefore included.

Resistances are chosen so that the model did not violate the minimum and maximum voltages for gates and voltage sensors. Since typical max and min values are much lower than the system working voltage V_r, the values were picked based on the relation

$$R_I \ll R_{II} \ll R_{III} \ll R_{IV}. \tag{3.7}$$

With $R_I = 500\ \Omega$, $R_{II} = 59\ \text{k}\Omega$, $R_{III} = 5\ \text{M}\Omega$ and $R_{IV} = 595\ \text{M}\Omega$, the measured voltages are kept between –5 V and 5 V at $V_r = 600$ V and the max current is kept below 10 mA.

Table 3.4: Truth table for senors. V_c is assumed to be floating.

Input			**Output**					
V_a	V_b	V_c	g_{ac}	g_{ab}	g_{ba}	g_{bc}	g_{cb}	g_{ca}
0	0	0	0	0	0	0	0	0
0	1	$\frac{1}{2}$	0	1	0	0	0	0
1	0	$\frac{1}{2}$	0	0	1	0	0	0
1	1	1	0	0	0	0	0	0

3.4 Control Unit & Current Source

The main task of the control unit and current source is to ensure ground potential in the chassis. The idea is to process V_{gnd} supplied from the sensors together with V_{ch} from chassis in a μ-processor. It can be described in the following steps:

1. The potential difference $v_{gnd} = V_{ch} - V_{gnd}$ is measured and sent to a μ-processor. This could be done either directly with the processor or with a separate voltmeter. Caution has be taken if measuring directly with the processor since they are typically sensitive to over-voltages and negative voltages.

2. A reference signal s_{ref} is generated based on v_{gnd} and a desired response time. The signal must be able to steer v_{gnd} towards a reference voltage v_{ref}.

3. An accepted value for i_{feed} is calculated based on the reference voltage and compared to the feed current's momentary value. If s_{ref} would mean a too high or too low i_{feed}, a signal is generated to control certain safety measures. An example would be to disconnect the vehicle from the grid.

4. The signal s_{ref} is sent to a controlled current source that feeds a current i_{feed} to the chassis. In the end, s_{ref} was chosen so that $s_{ref} = i_{feed}$.

3.4.1 The reference voltage v_{ref}

A reference voltage must be low enough to ensure an accepted touch current at all times. This includes a margin for possible voltage drops in the sensors that make V_{gnd} differ from V_0. The reference voltage is determined from a criterion on the wanted chassis potential $V_{gnd}+v_{ref}$, i.e.

$$|V_{gnd} + v_{ref}| \leq i_{max} R_{min}, \tag{3.8}$$

where $i_{max} = 2$ mA and $R_{min} = 2$ kΩ are the maximum allowed touch current and the minimum possible resistance of a human body, respectively. Note that v_{ref} is a fixed value that must suffice for all possible values of V_{gnd}. Assume

$$0 \leq V_{gnd} \leq M \tag{3.9}$$

for some positive constant M. Combining (3.8) and (3.9) yields

$$-i_{max} R_{min} \leq v_{ref} \leq i_{max} R_{min} - M. \tag{3.10}$$

In the best of worlds, M is close to zero and the natural choice would be $v_{ref} = 0$ V. A better approach could be to pick a slightly negative value, since the more M differs from zero, the tighter the interval (3.10) becomes. In a worst case scenario with M = 8 V, the voltage $v_{ref} = -4$ V is the only viable option. However, for the sake of this report, $v_{ref} = 0$ V and M = 0 V are assumed. Note that if v_{gnd} is scaled down with the use of series resistors (see Figure 3.5), v_{ref} must be scaled down with the same factor.

3.4.2 Maximum and minimum value of i_{feed}

The main reason for a restriction on i_{feed} is spelt *fault detection*. As will be explained in the next paragraph, the required feed current is highly dependent on fault size. It also depends on the chosen reference voltage. To find a mathematical expression for it, a model similar to that in Figure 2.2 from section 2.1.1 is considered. Since the feed current in steady state can be characterised as d.c., all a.c. components have been excluded. This also includes the isolated parts, since they do not affect the touch current as long as the converter works properly. A new model — the grid-to-ground (GTG) model — is depicted in Figure 3.7. Two levels of simplification are present. The lower level of Figure 3.7a means a higher complexity, and vice versa for the higher level of Figure 3.7b. Note that a current source has been placed across R_1, but placing it at R_2 would have yielded similar results.

The resistances in Figure 3.7b is derived as

$$R_2^* = \frac{(R_2 + R_0)\, R_{\text{t}} R_{\text{h}}}{(R_2 + R_0)\,(R_{\text{t}} + R_{\text{h}}) + R_{\text{t}} R_{\text{h}}} \tag{3.11}$$

and

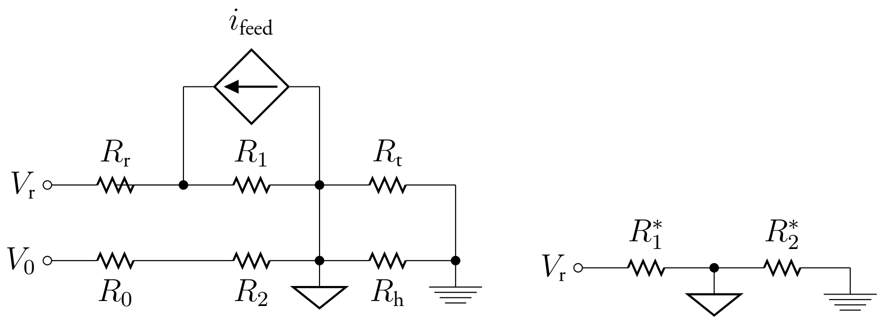
$$R_1^* = R_{\text{r}} + \frac{R_1 v_1}{v_1 - R_1 i_{\text{feed}}} \tag{3.12}$$

where v_1 is the voltage across R_1. It is given by

$$v_1 = V_{\text{r}} - V_{\text{ref}} - R_{\text{r}} \frac{V_{\text{ref}}}{R_2^*}. \tag{3.13}$$

Furthermore, the voltage v_{h} across R_{h} can be expressed as

$$\begin{aligned} v_{\text{h}} &= \frac{R_2^*}{R_1^* + R_2^*} v_{\text{r}} \\ &= \frac{R_2^*\,(v_1 - R_1 i_{\text{feed}})}{R_1 v_1 + (R_{\text{r}} + R_2^*)\,(v_1 - R_1 i_{\text{feed}})} v_{\text{r}} \end{aligned} \tag{3.14}$$



(a) GTG model – level 1 **(b)** GTG model – level 2

Figure 3.7: D.c. model of an electric vehicle connected to the grid.

where the last expression is derived with the use of (3.12). The voltage v_{h} can also be expressed as

$$v_{\mathrm{h}} = V_{\mathrm{ref}} \tag{3.15}$$

which, combined with (3.11) and (3.14), yields an expression for i_{feed},

$$i_{\mathrm{feed}} = \frac{v_1}{R_1}\left(\frac{R_2^* v_{\mathrm{r}} - V_{\mathrm{ref}}\left(R_1 + R_{\mathrm{r}} + R_2^*\right)}{R_2^* v_{\mathrm{r}} - V_{\mathrm{ref}}\left(R_{\mathrm{r}} + R_2^*\right)}\right). \tag{3.16}$$

Since the reference potential was chosen $V_{\mathrm{ref}} = 0$, (3.17) can be simplified to

$$i_{\mathrm{feed}} = \frac{V_{\mathrm{r}}}{R_1} \tag{3.17}$$

with the use of (3.13). Note that R_1 represents a fault from chassis to V_{r}.

In a fault-free scenario, no feed current can flow between pickup and chassis. This is not a problem in itself, since the conductive properties of the tires would be enough to keep V_{ch} close to ground potential. However, it would make it hard to determine whether the control unit is working or not. If a fault was to occur without a functional control unit, the chassis potential could settle at a dangerous level. By introducing two small predefined faults R_1 and R_2, a feed current would flow even in a fault-free scenario, thus equalise a non-functional control unit with $i_{\mathrm{feed}} = 0$ mA. Observing the chassis potential would also work.

As a last remark, a small current margin would make room for fluctuations in the regulation process. It was chosen to 5% of the feed current for the given accepted fault $R_{\mathrm{limit}} = 100$ kΩ. Furthermore, the predefined faults were $R_1 = R_2 = 10$ MΩ, resulting in a maximum feed current of 6.3 mA and a minimum of slightly more than 0 mA.

3.4.3 Reflections on current source properties

The feed current has to come from somewhere on-board the vehicle. In traditional electric vehicles, there are two sources to chose from: the traction battery and the auxiliary battery. Since the feed current is quite small, it does not seem to matter which battery to draw it from. However, the need for galvanic isolation must be evaluated regardless choice of battery. In this report, the actually need of isolation has not been determined. The use of it is recommended, though, since it is better to be safe than sorry.

Up to this point, the discussion has only included d.c. elements and steady state characteristics. However, at the exact time a fault occurs, there is an instant change in V_{ch} and i_{h}. This is because a d.c. model has no voltage or current damping properties. Although the control unit quickly adopts to the new state and sets V_{ch} to V_{ref}, humans could already have been exposed to a dangerously high voltage. To introduce voltage damping, a capacitor is simply connected across the voltage source as depicted in

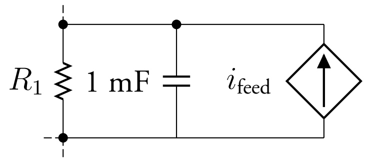


Figure 3.8: The current source and capacitor across R_1.

Figure 3.8. Voltage peaks are then absorbed in the capacitor, which gives the control unit some time to adopt to the changes. The capacitance value is determined from how much damping is needed and was chosen to $C = 1$ mF.

3.5 Final Model Overview

Here, the different system parts described in this chapter are merged together (Figure 3.9). The model is color-coded as follows:

RED On-board battery and load, i.e. the load circuit.

BLUE Diode rectifier as part of the battery charging system.

VIOLET Sensor circuit as it is intended. It is similar to a three-phase full-wave bridge rectifier without the three diodes that should be connected to high potential. The model that is described in Figure 3.5 is mainly used to increase the simulation stability. In principle, both models do the same thing.

ORANGE Resistance R_1, resistance R_2, the current source and the added capacitor, i.e. the compensation circuit.

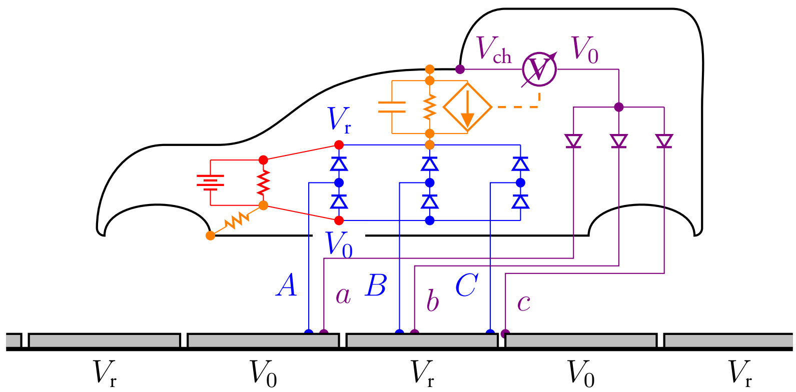


Figure 3.9: An overview of the full model.

Chapter 4

Simulation

The software used for simulation is Simulink, a graphical programming environment for modelling and simulation. Notably, the most frequently used library is Simscape, which provides means of modelling physical electric system. The simulation settings are shown in Table 4.1.

Table 4.1: Simulation settings.

MATLAB version	2015a
Type	variable-step
Solver	ode15s
Max step size	10 ms
Relative tolerance	10^{-3}
Absolute tolerance	auto

Simulations are separated into two phases. The first phase involves creating a reference model of an EV connected to externally grounded rails. This includes the possibility to introduce faults at different locations and a model of a human touching the electric chassis. In the second phase, the safety system is added. Initially, this addition introduced too much complexity to the model and the simulations would not run. Therefore, a new model was created to include only the important parts of the system. Galvanically isolated circuits on-board the vehicle was removed, resulting in a vehicle model that closely resembles the GTG-model explained in section 3.4.2.

4.1 Reference Model

The top layer of the model is shown in Figure 4.1. Starting at the rails, an ideal voltage source sets the two potentials to V_r and V_0. Two switches, located between the vehicle and the rail, resemble the pickup mounted on the vehicle underbody.

They are controlled manually but typically only used as short circuit connections. The other blocks in the figure model a grid-connected EV, a human, vehicle tyres and a voltmeter. Note that amperemeters look similar to the voltmeter but are labeled with an A instead of a V.

Continuing on to the vehicle model depicted in Figure 4.2, an ideal solid-state transformer is used as a converter to model galvanic isolation. For stability purposes, a decoupling capacitor C_{prim} and an inductor L_{sec} are placed on the converter's primary and secondary side, respectively. The secondary side is then connected to a traction battery with voltage V_{battery} and internal resistance R_{emk}. Another decoupling capacitor C_{ll} decouples the battery from the inverter. The capacitance is chosen so that the total energy stored equals that in [6]. For simulation speed purposes, the inverter and motor are modelled as a resistive load R_{load} only. This finalises the circuit that draws traction power from the grid.

Four connections between the chassis and the on-board voltage class B circuit exist. Two of them model the monitoring system as described in section 2.1.4 and the other two are faults that can be introduced manually. There are also connections from chassis to primary side of the converter that represent primary side faults. They are the main faults considered during simulations and are denoted R_1 and R_2. Finally, the human model is shown in Figure 4.3. Just like the faults, the human is controlled with a switch and can be disconnected from the chassis when desired.

For models of the rail, the pickup, the converter, the traction battery circuitry, the faults and the monitoring system, see Appendix B. For a collection of default parameter values, see Table 4.2.

Table 4.2: Default base model parameters.

V_{battery}	600	V	R_1	10	MΩ
V_{r}	600	V	R_2	10	MΩ
V_0	0	V	R_{t}	10	MΩ
C_{p}	600	nF	R_{p}	375	kΩ
C_{n}	600	nF	R_{n}	375	kΩ
C_{prim}	10	mF	R_{load}	5	Ω
C_{skin}	220	nH	R_{emk}	10	mΩ
C_{ll}	600	μF	R_{skin}	1.5	kΩ
L_{sec}	1	μH	R_{body}	500	Ω
R_{short}	1	$\mu\Omega$	R_{open}	1	GΩ

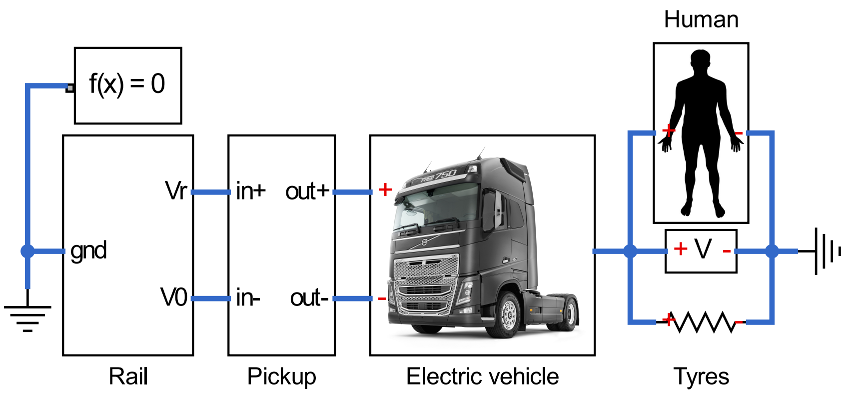


Figure 4.1: Overview of reference model.

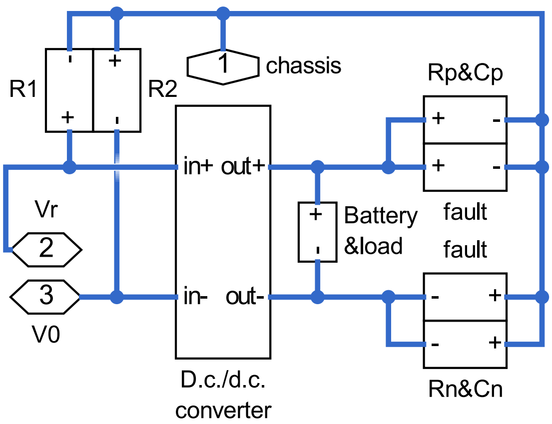


Figure 4.2: Model of an ordinary electric vehicle connected to the grid.

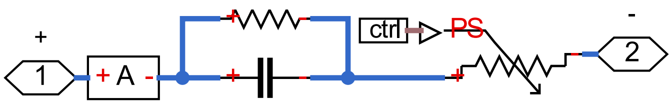


Figure 4.3: Model of a human body. The variable resistor models a switch.

4.1.1 Characteristics

Some characteristics of the model are shown below. Figure 4.4 shows the on-board fault monitoring system response for three fault levels at R_n and three capacitance values of C_p and C_n. In Figure 4.5, touch voltage and touch current are plotted as functions of R_1 and R_2. Other parameters are at default values.

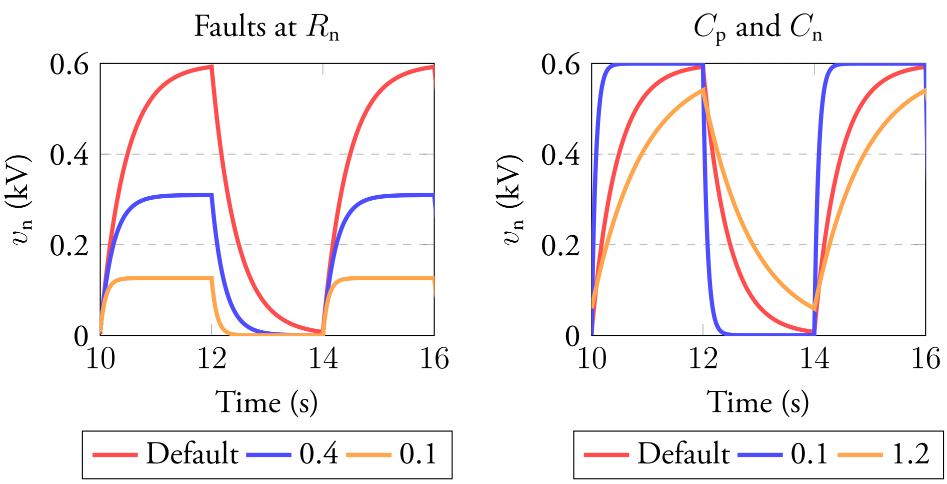


Figure 4.4: Response of an on-board monitoring system when faults and stored energies are introduced. Units in MΩ and μF.

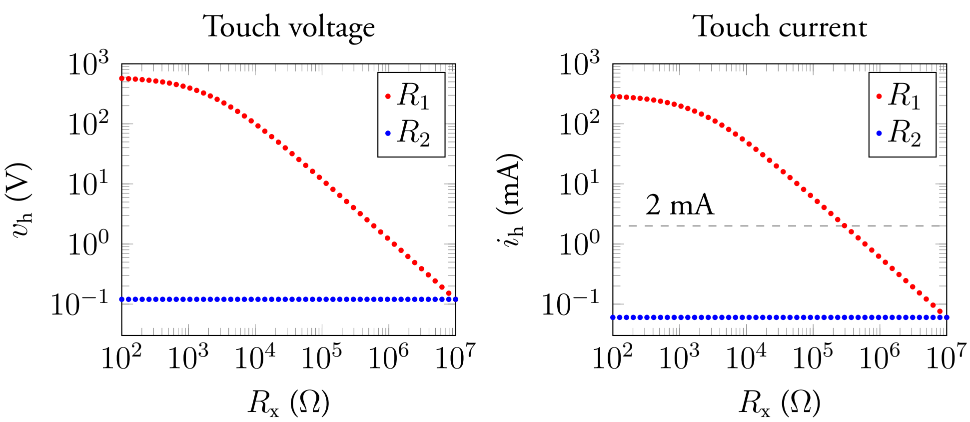


Figure 4.5: Voltage across and current through a human for different R_x. The 2 mA threshold is marked with a dashed lined. Note that a fault from chassis to V_0 (R_2) is not dangerous to a human body.

4.2 Implementation of Safety System

As previously mentioned, the model stopped working after the safety system was introduced. Therefore, most of the vehicle circuitry was removed. This includes the converter, the battery, the load and the monitoring system with corresponding faults. An overview of this new model is shown in Figure 4.6.

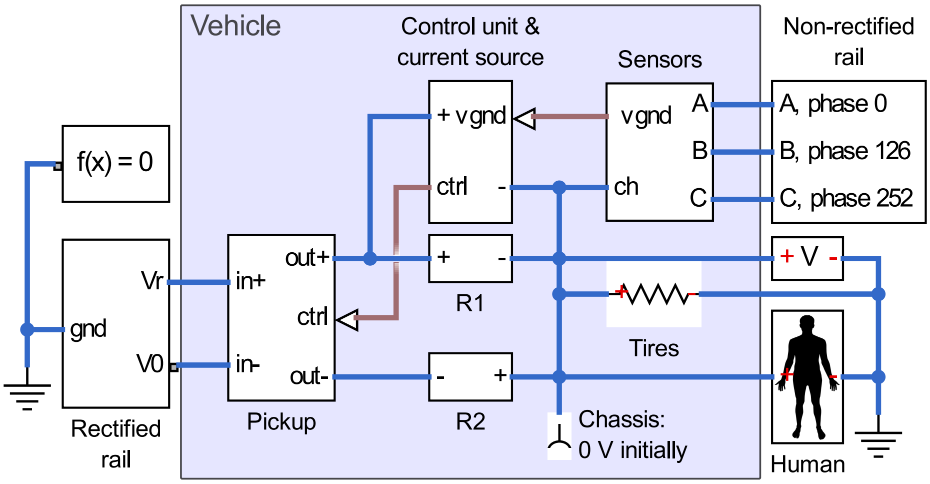


Figure 4.6: The new model.

4.2.1 Modifications

Apart from the removal of the on-board voltage class B system, the pickup is modified to better model a real situation. To simulate lost connection, random number generators are introduced to randomly open the switches 1% of the time for a period of 10 ms, see Figure 4.7. A control signal input is also introduced, mostly to illustrate the existence of a signal to disconnect the vehicle from the grid.

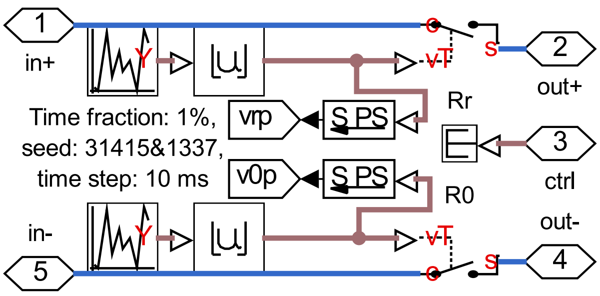


Figure 4.7: Modified pickup.

4.2.2 Add-ons

In contrast to the pickup, which is assumed to have a working rectifying system, the sensors need a different source of voltage. Therefore, another rail block is added consisting of three voltage sources controlled with pulse generators (see Figure 4.8). They work at a common frequency of 4.17 Hz and a phase shift of 0°, 126°and 252°, respectively, that sets the voltage high and low. The phase shifts correspond to the dimensions from Figure 3.2 and the frequency is calculated with

$$f = \frac{2l_\mathrm{r}}{v_\mathrm{car}}, \tag{4.1}$$

where l_r = 1 m is a rail section length and v_car = 30 m/s the vehicle velocity. Thus, the potentials are set to high every other section as they would in a physical system. Moreover, rail section gaps and soiled rail sections are introduced by means of variable resistors at each contact points. The phase and frequency controlling the gap resistances are adjusted to correctly match (4.1), whereas soil are introduced manually.

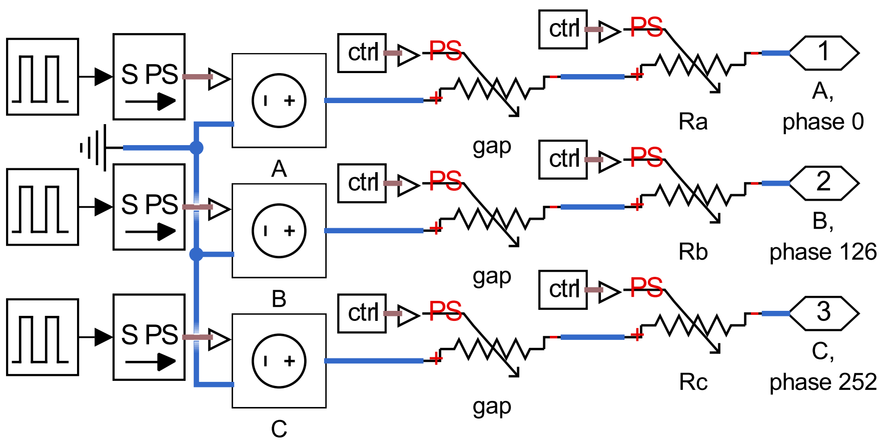


Figure 4.8: Non-rectified rail model.

The sensor model is more or less identical to the one illustrated in Figure 3.5, but there are minor differences. One is that this model has small resistances connected between gates and chassis, as seen in Figure 4.9. They are introduced to cope with convergence problems in the transient initialisation process. Moreover, voltmeters are added to measure the gate voltages across the 500 Ω-resistors to know the state of the gates, i.e. to check if the ground reference is good enough. This works very well, since the gates are modelled as voltage controlled switches with a voltage threshold of 4.99 V to detect even the slightest of voltage drops. Of course, using physical devices such as MOSFETs would have been more realistic, but they sadly invoked stability problems during simulations.

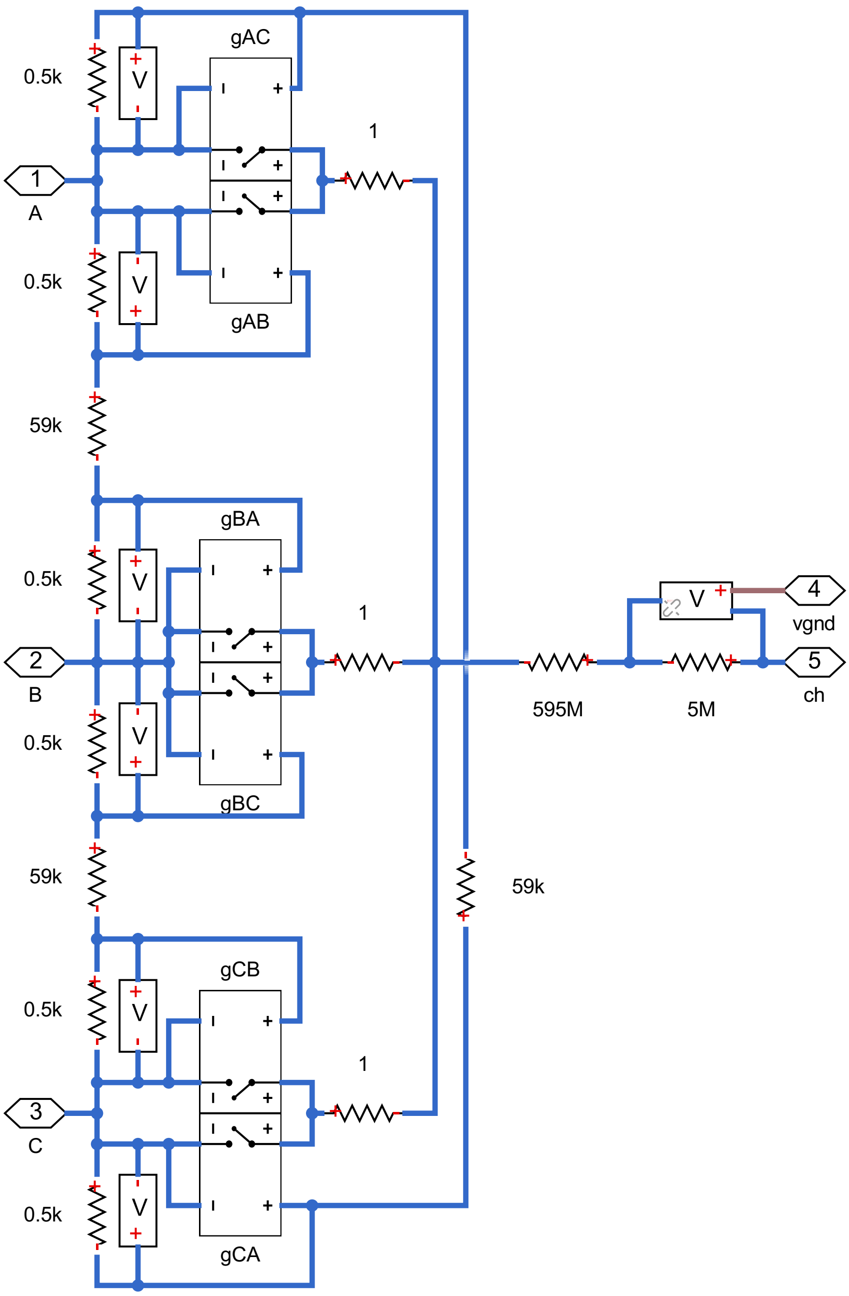


Figure 4.9: Sensor model. Small resistances were added to the right of all gates to ease simulation.

As v_{gnd} is continuously monitored, the instantaneous values are sent to the control unit block. It consists of an in-port for v_{gnd}, two out-ports for s_{ref} and the control signal, a PI-regulator and logics to detect faults. The regulator components are in the top of Figure 4.10 with parameters written next to the corresponding blocks. The workings of the blocks should be rather self-explanatory.

The fault detection logics consists of blocks below the regulator. Two switches are used to check for:

An elevated chassis potential The output from the block *vch check* is 0 below 4 V and 1 above 4 V.

A reached maximum feed current The output from the block *ifeed check* is 0 below 6.3 mA and 1 above 6.3 mA.

When either of these two outputs turns to 1, a feedback loop ensures that the ctrl signal does not change back to 0.

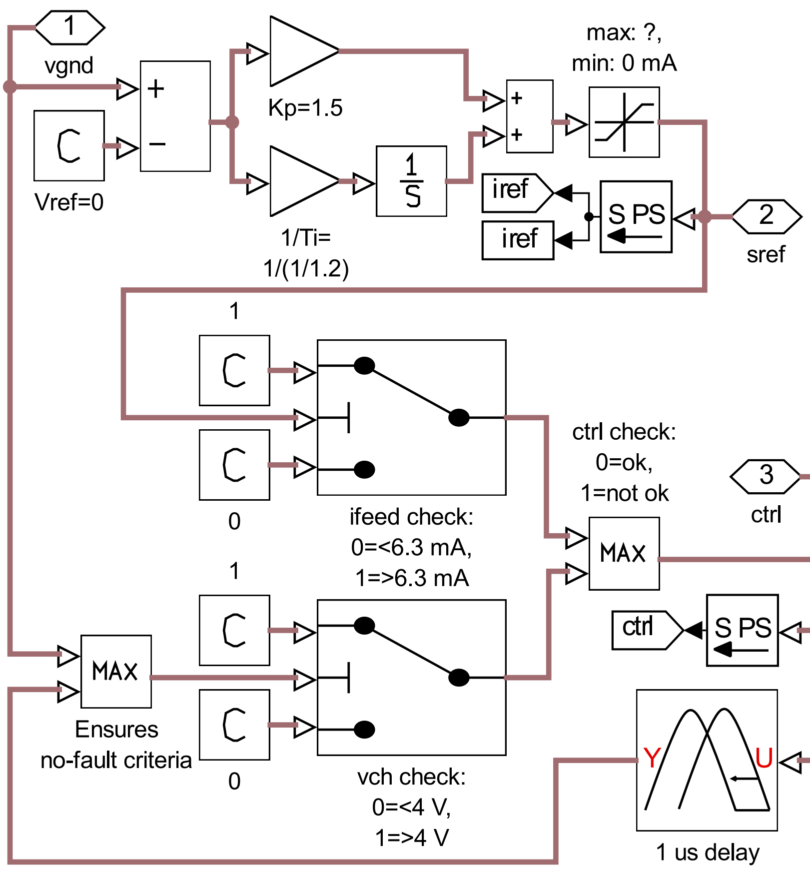


Figure 4.10: Control unit.

Lastly, s_{ref} is sent to a current source and converted to the feed current $i_{feed} = s_{ref}$. The stabilising capacitor of 1 mF is correctly connected in parallel with the source block as seen in Figure 4.11. Note that both the control unit block and the current source block are subsystems in the block "Control unit & current source", see Appendix B.

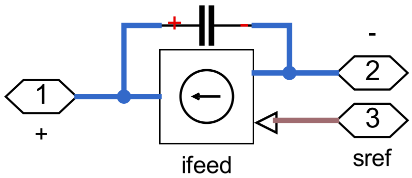


Figure 4.11: Current source.

Chapter 5

Result

Results from simulations are shown here. Throughout this chapter, all faults are located at R_1 and are introduced at 0.5 s. A reference case has been added below that shows the effect on a human body that touches an electrical chassis. The human electric characteristics are at default values.

As can be seen in Figure 5.1, touch currents for a fault-free scenario are not dangerous to a human, not even for a human soaked in water. At a fault of roughly 300 kΩ, the current becomes noticeable. Beyond 300 kΩ, currents start to become harmful.

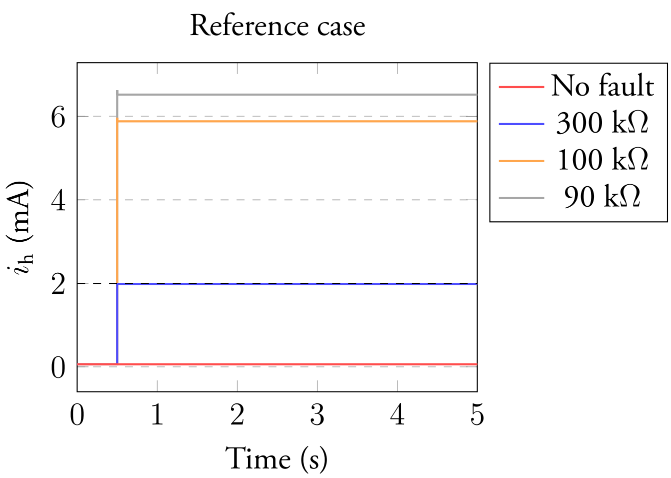


Figure 5.1: Touch currents without the safety system. Human interference is modeled from start. The d.c. threshold for tingling sensation is marked with a black dashed line.

5.1 Introducing the Safety System

After introducing the safety system, faults at R_1 are counteracted as the chassis potential is kept close to $V_{ref} = V_0$. This is shown in Figure 5.2 and corresponding feed currents in Figure 5.3. Troughs are due to lost connection to V_r during 10 μs.

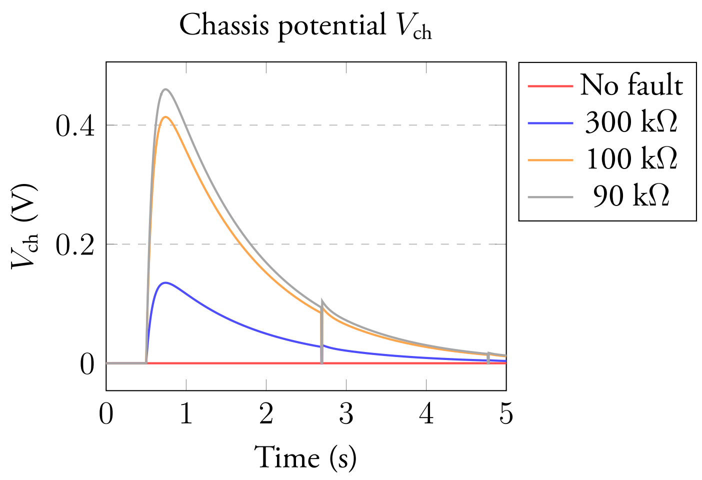


Figure 5.2: Chassis potential to ground. The safety system is active from start.

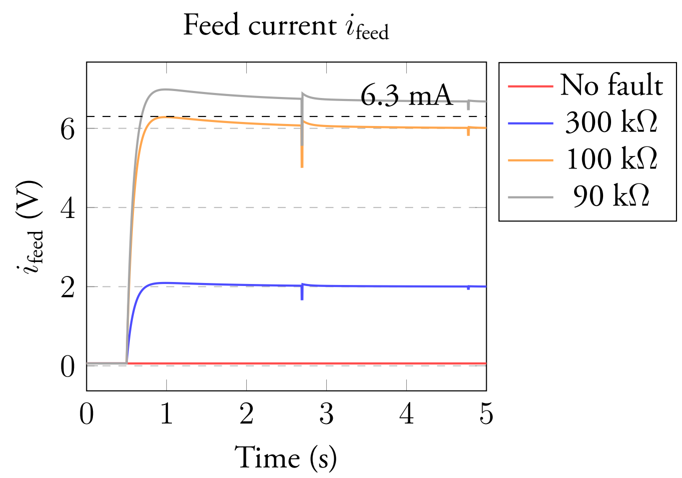


Figure 5.3: Feed current required to control v_{ch} from Figure 5.2. The dashed line indicates a chosen maximum accepted current of 6.3 mA.

5.2 Adding Human Interference

With the safety system active, a human with a critically low total body resistance (2000 Ω) is protected from electric shock. Touch currents are shown in Figure 5.4 and corresponding feed currents in Figure 5.5. As previously mentioned, troughs are due to lost connection to V_r. Additionally, note the dangerously high peak at 2.7 s.

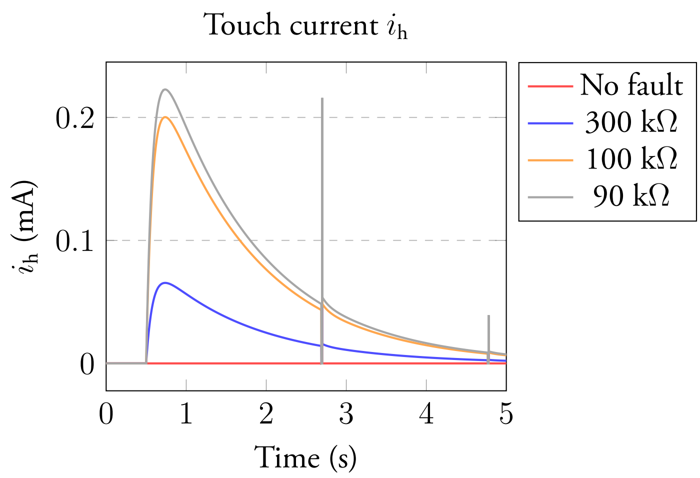


Figure 5.4: Touch currents for a human.

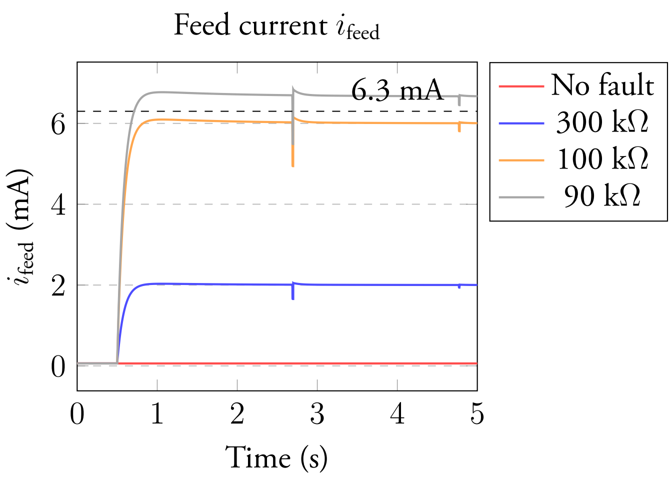


Figure 5.5: Corresponding feed currents to Figure 5.4. The dashed line indicates a chosen maximum accepted current of 6.3 mA.

5.3 Varying the Capacitance

The capacitor bank connected across the current source greatly affect the time between fault occurrence and peak potential of the chassis, as seen in Figure 5.6 with R_1 = 10 kΩ. In Figure 5.7, a very large fault of 10 Ω is instead introduced. Note that feedback and the regulation process are not adopted to the new capacitance values.

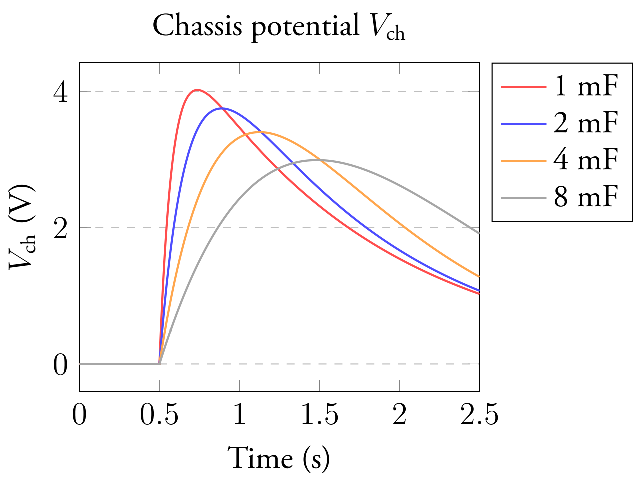


Figure 5.6: The capacitor bank's influence on the chassis potential for a fault R_1 = 10 kΩ. The maximum allowed chassis potential is 4 V.

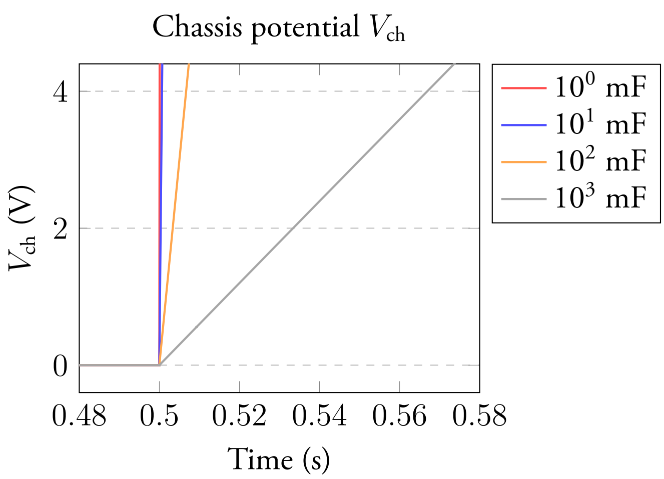


Figure 5.7: The capacitor bank's influence on the chassis potential for a fault R_1 = 10 Ω. The maximum allowed chassis potential is 4 V.

Chapter 6

Discussion

Questioning the existence of a protective earth connection is a very sensitive matter. Indeed, it constitutes a very effective way to protect personnel from electric chock. In this chapter, certain aspects and choices that may seem unjustified are explained more thoroughly.

6.1 Insulation vs. Active Components

Traditionally, non-grounded vehicles conductively connected to an earth grounded electric supply must have double or triple insulation that encapsulates high-voltage systems. An example of this is trolleybuses as explained in section 2.2.4. In principle, this approach is possible for the charging technology used in this project. If applied, however, the extra insulation would mean a significant weight increase in cars that are much smaller (and lighter) than buses. It would also add volume to cars in a way that may be unwanted. In the end, though, extra insulation may be unavoidable, but it was the purpose of this project to find a solution that minimises the use of it.

It is arguable that an active compensation of fault currents may violate insulation criteria too much. The addition of a current source in the way it was done in this project assumes relatively bad insulation of the chassis. A too high insulation resistance would require an extremely high source voltage to control the compensation current as desired. Although it may be possible to find a technical solution to this, it would be hard to convince authorities that such a system does not infringe on safety regulations.

6.2 The Compensation Capacitor

A capacitor of 1 mF was added to the compensation circuit in the final stage of the simulation. The reason behind this is twofold: it models stray capacitances and prevents the chassis potential from changing faster than the regulator can handle. Since stray capacitances are typically much smaller than 1 mF (at least in a system with a good design), most of the capacitance comes from an actual physical capacitor placed between chassis and high voltage. As it turns out, though, such a large capacitor would probably add more problems than it would solve.

The simulations does not model the transformation and rectification of the grid voltage. This means that a 300 Hz ripple with an amplitude of about 30 volts will ride on top of the grid d.c. signal. Such a substantial a.c. component would easily propagate though the added capacitor and straight to the chassis. Therefore, it is worth noting that the capacitor is not essential to the system and can be removed if necessary.

6.3 Additional Topics

Further discussion on relevant topics is shown here.

6.3.1 Absence of components

Some important components were not included in the simulation model. This includes the three-phase diode rectifier, the load and the battery. It was not the intension of this project to exclude them from the final model, but it turned out to be best that way. It should be considered when consulting the results.

6.3.2 Voltage peaks

Peaks as the ones seen in Figure 5.4 are to be expected. They are caused by a drop in compensation current following a lost connection to V_r. The current drops because the chassis potential are naturally kept close to ground when a connection to a high electric potential is not present, i.e. a compensation current is redundant in such a case. A fraction of a second later, when the connection to V_r is reestablished, there is once again a need for a compensation current. However, it is initially too small. Consequently, the chassis potential are higher than the reference and the touch current is temporarily increased.

6.3.3 Non-converging equations in Simulink

Non-converging equations was the main source of interruptions during the simulations work. This was probably due to the author's poor Simulink experience. Therefore, another software may have been a better alternative.

6.3.4 Resistivity of road slush

There is little to no information to be found on possible fault sizes. Since road slush is likely to stick to the side of the pickup during normal operation, it would be valuable to determine the resistivity of slush.

Chapter 7

Conclusions & Future Work

Conclusions and future work are presented here. Overall, the project has been successful in finding a plausible alternative to a safety ground connection, although further work is required.

7.1 Conclusions

The concept of an active grounding system show promising results. It is proven that arbitrarily large faults can successfully be suppressed. By calculating the required compensation current needed to suppress a certain fault, too large faults can be detected by means of current monitoring. Plausible fault sizes would need to be determined in order to design a model properly, through, since larger faults seem to require a faster system response.

A lost ground reference is detected directly with the sensor unit from Figure 3.5. Note that the unit also detects a lost V_r-reference as a safety risk, although it is not. This is not a problem from a safety perspective, but it would prevent battery charging more often than it should.

Since the simulations do not include all relevant components in an electric vehicle, the results do not cover all scenarios.

7.2 Future Work

Simulations are great for model evaluation, but building a physical model is eventually imperative. Thus, it would be a good next step to take. A physical model is partially complete (see Appendix C), but it requires further electrical work. This includes work on the sensor circuit, current source, capacitor bank and regulator unit.

There is little to no information to be found on fault occurrence frequency and possible fault sizes. For instance, finding the minimum plausible resistivity for road slush would be a great contribution. Furthermore, time could be spent on faults that only last for a short time. It could i.e. be slush on the pickup side that later falls of or is thawed away. Additional work could also include grounding system activation and how it should be arranged.

Evaluation of ways to add redundancy and diversity to the system is also welcome. It would certainly make the system more robust to different fault scenarios. However, adding too much complexity to a system could be problematic, so it needs to be carefully considered.

As a final remark, further evaluation of the sensor circuit is needed. Currently, it does not differentiate a lost ground reference from a lost V_r-reference. A solution could be to incorporate the pickup connectors in the sensor unit. Whenever the contact with either V_0 or V_r is completely lost, so is the possibility to charge the battery. If designed in this manner, the system would not interrupt battery charging but still provide protection.

References

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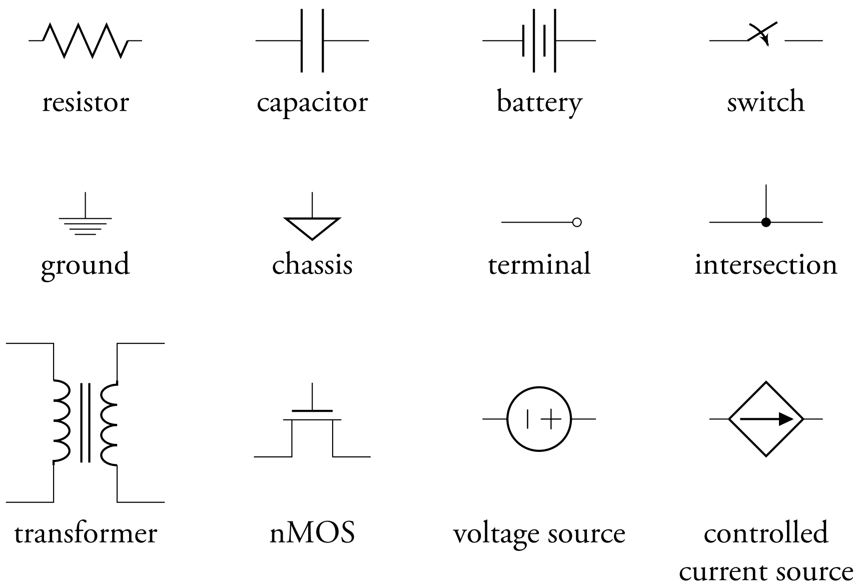
Appendix A

Symbols

Electrical symbols used in the report are shown here. Those used in Simulink blocks are intentionally not shown.

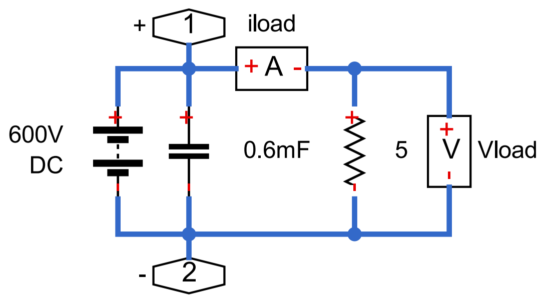


Symbols

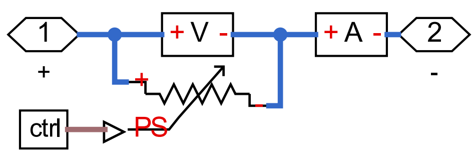
Appendix B

Simulink Blocks

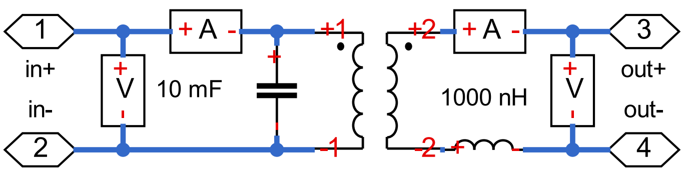
A collection of most Simulink blocks that are not shown in the report. They are added in no specific order.



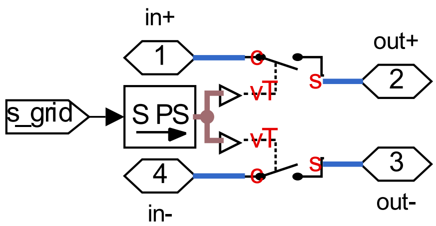
Battery & load



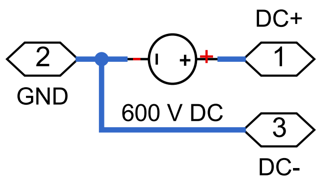
Fault



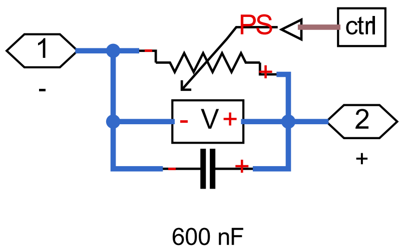
D.c./d.c. converter



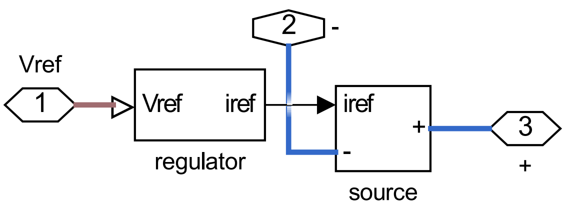
Reference model pickup



Reference model rail



On-board fault monitoring

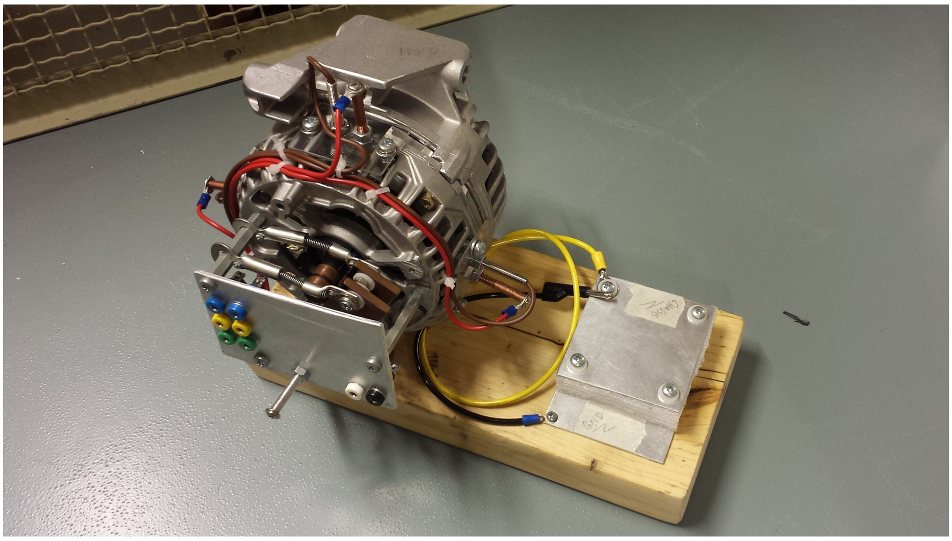


Regulator and current source

Appendix C

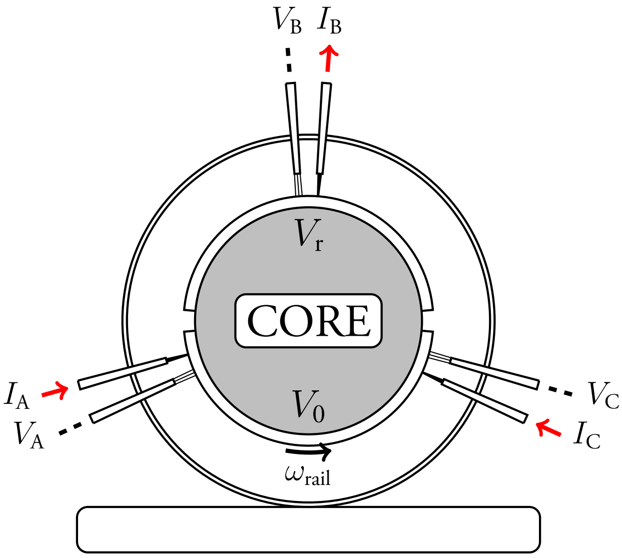
Experiment

The part of the experimental setup that was successfully built can be seen in the figure below. It models the rail, the pickup, the brushes and the electric chassis. All components are mounted on a wooden foundation to increase stability and make the model easier to move around. The piece is roughly 34 x 23 x 25 cubic cm at its maximum length, height and depth. Illustrations of the cross section and front panel are shown on the next page.



Physical model of rail, pickup, brushes and chassis

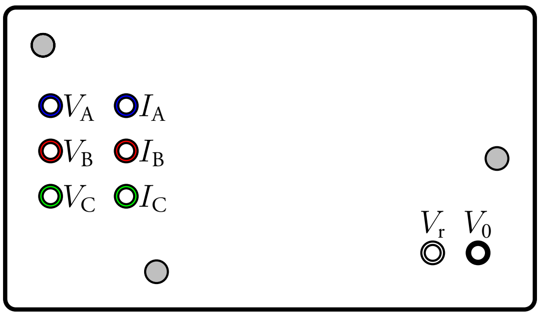
The main component constitutes a car alternator from which the stator is removed. Two aluminum plates of roughly 160 x 30 x 1 cubic mm models the rail sections. They are attached to the rotor with steel wires and separated with small pieces of insulation material. The plates are connected to slip rings that allow them to be powered while the rotor is rotating. Furthermore, three copper cylinders of about 80 mm in height and 3 mm in radius are used as the pickup connections, whereas



Cross section of the model

three similarly sized steel cylinders are used as the brushes. Two small springs are soldered to one end of each brush cylinder for an improved rail-to-brush contact. The pickup cylinders are instead prepared with only one spring attached to a small piece of copper and some conductive elastic threads for better conduction properties. The cylinders are placed in the centre of squared pieces of plastic that are mounted on the alternator metal frame to ensure isolation of the frame from the rail working voltage.

Cylinder placement is chosen so that the pickup and brushes are in contact with both rails at all times. Wiring is arranged so that all connections are available on the front panel below. Additionally, a model of the car chassis is created as a metal plate on top of both an insulator and a grounded metal plate, placed next to the alternator. To manually drive the system, an electric screwdriver is to be used.



Front panel