Control Unit for Disconnection of Traction Battery in Electric Vehicle

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Foreword

This report was made as the report part of a bachelor thesis at Chalmers University of Technology in Göteborg, Sweden. The thesis was done in cooperation with Autoliv Development AB, who supplied the idea for the project.

I would like to extend a thanks to David Sturk from Autoliv for the opportunity to work with this thesis and to my supervisor Lennart Widén for feedback and help during the work process. Another thanks should be extended to Per Gustafsson for previewing and giving feedback on the report.

Abstract

This report describes three options for the design of a triggering mechanism for a battery disconnection system in electric vehicles (EVs). The disconnection method itself is presented as well, but the focus is on how to trigger the disconnection sequence. The currently available disconnection method requires an external signal in order to activate, and the goal of this report is to present a way to trigger the activation independently from other electronics in the EV and to investigate whether this method of battery disconnection is better than the conventional means. To solve this, options that would function in theory were looked into. No actual prototypes were built and tested, but the circuits were theoretically investigated. Three viable design ideas were investigated, whereof one was found to not be practically feasible. The other two methods were concluded to at least work in theory, and both of them to be more efficient at disconnecting the battery than the conventional means of doing so. These construction designs might not be optimal, and further development could be applied to optimize them into a commercial product.

Abbreviations

EV	Electric Vehicle
PSS	Pyrotechnic safety Switch
NO	Normally Open
NC	Normally Closed
OP	Operational Amplifier
IC	Integrated Circuit

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1. Introduction

1. 1 Background

Today sustainability is an important trait to society. One example of a sustainable piece of apparatus is the electric vehicle (EV). And of course, with the use of EVs, comes the demand for safety. This does not only include air-bags and seat-belts, or other visible safety devices, but there are also systems for increased safety to be found under the hood of the car.

One thing that is implemented as a security measure is the disconnection of the EV's battery in the event of something going wrong and a high fault-current becomes present in the system. This is done through the implementation of fuses and relays to break the circuit. These have their limitations however, and their efficiency is highly dependent on the magnitude of the fault-current: Fuses melt faster at high current whereas relays needs to be physically larger in order to handle higher current.

Thus, there is room for improvement in the field of battery disconnection in EVs, and Autoliv have products available to break the connection to the battery with use of pyrotechnical components instead of the usual fuses.

1.2 Purpose

This report covers the design of a few options on how to trigger pyrotechnical switches implemented to disconnect the traction battery in the event of a fault current in an EV. These alternatives are then compared with the conventional means of disconnecting the battery regarding circuit breaking effectiveness.

1.3 Delimitations

No actual prototype of the presented designs will be built as part of this thesis project. The cost of the components have not been taken into consideration. The size of the circuits presented is also not considered. All components are considered ideal in terms of in- and output resistances, response time, conductivity, and overall desired behavior. The response time of active components is considered to be short enough to not have to be taken into consideration since it is in the timespan of nanoseconds. The triggering current for the pyrotechnical switches is considered to not have to be exactly what the datasheet suggests, as long as the relation between the current's magnitude and duration remain the same.

1.4 Scope

The construction options shall be able to trigger the switches without any external control signals from already present electronics in the EV. The circuits should be independent of other electronics in the EV. The triggering mechanisms should strive to enable the pyrotechnical disconnection method to be faster than the conventional method. The mechanism should trigger the disconnection at a fault current of 500 A.

2 Technical Background and Components

2.1 Technical Background

In this chapter, the technical background for the report is presented to offer a better insight of the intended function of the disconnection mechanism.

2.1.1 Handling a short circuit in an EV today.

Today, the way to handle an extreme fault-current in an EV due to a short-circuit is to combine fuses and relays. A fuse is placed in series with a relay along with the EV's battery to disconnect the battery when needed. The combination of the two disconnection devices is done due to their different intervals of function. Whereas the fuse explodes quickly when the current is extremely high above the current rating, the relay is used for daily usage to activate and deactivate the circuit, and has the advantage of not having to be exchanged every time it is used [2].

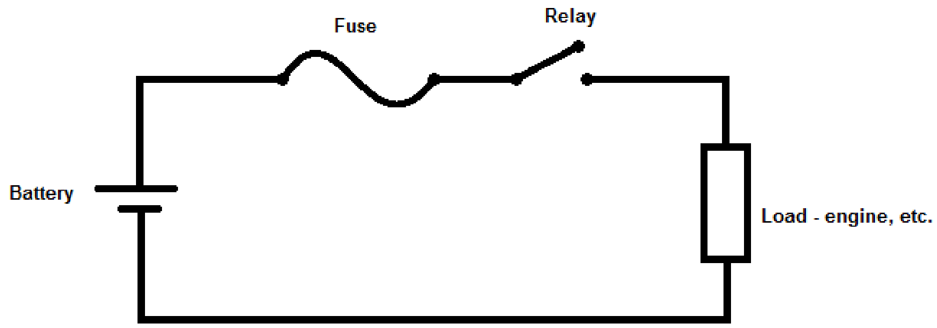

Figure 1, model of an EV system.

2.1.2 Electric arcs, AC and DC.

A key element of the hardships of breaking a circuit is the risk of producing an electric arc between the ends that are separated. An electric arc is when the current flowing through two previously connecting ends is strong enough to sustain a connection even when the ends are separated. The gap of air between the electrodes becomes ionized and conductive, resulting in a bright arc of lightning as the current flows through the gap [3].

Arcs are less of a problem when disconnecting alternating currents. At least if the load is not largely inductive. A typical alternating current will periodically be zero, and thus an arc will never last longer than one cycle of alternation. That is, if an arc is formed at all. If the disconnection takes place when the current happens to be zero, no arc can be formed. Breaking a circuit when the current is zero can be exploited to perform safe disconnections.

However, a direct current is not as simple to cut as an alternating one, since it usually does not pass zero naturally. This is the case when the risk for an arc has to be considered. A direct current through an inductor is at particular risk to form an arc, as the inductor will continue to drive the current even if its power supply is cut off due to its inherent trait of being slow to adapt changes in current.

2.1.3 Breaking a direct current.

One way to disconnect a high voltage circuit and avoid a lasting lightning arc is to allow the current to take a different route than through the switch where the arc would have been formed. Another way is to make the current drop to zero before disconnection.

For example: in accordance with a patent from 1967, an arc can be avoided by using a setup with two switches and a high-impedance exploding wire. The two switches are in series with each other, and the exploding wire is connected in parallel to the second of the switches. The two switches carry the load current. The idea is that upon activation the first switch opens partly and a small arc forms between its electrodes. Then, the second switch disconnects. Upon the second switch's disconnection, the impedance in that wire can be considered to be greatly increased, and the current is forced to travel through the exploding wire instead since it is a relatively good conductor compared to the gap of air in the switch. The wire becomes heated from this. This allows the second switch to be moved far enough to not ignite an arc. Subsequently, the wire melts and instead becomes a good insulator, forcing the current to become virtually zero. Now, the first switch can safely disconnect without igniting any lasting arcs [4].

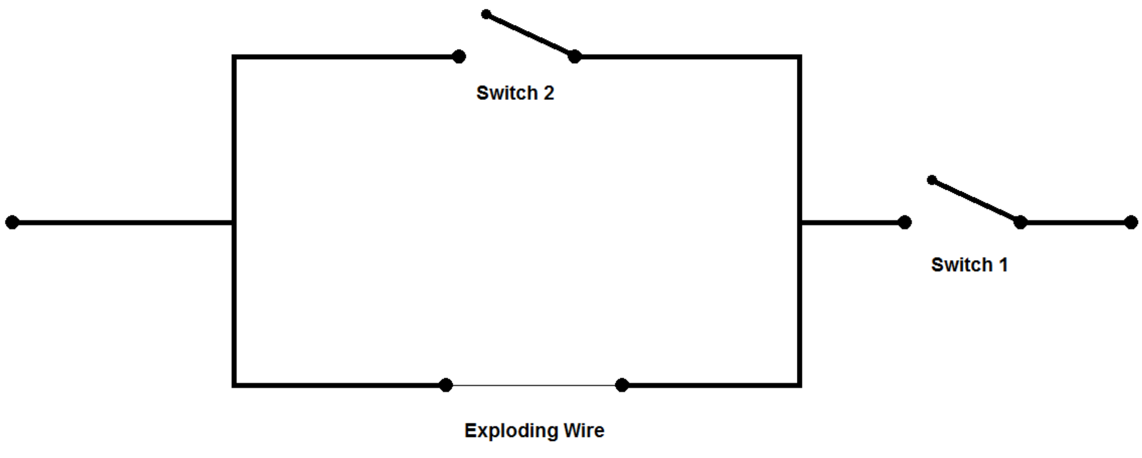

Figure 2. Schematic of a direct current disconnection method.

This method does however require the ignition of smaller arcs, and the switches' electrodes are likely to sustain some surface deformation due to the heat [3]. But, it is an example of how to break a direct current by utilizing a combination of an alternate route and a current brought to zero.

2.1.4 Explanation of Autoliv’s battery disconnection with PSSs (Pyrotechnical Safety Switches).

Autoliv’s idea of how to disconnect the traction battery from the rest of an EV whenever an accident or other mishap has caused a high fault current, is to use a combination of a PSS/NO and a PSS/NC. This combination will enable a disconnection of the battery pack without any arc appearing where the disconnection is executed [11].

The system of an EV can be modelled with a voltage source - in this case a battery connected in series with an inductive load. This circuit is supplemented with a PSS/NC that the load current will pass through at normal operation, and a bypass circuit with a PSS/NO that will be essential for the prevention of the creation of an arc.

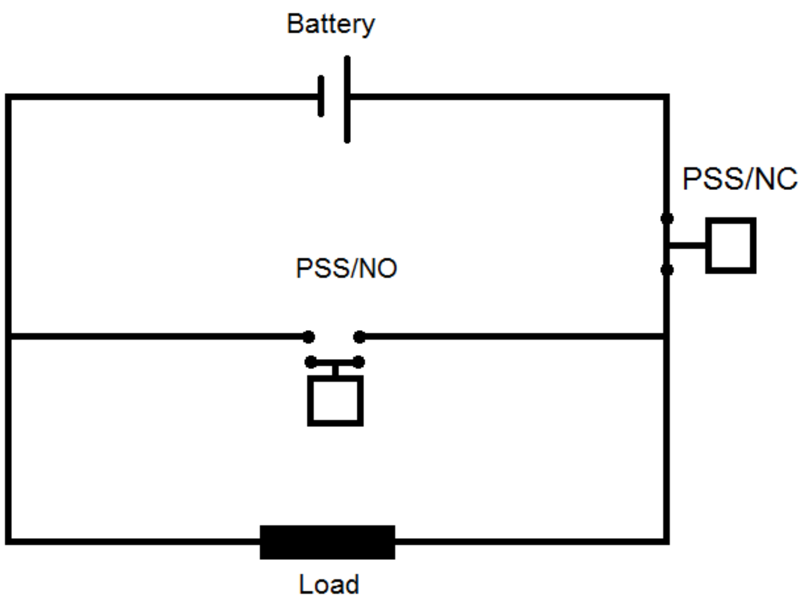

Figure 3. Model of the system at normal operation.

When a high fault current is detected, the PSS/NO first connects the bypass circuit. This provides the current an alternative route to take. A brief period of time later (0,5 ms), the PSS/NC cuts the battery pack away from the rest of the system.

The disconnection process can be viewed as a series of consecutive circuits. The following figures illustrate the same circuit in different moments in time. One case when the system is unchanged, with the exception that it suffers from a high fault current. One case when the PSS/NO has connected the bypass circuit and provided an alternative route around the battery. In the final case, the PSS/NC has disconnected the battery pack from the rest of the circuit. This last case can in turn be viewed as two different steps of disconnection, where the first means that the conducting wire is almost cut, and the second means that it is cut entirely.

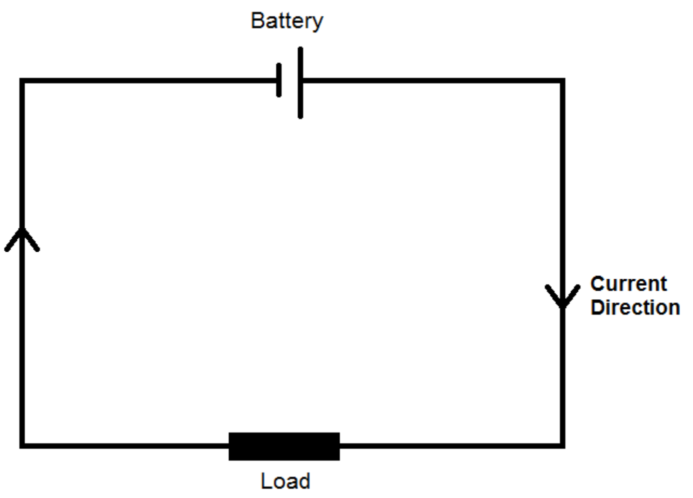

Figure 3.1. The system in an unchanged state.

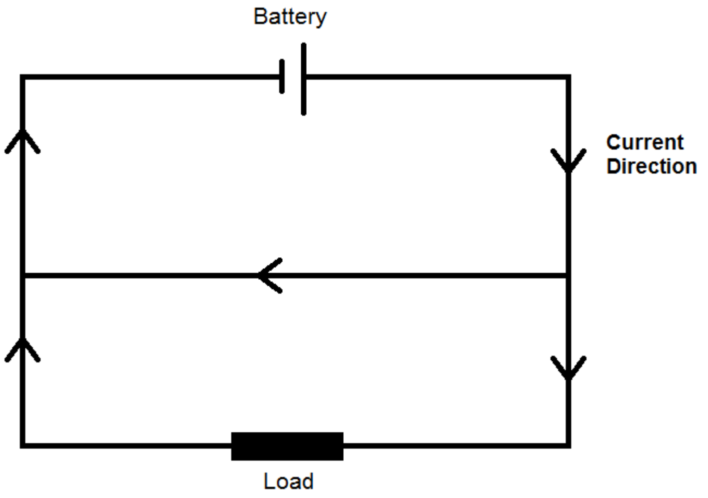

Figure 3.2. The PSS/NO has connected the bypass circuit. A small amount of current passes through it.

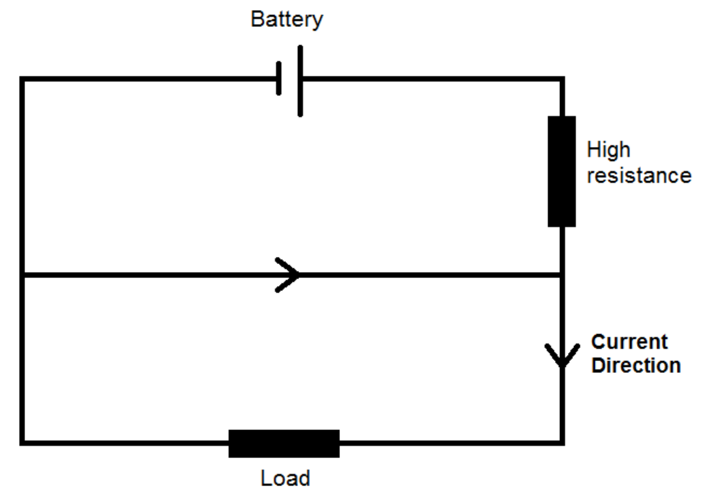

Figure 3.3. The PSS/NC has almost cut through its conductor. The current through the battery is temporarily zero.

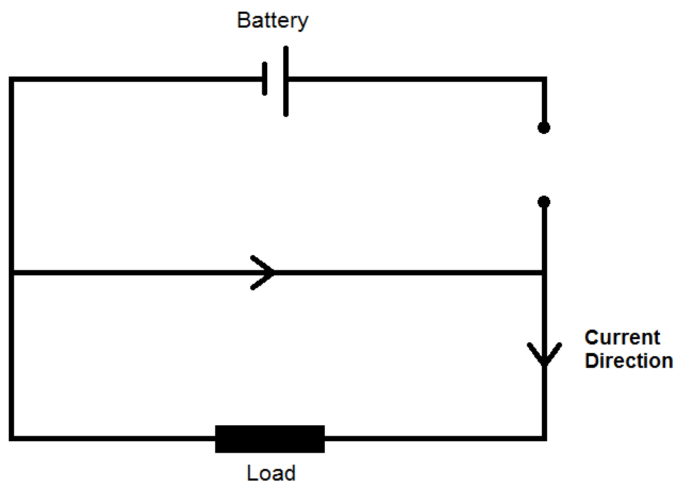

Figure 3.4. The battery pack is entirely disconnected. The remaining current is what has been built up in the load due to its inductance.

In figure 3.2, the battery pack has been short-circuited, and a current begins to flow through the bypass circuit since current prefers to travel through the least resistive route. After a short period of time - a few parts of a millisecond, the PSS/NC begins its disconnection. In figure 3.3, the disconnection is considered almost finished, and the conductor is as good as cut. This can be viewed as the PSS/NC representing a close to infinite resistance for a short moment.

The energy-charged inductive load continues to impel a current that would have caused an arc to form in the PSS/NC, but since the much less resistive bypass circuit provides an alternative route, the current choses to flow through this wire instead. All current now flows through the bypass circuit, and the battery current becomes momentarily zero. The PSS/NC is thus allowed to fully disconnect to figure 3.4 without any lasting arc appearing. This is not entirely unlike the patent with the exploding wire that was presented earlier.

2.1.5 Fault current appearance

The appearance of a fault current used in this report is taken from an experiment of a simulation of a short-circuited EV battery, performed by Autoliv.

A battery pack was connected in series with a contactor that regulated the opening and closing of the circuit along with an inductive load to represent the EV system.

From the measurements made, the current was found to rise somewhat linearly with a rate of approximately 1400 A/ms.

2.2 Components

In this chapter, all non-intuitive components used in the design of the triggering mechanism and the comparison thereof are presented.

2.2.1 PSS, Pyrotechnical Safety Switch.

The so called Pyrotechnical Safety Switch, or PSS, is a device that utilizes a small pyrotechnical charge in order to either couple or decouple a conductive wire. A control signal with a high enough current causes the PSS's pyrotechnical charge to explode. The explosion then propels a non-conductive guillotine head through the PSS's conductor, thus breaking the circuit (this is referred to as a PSS/NC - Pyrotechnical Safety Switch Normally Closed). In a similar manner, the explosion can be used to thrust a conductive beam between two open ends in the PSS to instead create a connection (this is referred to as a PSS/NO - Pyrotechnical Safety Switch Normally Open) [1].

A PSS has an initiator resistance of between 1,7 and 2,5 ohm. That is, the resistance the PSS will have in the circuit that will handle its triggering. The magnitude of current required to fire a PSS is 1,75 A over 0,5 ms. These values are the same for both the normally open and the normally closed PSS [18].

2.2.2 Fuse

A fuse is a short length of wire that is used at part of a circuit to break the circuit if a too large current occurs. This wire is made out of a material that is supposed to melt and disappear when a too high current flows through it. When it melts, it no longer conducts, and thus the circuit is disconnected. Due to the fuses functioning on their own without any external control signals, they are reliable as long as the voltage over the fuse is not large enough to create an arc even after the fuse has blown, or the overcurrent too low to quickly melt the fuse. The higher the current is above the fuse's break-current, the faster it melts. However, if the currents is a lot higher than that, an arc might appear. Fuses have to be replaced once they have been blown. They are one-time use components [16].

2.2.3 Relay

A relay is a component that can either open or close a circuit. The relay is a switch - a conductive beam that connects two ends. This metal beam is suspended with a spring to be pressed against the two points in order to connect them. Close to this beam is a coil through which the relay's control signal passes when the relay's state is to be changed. When the current passes through the coil, it induces a magnetic field that pulls on the beam, making it disconnect from either one or both of the ends, and thus the circuit is broken [17].

As opposed to the fuse, relays can be used several times. They are however not passive components, and they need a control signal to tell them when to act. Relays are superior to the fuse when it comes to breaking the circuit when the fault-current is not extremely high. However, with high fault-currents, arcs are more likely to occur as the relay disconnects [2].

2.2.4 The Rogowski coil and measuring transient currents

A Rogowski coil is a construction used to measure alternating currents without interfering with the conductor through which the measured current flows. This is accomplished by encircling the conductor with a toroid coil with an air core. The magnetic field created by the current through the conductor will induce a voltage in the coil in accordance with Ampere's law. This voltage can then be used further to be measured without having to physically connect the measuring device with the conductor that is being measured.

The amount of voltage induced in the coil can be calculated by:

$$v = -\mu_0 nA \frac{di}{dt} \tag{2-1}$$

Where μ_0 is the permeability of air, *n* is the amount of windings of the coil per length unit, *A* is the cross-section area of the windings, and *di/dt* is the rate of change in the current through the conductor that the coil encircles. Thus, an equivalent result can be achieved from the equation (2-2):

$$v = -\frac{\mu_0 nA}{2\pi r}\frac{di}{dt} \tag{2-2}$$

where *n* instead is the total number of windings, and *r* is the major radius of the coil while the other parameters are the same as in the previous equation (2-2) [5].

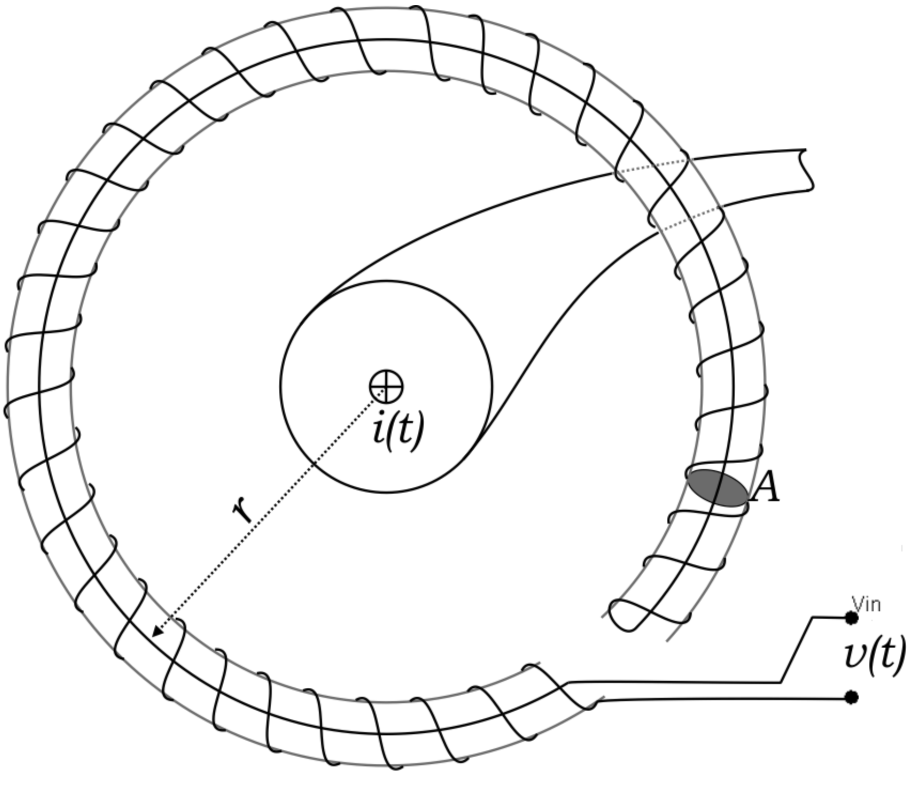

Figure 4. Schematic of a Rogowski coil [19].

Since the voltage output is dependent on the change of the measured current, a direct current will not give any output, while a quick change in the current will give a higher output. This makes the Rogowski coil suitable for measuring transient events in a circuit that normally conducts a direct current but for some reason makes a hasty change - such as the fault current in an EV.

Why an iron core current transformer was not used

An iron core that is under constant influence of a magnetic field eventually saturates. That is - all the atoms in the iron core align in the same direction relatively to the field. This can lead to undesirable behavior when it comes to recognizing the fault current, as the iron's permeability is not linear [13]. Since the iron core in the purpose here will be surrounding a wire through which a direct current constantly flows during normal operation, the iron will surely saturate. Differently from an iron core current transformer and other ferromagnetic cored devices, a Rogowski coil is linear and will never saturate [12]. A core of iron also weighs significantly more than a core of air.

2.2.5 Transistor

A transistor is usually a component with three contact pins: emitter, base and collector, that either conducts or does not conduct, depending on a regulation signal. This can be used as a switch that controls the flow of a higher current through the use of a much smaller current. The regulation current is called the Base Current (I_B), and the current being regulated is referred to as the Collector Current (I_C). The Collector Current is decided through a trivial relation to the Base Current, and an amplification constant (h_{FE}) that varies between different transistors.

$$I_C = I_B \cdot h_{FE} \tag{2-3}$$

Additionally, the Collector current can never be higher than the resistance and voltage over the collector end allows, according to:

$$I_{C\,MAX} = \frac{E}{R_C} \tag{2-4}$$

where $I_{C\,MAX}$ is the maximum achievable current, E is the voltage over the transistor and any load connected to the Collector end, and R_C is the impedance of any load on the Collector end [6].

2.2.6 Comparator and the Schmitt trigger

A comparator is an implementation of an operational amplifier (OP) that is used to compare two different voltages. The OP will saturate in either high or low output voltage, and thus indicate which of the input voltages is higher. This can be used to indicate when an input voltage reaches a certain magnitude. The construction is trivial - the input voltage is connected to one side of the OP, and a reference voltage is connected to the other side. If the (+) side voltage is higher than the (-) side voltage, the OP will output its higher supply voltage. Analogously, the OP will output its lower supply voltage if the (-) side voltage is higher than that of the (+) side.

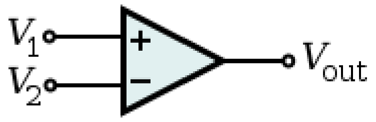

Figure 5. Figure of a comparator [9].

Figure 5 shows a comparator with input voltages V_1 and V_2, where the output v_{out} will be the comparator's respective supply voltage when either input voltage is higher than the other.

The comparator is however sensitive to fluctuations in the compared voltages. If they are almost the same, small variations can make the output vary unfavorably. A way to prevent this is to use a so-called Schmitt trigger implementation of the operational amplifier. This is done by connecting the OP's output back to the reference input via a resistor, and yet another resistor from the reference input to the reference voltage. This will create two threshold voltages where the output will change, instead of just one. The (-) side voltage must overcome a certain voltage for the OP to output its low supply voltage, and sink below another, lower, voltage for the OP to output its high supply voltage. This way, fluctuations in the voltage will not be as prone to create a change in the OP's output.

However, due to how it is coupled, the output will be high when the input reaches the lower threshold, and low when the input reaches the higher threshold; it is inverted.

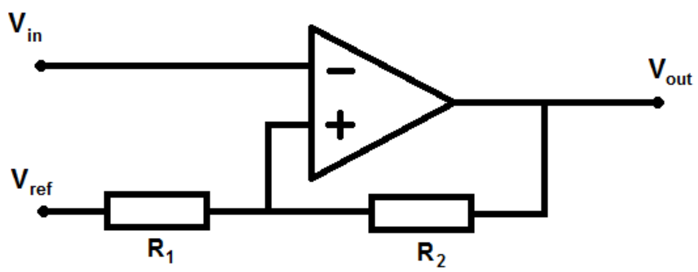

Figure 6, a schematic of a Schmitt trigger, with the input V_{in}, and the output V_{out}, the resistors R_1 and R_2 decide the threshold voltages together with the reference voltage V_{ref}.

The threshold voltages are calculated with the following equations:

$$V_{Tmid} = V_{ref} \frac{R_2}{R_1+R_2} \tag{2-5}$$

$$V_{Twidth} = 2E \frac{R_1}{R_1+R_2} \tag{2-6}$$

$$V_{T\pm} = V_{Tmid} \pm \frac{V_{Twidth}}{2} \tag{2-7}$$

Equation (2-5) gives the middle of the threshold voltages of the Schmitt trigger.
Equation (2-6) gives the width between the threshold voltages. *E* is the supply voltage.
Equation (2-7) gives the separate threshold voltages.

Through varying the values of the resistors and the reference voltage, preferable threshold values of the Schmitt trigger can be achieved [7].

2.2.7 Integrator

An integrator is a circuit that outputs the negative integral of the input voltage. It is constructed by an operational amplifier with a capacitor reconnecting the output to the OP's (-) input, and a resistor between the (-) input and the input voltage.

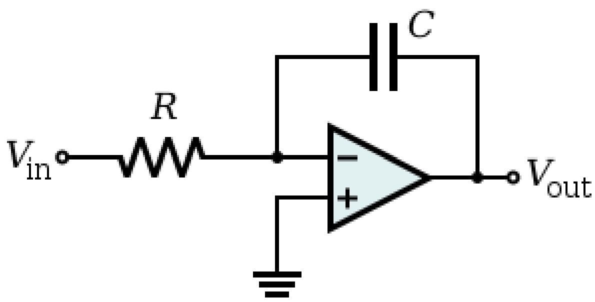

Figure 7. An integrator circuit, where V_{in} is the integrator's input voltage, R is the integrator's resistor, C is the capacitor, V_{out} is the integrator's output voltage [10].

The integrator's output is dependent on the value of the resistor and the capacitor, and of the magnitude of the input voltage according to the following equation:

$$\frac{V_{in}}{R} = -C \frac{dV_{out}}{dt} \tag{2-8}$$

In equation (2-8), dV_{out}/dt is the rate of change of the integrator's output.

The values of the resistor and the capacitor can thus be defined to gain a desired change in output. And if the time during which the input voltage has a certain value is known, the parameters can be chosen so that a certain output voltage is reached at the end of this span of time [8].

3. Design

In this part of the paper, a suggestion of a design of a potential triggering mechanism for the PSS-combination is presented. Three different methods were thought of for the triggering mechanism, with varying complexity and reliability. They all have to meet the demands of the PSS triggering requirement, and have to be reasonably implemented.

The triggering requirement for a PSS is 1,75 A of current over 0,5 ms, but due to the appearance of the fault current and a desired limit for the fault current's magnitude before being cut, the time for during which a current will be sent through the PSS will not be much more than 0,3 ms. It is assumed that the PSS will still fire if the triggering current is high enough to still deliver the same amount of energy to the PSS. Due to this shorter period of time, a current of approximately 3 A will be strived for.

The size of the detecting coil will be such that it can encircle the wire through which the fault-current will travel. Assuming a circular wire with insulation of a total area of 2 cm^2, the inner radius of the detecting coil must thus be roughly 8 mm.

3.1 Using a Rogowski Coil

This alternative to trigger the PSS requires nothing but a coil, thus making it the least complex solution for the problem. No external power supply is required, and the design would be entirely passive.

The solution may be successfully achieved by determining the necessary parameters of the coil and by selecting a target voltage to reach using the variable parameters. The target voltage being a voltage that – given the whole coupling's resistance, yields a current high enough to trigger the PSS. In this construction, the minor and major radius of the coil were predefined due to size of the cables used in EVs, leaving the number of windings to be the variable available to reach the desired voltage. The number of windings, together with the minor radius of the coil makes out the length of the wire. The length, in combination with the thickness of the wire and the material of the wire (copper) defines the wire's resistance. The current is equal to the voltage divided by the resistance. By combing this, the equation (3-11) for the desired current depending on the number of windings could be determined.

$$v = -\frac{\mu_0 nA}{2\pi r}\frac{di}{dt} = R \cdot I \qquad (3\text{-}1)$$

eq. 3-1 yields:

$$I = -\frac{\mu_0 nA}{2\pi rR}\frac{di}{dt} \qquad (3\text{-}2)$$

The resistance *R* of the coil's wire can be determined by

$$R = \frac{\rho l}{a} \tag{3-3}$$

where ρ is the resistivity of the wire's material, in this case copper, *l* is the length of the wire, and *A* is the cross sectional area of the wire.

Assuming that the maximum number of windings that can possibly fit on the coil without overlapping is used, the diameter of the wire and length of the wire can be determined by the number of windings. Subsequently, the resistance of the wire can be deduced. The inner radius of the coil determines the maximum possible diameter of the wire:

$$D = \frac{O}{n} \tag{3-4}$$

where *O* is the inner circumference of the coil, and *D* is the diameter of the wire. *O* would thus be depending on the coil's major radius *r* minus the minor radius r_m. The area of the wire is directly proportional to the diameter.

The length of the wire is determined by the number of windings, and the cross-sectional area of the coil. For each winding, the length is as long as the minor circumference of the coil.

$$R = \frac{\rho l}{a} = \frac{\rho 2\pi\sqrt{\frac{A}{\pi}}n}{\frac{D^2}{2^2}\pi} = \frac{\rho 8\sqrt{\frac{A}{\pi}}n}{\frac{O^2}{n^2}} = \frac{\rho 8\sqrt{\frac{A}{\pi}}n^3}{(2\pi(r-r_m))^2} = \frac{\rho 8\sqrt{\frac{A}{\pi}}n^3}{(2\pi(r-\sqrt{\frac{A}{\pi}}))^2} \tag{3-5}$$

Equation (3-5) shows the resistance of the wire in a Rogowski coil, depending on the number of windings *n*, the area of the windings *A*, and the major radius of the coil *r*.

$$l = 2\pi r_m n \tag{3-6}$$

Equation (3-6) describes the length of the coil's wire *l*, depending on the number of windings *n* and the coil's minor radius r_m.

$$a = (\frac{D}{2})^2\pi \tag{3-7}$$

Equation (3-7) yields the wire's cross-sectional area a depending on its diameter *D*.

$$D = \frac{O}{n} = \frac{2\pi(r-r_m)}{n} \tag{3-8}$$

Equation (3-8) yields the wire's diameter *D*, depending on the number of windings *n* and the major *r* and minor r_m radius of the coil.

$$r_m = \sqrt{\frac{A}{\pi}} \tag{3-9}$$

Equation (3-9) determines the coil's minor radius r_m, depending on the cross-sectional area *A* of the windings.

Equation (3-5) determines the coil's resistance. If the cross-sectional area of the windings is fixed, as well as the major radius of the coil, then the resistance can be variable depending on the number of total windings. Using equation (3-5) together with the equation (3-2) for the current given from the Rogowski coil at a certain resistance, the desired current can determine the number of windings required to achieve the goal. This is, as previously stated, the case where the windings do not overlap and are calculated to be as many as can possibly be fit on the coil.

Given that all parameters are set except for the number of windings, Equation (3-5) can be simplified into

$$R = kn^3 \tag{3-10}$$

where k is a constant value given by ρ, r, and A. That is - all values that are not defined to be variable. The current given by the Rogowski coil can thus be given by the following equation.

$$I = -\frac{\mu_0 A}{2\pi r k n^2}\frac{di}{dt} \tag{3-11}$$

A and r has to be the same as when determining k.

From here, it is possible to decide the number of windings for the coil given a desired magnitude of current. Calculations are presented in Appendix 1.

However, this method has its limitations due to that the diameter of the wire makes the coil's inner radius smaller, and thus it would eventually not be able to encircle the wire in the EV through which the fault current flows. This equation (3-11) is also only taking into consideration the resistance of the coil itself, and not the combined total of resistances that would also include any wiring from the coil to the PSS, and the PSS's own resistance.

Should this be taken into consideration, with the estimation that the PSS's resistance of roughly 2 ohm is the most relevant value to consider, the equation would look slightly different, and thus result in an unrealistic number of windings.

$$I = -\frac{\mu_0 n A}{2\pi r R + 2}\frac{di}{dt} \tag{3-12}$$

This is based on the assumption that the cross-sectional area of the coil is kept the same, and the inner radius as well. Even with the approximation that the coil's resistance would remain the same, that is - the increased length of wire is not considered when the area is increased, it would demand a significantly larger area to get close to the desired current. Such a coil would simply not be possible to use. Appendix 1 provides a calculation where the area becomes 60 cm^2 for an otherwise reasonably dimensioned coil. The Rogowski coil equation (2-1) is also assuming that the area of the windings is relatively small compared to the size of the whole coil.

Deductively - using only the coil could theoretically create a current that is large enough to trigger the PSS, but only in the coil itself and if it is without any further resistance. Something else has to be added to the construction in order to make it work.

3.2 Rogowski Coil, Comparator, and Transistor

Since the coil itself could not produce a current of enough magnitude to trigger a PSS, the current has to come from elsewhere. A way to accomplish this is to let the coil toggle a transistor through which a much higher current can be produced. To help with the overall stability and precision of the implementation, the coil is connected to a comparator that in turn decides if the transistor should conduct or not. Calculations on appropriate values can be found in Appendix 2.

This solution is a bit more complex than the first alternative, but it has the significant upside that it could actually be realistically implemented. The coil can be conveniently proportioned to a manageable size since other components can be adjusted to suit the coil.

$$V_C = -\frac{\mu_0 n A}{2\pi r}\frac{di}{dt} \qquad (3\text{-}13)$$

Equation (3-13) gives the expected voltage V_C from a Rogowski coil.

Due to the fact that the coil itself does not have to produce the required current, the resistance of the coil is fairly irrelevant as long as it is high enough to not let the current damage the comparator. This is managed by adding a resistor to the comparator's input if it would be necessary.

Given the expected output of the coil in the event of a fault current, the reference voltage of the comparator is set to this value to be the threshold for triggering the PSS. This is realized by the use of two differently sized resistors connected to an external voltage source, with the reference voltage being taken from between the two. The value of one of the resistors is defined by choice, and the other one is selected appropriately from the following equation, using the value *E* as the voltage source:

$$V_{ref} = E\frac{R_2}{R_2+R_1} \qquad (3\text{-}14)$$

In equation (3-14), the V_{ref} is the reference voltage that the coil has to overcome for the PSS to fire, *E* is the supply voltage that is divided to obtain the desired threshold voltage, R_1 and R_2 are the two resistors.

Since the desired reference voltage and the supply voltage are known, and one resistance value is chosen freely, it is a trivial task to calculate an appropriate value of the second resistor.

$$R_1 = \frac{ER_2 - R_2 V_{ref}}{V_{ref}} \qquad (3\text{-}15)$$

Equation (3-15) shows how to determine R_1 if R_2 is known.

On the comparator's output, a diode is connected in series with a resistance. This shall prevent a current to flow through the transistor's base when it is not supposed to. The resistor R_3 is chosen so that the current flowing to the transistor's base gives the desired collector current. This of course depends on what current amplification constant h_{FE} the used transistor has. There is also a voltage drop over the diode V_D and the transistor V_t.

$$I_C = h_{FE} I_B \qquad (3\text{-}16)$$

$$I_B = \frac{E - V_D - V_t}{R_3} \qquad (3\text{-}17)$$

$$R_3 = \frac{E - V_D - V_t}{I_B} \qquad (3\text{-}18)$$

Equation (3-18) describes how to determine the appropriate resistance after the comparator in order to achieve the desired current.

The supply voltages to the operational amplifier and the triggering current could be taken from either the EV's 12 V battery, or from an additionally added battery that only supplies the triggering circuit.

The complete circuit would thus be as follows:

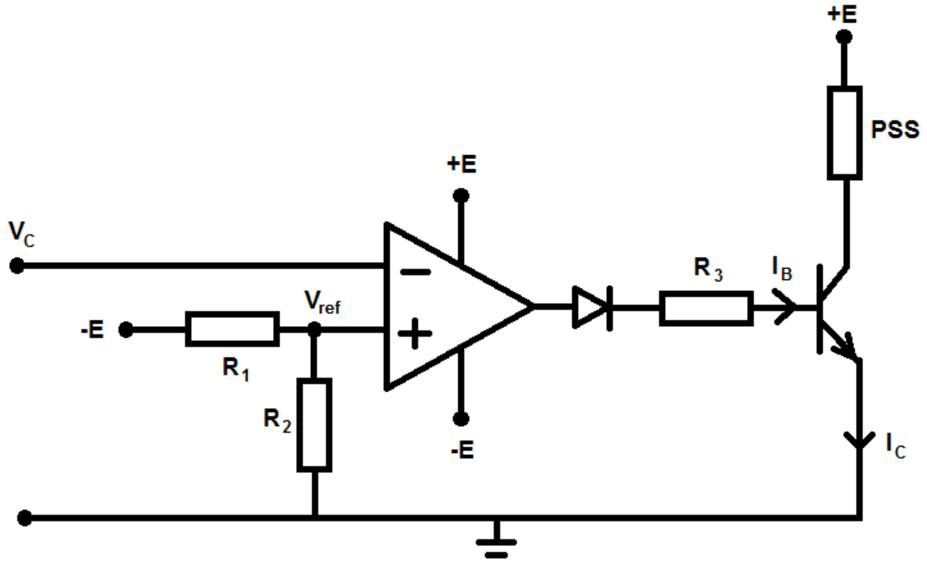

Figure 8. Suggestion of a triggering circuit for one PSS.

This trigger construction is designed to fire one PSS. However, the combination includes two of them that should be fired with a small interval of time between them. In order to trigger the second PSS, an integrator together with another comparator could be implemented. The integrator could for example take the output from the comparator in the circuit above as its input. This would linearly output an increasing voltage until it reaches high enough to overcome the threshold of the new comparator. To this comparator, a similar design as above could be added to trigger that PSS. However, there could be a loss in the amount of time that this secondary circuit will actively be outputting its triggering current, so the current might have to be somewhat larger. A Schmitt trigger comparator might be more suitable for the secondary comparator since it would be able to utilize the output from the integrator for a longer period of time and thus let the second PSS have the same magnitude of triggering current as the first one.

Thus, the integrator will give an increasingly lower output when given the high voltage from the first comparator. This works well with how the Schmitt trigger works, since its output will be high when its input reaches its lower threshold value, and low when the input reaches the higher threshold value. The parameters of the Schmitt trigger can be adjusted so that its output will be delayed for a period of time equal to the length of the signal pulse from the first comparator. However, this is with ideal circumstances where the integrator reaches its minimum as late as possible, and actually does reach it. If the pulse from the first comparator is not long enough, the integrator will never reach its minimum and thus never trigger the second comparator. It would be wise to take some precautions and not use the extreme values of the integrator as the threshold values of the Schmitt trigger. Some measure of buffer ought to be used, but at the expense of a shorter delay. This should not be much of an issue however, since a short delay time could actually be preferable.

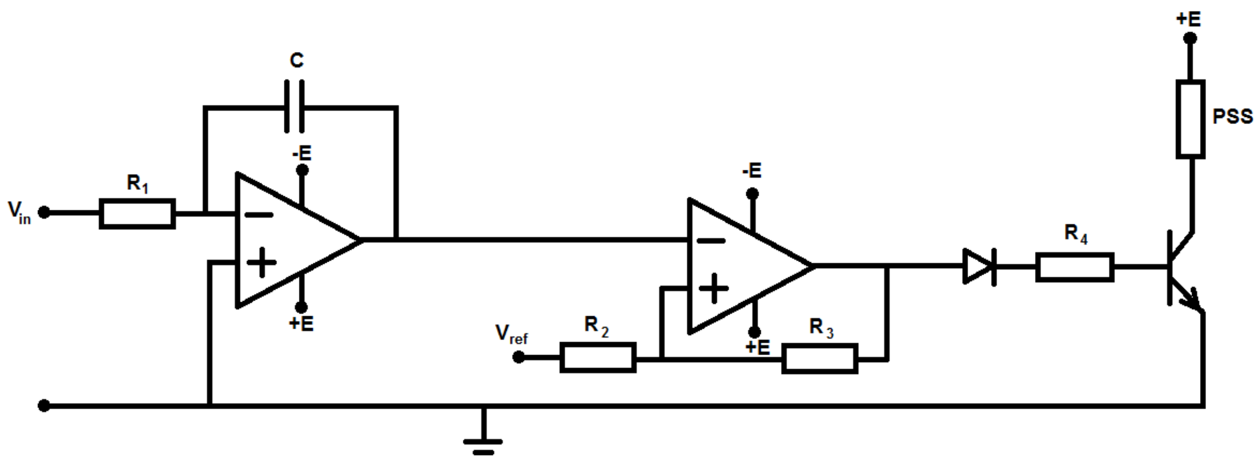

Figure 9. The additional circuit that triggers the second PSS, where V_{in} is connected to the output of the operational amplifier in Figure 8.

The graph below shows the intentional function of the delay circuit.

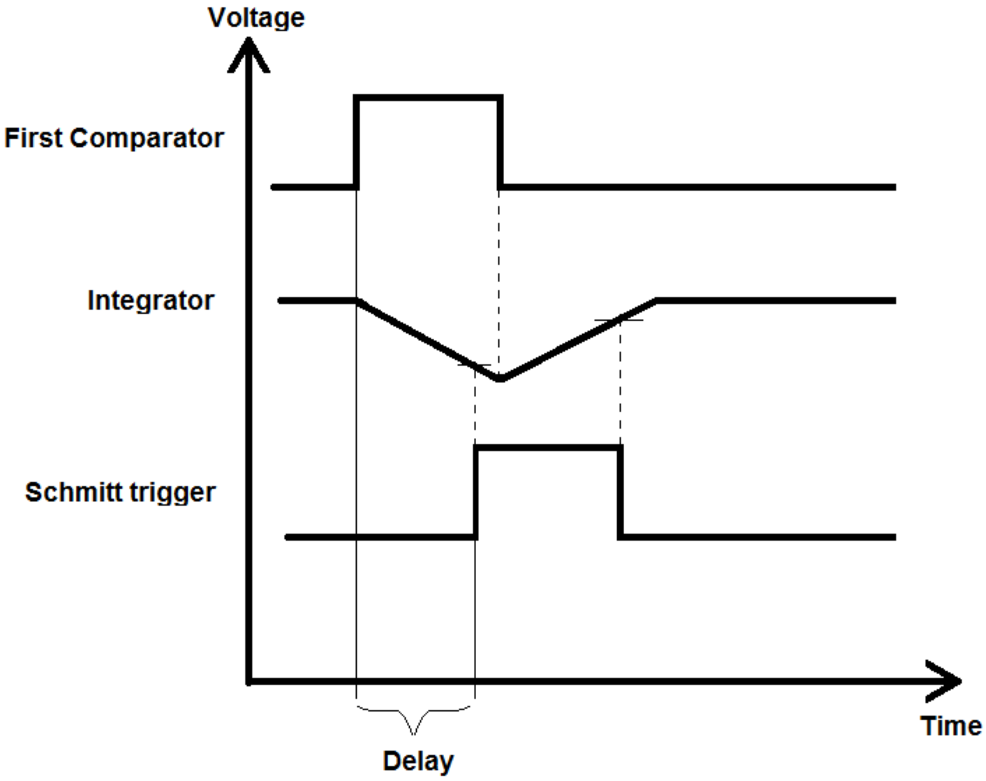

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Figure 10. Concept graph of the delay circuit mechanism.

Calculations of how to dimension the parameters in Figure 9 are given in appendix 2.

3.3 Rogowski Coil, Comparator, IC, and Transistor

The third, and probably the most accurate option for a trigger design is similar to the previous one, but with the addition of an integrated circuit (IC) that controls the currents for firing the two PSSs. This provides a simple solution to the issue of triggering each PSS at a separate time. It also makes it possible to give each PSS the appropriate triggering current that is defined in its data sheet.

What exact IC to be used is not discussed here, since they are too numerous and too various for a general exemplification.

The IC takes the output from the comparator as an input, and has two separate outputs, each of which are connected to a transistor that is ought to drive the triggering current for each PSS - similar to the previous design suggestion.

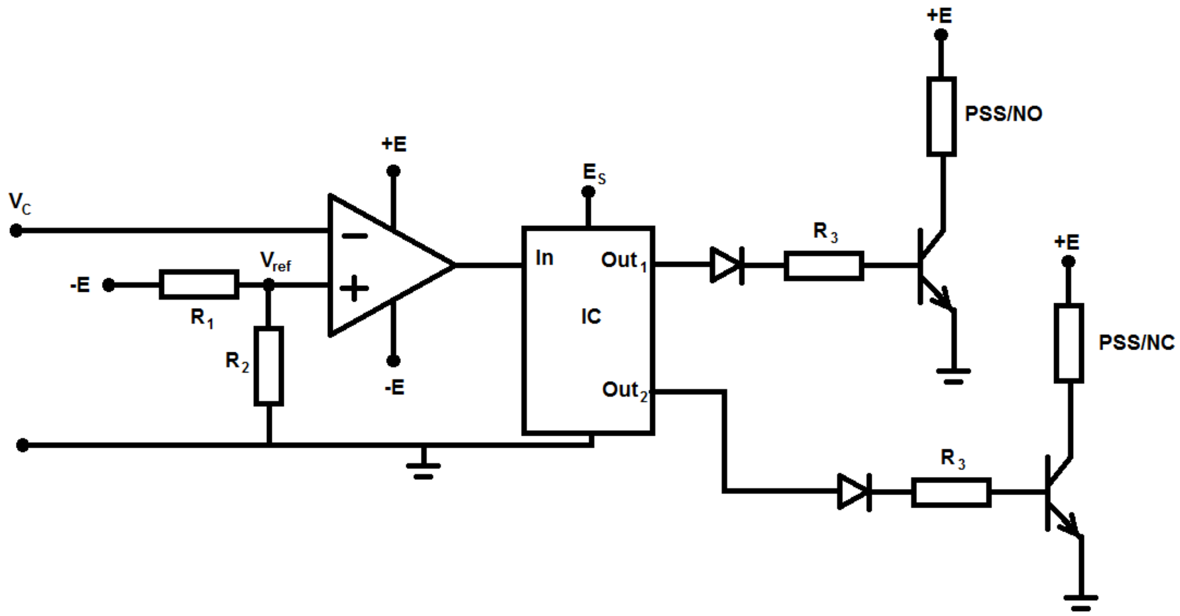

Figure 11. Triggering circuit with an IC, where E_S is the IC's supply voltage.

In Figure 11, the values of the resistors R1 and R2 could be the same as the corresponding ones in construction suggestion 2, but the resistors R3 that determine the base current for the transistors should be altered to give a collector current of 1,75 A since this probably is the most optimal triggering current if given for 0,5 ms. How to determine these is exemplified in Appendix 2.

The program for the IC would be a simple one in function, since its main purpose would be to handle the delay between the two PSSs. An example of how such a program is presented in Appendix 3.

The parameters for this solution's comparator and detecting coil could be the same as the ones in the previous solution, but given the more easily variable behavior of the IC, the length of time during which the detecting coil gives an output is not as important. The IC could be programmed to either trigger the two PSSs as soon as it detects a logical one (1) as its input, or it could be required to detect that one for a longer period of time before actually disconnecting the battery. This would solve any issues with falsely detected fault-currents as the EV starts.

4. Comparison and Discussion

4.1 Comparison to Fuse and Relay

Given the examples of triggering mechanisms for the combinations of PSSs in the previous chapter, it is worth comparing this method to the conventional fuse and relay disconnection option.

As is described in Appendix 2, the amount of time it takes from the moment a fault-current of sufficient magnitude occurs to when the battery has been disconnected entirely, is approximately 0,6 ms. That is - 0,3 ms for the PSS/NO to fire, another 0,2 ms delay for the PSS/NC to fire, and an additional 0,1 ms for the PSS/NC to be entirely done disconnecting. Since a comparator has a response time of the magnitude microseconds, any delay in the circuit can be considered small enough to disregard.

Even if the trigger-solution with an integrated circuit is used, the time to trigger both PSSs would be just above 1,1 ms.

The amount of time it takes for a relay of appropriate size to disconnect is up to 10 ms [15]. This is on its own a longer period of time than it takes for the PSS combination to disconnect the battery. And the relay also has to be triggered, which adds additional time until disconnection.

The time it takes for a fuse to blow depends as previously stated on the strength of the current flowing through it. Given the fault current’s increase rate of about 1400 A/ms , it takes roughly 0,35ms for the current to reach 500 A. At 500 A, it takes almost a whole second for a fuse marked for 150 A to blow [14]. Since the current has been rising up to 500 A for a while, it would not take the full second for the fuse to blow since the energy would already have been passed into it. Though still, a relatively vast amount of time would pass before the circuit was broken.

With these fault-current conditions, the PSS-combination reacts a lot faster than the conventional fuse and relay. With a faster response time, the amount of damage caused to the battery electronics due to a fault-current would be decreased.

4.2 Discussion

The goal of this report was to find a means to trigger the PSS combination efficiently. This was indeed accomplished, and the solutions are presented previously.

The initial idea was to trigger the PSSs with a coil only, which was found to not be a feasible option. Not only would a Rogowski coil of sufficient properties be unrealistic, but to have only a coil would probably not be a sustainable choice due to the coil's output nature. Whenever the EV was shut down or started up, the current would change, and the coil would give an output. Small amounts of current would thus be sent through the PSSs time and again, and this might affect the pyrotechnical charge negatively.

The second option, to trigger the PSS with some additional circuitry to the coil at least turned out to be an in-theory-working-construction. However, this does not reach the secondary goal of having the triggering mechanism entirely independent of outside influence since it does require a supply voltage. But, this is a small setback since the primary objective of triggering the PSSs was reached. The circuit still suffers from the fault that it might give the PSSs a tiny burst of current when the EV accelerates. Should the rate of change of the EV's operation current of about 30 A be the same as the fault-current, the coil would give an output large enough to exceed the comparator's reference voltage for about 0,02 ms. This is not long enough to make the PSS trigger, but it is a fifteenth of the time that would be required, and that is not far away if this happens repeatedly. This might affect the PSS's triggering pyrotechnical charge negatively, as it might fire unintentionally, or perhaps not fire at all when supposed to.

The third alternative, to add a more intelligent digital circuit to the construction would remove the need for the delay-circuit in option two. This would make the triggering mechanism more reliable. The digital circuit could also be programmed to have some additional requirements for triggering. For example, the coil could have to give the output for a fault for a certain period of time before the PSSs are triggered. This could be better, since the coil might give an output large enough to give the digital circuit a "go" signal when the EV accelerates.

As presented in chapter 4.1 about comparison between the different disconnection methods, the disconnection is completed faster with the use of the PSS combination along with either of the functional triggering mechanisms. A faster disconnection of the battery in the event of a fault current could enhance the traction battery's chances of not sustaining any damage.

The disconnection method has to, of course, be reliable. Should the EV be part of a collision accident and somehow gets its exterior in contact with the battery's circuit so that it starts conducting a current, the battery has to be disconnected so that no person gets harmed when touching the car body. A fuse is pretty reliable to ensure the battery's disconnection since it melts on its own without any external signal. The detection and disconnection method of the PSS combination as presented in this report requires that the triggering circuit still has sufficient supply voltage when the fault-current occurs. The PSS combo is thus slightly less reliable, but if the supply voltage is taken from a well-protected battery dedicated to the circuit, then there should be no problem.

The PSS combo disconnection mechanism also has the downside that it does not trigger unless the fault current is large enough. Though this is also true for a fuse, and thus a relay would still have to be present to break smaller fault-currents. Of course disconnecting the battery when the EV is not in use has to be possible, so a relay is necessary anyway, though the PSS-solution in combination with a relay would allow a smaller relay to be used..

The reason for the PSSs to only get a triggering current for 0,3 ms rather than the data-sheet suggested 0,5 ms is that the fault current was defined to only reach approximately 500 A. The rate of change of the fault current only gave a time-span of 0,3 ms before the 500 A roof was reached, and since a coil cannot detect a stable direct current, the triggering would have to be finished before the current leveled out.

References

[1] *Pyroswitch / PSS - Safety Switch and Closing*, Autoliv, Autoliv Inc. 2015, http://pyroswitch.com/index.php?id=3 (Acc = 2015-09-02)

[2] Merkel, T. (2014). Hochvolt-Relais von morgen: Sichere Minimalisten. *Hanser automotive OEM supplier. 2014.* pp. 106-108

[3] Contact Arc Phenomenon, Picker Components, http://www.pickercomponents.com/pdf/application%20note/Contact_ARC_Phenomenon.pdf (Acc= 2015-09-02)

[4] Orville Richard E, Slettten Andreas M, Uman Martin A, Venturino Anthony J (1970). *High-voltage direct current circuit interrupter.* Patent nr. US3544843 A

[5] Kojovik L.A., Beresh R., Bishop M.T., Javora R. , Magruder B., McLaren P., Mugalian B., Offner A. 2010. Practical Aspects of Rogowski Coil. *PSRC - IEEE PES Comittees* http://www.pes-psrc.org/Reports/Practical%20Aspects%20of%20Rogowski%20Coil%20Applications%20to%20Relaying_Final.pdf
(Acc = 2015-09-26)

[6] Molin, B., (2009). *Analog Elektronik*. 2:nd edition. Poland, Pozkal. pp 255-265.

[7] Molin, B., (2009). *Analog Elektronik*. 2:nd edition. Poland, Pozkal. pp 40.

[8] Molin, B., (2009). *Analog Elektronik*. 2:nd edition. Poland, Pozkal. pp 470.

[9] [*Figure of a comparator*] https://upload.wikimedia.org/wikipedia/commons/0/0d/Op-Amp_Comparator.svg
(Acc = 2015-10-14)

[10] [*Figure of an integrator*] https://upload.wikimedia.org/wikipedia/commons/b/bd/Op-Amp_Integrating_Amplifier.svg
(Acc = 2015-10-14)

[11] Sturk D, (2015), *E-Vehicle Safety – Pyro Switch as High Voltage Circuit Breaker & Bypass*, Vårgårda, (Paper Number: 15-0163)

[12] Kojovic L.A., Bishop M.T., (2009). Comparative Characteristics of Iron-Core Current Transformers and Rogowski Coils for Applications for Protective Relaying Purposes. *IEEE Xplore.*
http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=4982539
(Acc = 2015-09-26)

[13] Permeability and saturation. *All About Circuits.*
http://www.allaboutcircuits.com/textbook/direct-current/chpt-14/permeability-and-saturation/
(Acc = 2015-10-30)

[14] *Automotive Fuse Catalogue*. (2013) https://www.pecj.co.jp/en/fuse/pdf/catalog.pdf
(Acc = 2015-06-03)

[15] *Capsule Contact Mechanism and High-Capacity Cutoff Compact Relay*
http://mt-system.ru/sites/default/files/docs/documents/File/PEW/EV%28AEV%29.pdf
(Acc = 2015-09-11)

[16] Fuses. *All About Circuits.* http://www.allaboutcircuits.com/textbook/direct-current/chpt-12/fuses/
(Acc = 2015-10-30)

[17] Woodford C., (2015). Relays. *Explainthatstuff.*
http://www.explainthatstuff.com/howrelayswork.html
(Acc = 2015-10-30)

[18] *Battery Disconnect Switch PSS 1*. (2015). Autoliv.
http://pyroswitch.com/fileadmin/user_upload/Pyroswitch/PSS-1_Technical_Data_Sheet_5_2015.pdf
(Acc = 2015-12-01)

[19] [*Figure of a Rogowski Coil*]
https://upload.wikimedia.org/wikipedia/commons/7/74/Rogowsky_coil.png
(Acc = 2016-02-09)

Appendices

Appendix 1

Calculations of the construction option with only a Rogowski coil.

Since the PSS needs a triggering current of 1,75 A during 0,5 ms, but only a time-span of 0,3 ms is offered before the current reaches 500 A, an appropriately larger current is needed.

$$1{,}75 \cdot 0{,}5 \cdot 10^{-3} = 875 \cdot 10^{-6} \quad \text{(A1-1)}$$

$$\frac{875 \cdot 10^{-6}}{0{,}3 \cdot 10^{-3}} = 2{,}9 \quad \text{(A1-2)}$$

Thus, a current of approximately 3 A would be required to trigger the PSS.

To come up with a coil that can put out the desired amount of current, a few parameters have to be determined beforehand. To get a manageable coil, the following values could be used:
A cross-sectional area *A* of the windings: 1 cm^2.
A major radius *r* of the coil: 1,5 cm.
And a current change *di/dt* of the encircled wire of $1{,}4 \cdot 10^6$ A/s.
The resistivity ρ of copper is $1{,}678 \cdot 10^{-8}$.
The permeability of air μ_0 is $4\pi \cdot 10^{-7}$.

$$R = \frac{\rho 8 \sqrt{\frac{A}{\pi}} n^3}{(2\pi(r - \sqrt{\frac{A}{\pi}}))^2} => \; R = kn^3 \quad \text{(A1-3)}$$

The coil's resistance was left to be dependent on the number of windings on the coil according to the equation above. The given parameters were put into the equation, and a *k*-value of ~0,000000219 was found. This was put into the following equation, that gives the output current of a Rogowski coil:

$$I = -\frac{\mu_0 A}{2\pi r k n^2} \frac{di}{dt} \quad \text{(A1-4)}$$

where then the current *I* and the number of windings simply were moved to create the following equation:

$$-n = \sqrt{\frac{\mu_0 A}{2\pi r k I} \frac{di}{dt}}. \quad \text{(A1-5)}$$

The desired current of 3 A was put into the equation along with all other known values, and resulted in a number of windings of 53.

This was verified by using the calculated number of windings to receive the voltage output from the Rogowski coil, as well as the total resistance of the wire. The voltage divided by the resistance then resulted in a total current of 3,03 A.

Any negative signs in equations were neglected, since the polarity does not really matter when only calculating absolute values. The direction of the triggering current through the PSS does not matter.

Taking the PSSs resistance into consideration, the result turns out quite differently. The resistance of the wire in the case where only the coil is considered is 0,033 ohm, calculated with the length and cross-sectional area of the wire used to create such a coil. The PSSs resistance of 2 ohm is significantly larger compared to the resistance of the coil, whose current reaches the desired magnitude due to the low resistance rather than outputting a high voltage. If the 2 ohm of the PSS is added to the coil's, the result changes significantly.

Given that all other parameters are the same as when the 3 A were achieved, and another 2 ohm is added to the resistance, the following equation is created:

$$I = -\frac{\mu_0 n A}{2\pi r(R+2)}\frac{di}{dt} \qquad \text{(A1-6)}$$

where R is the resistance of the successful coil, 0,033 ohm. The result is a discardable current of 0,049 A, which is far from what would be required.

Of course, parameters of the coil could be changed in an attempt to compensate for this loss of current. However, if the number of windings is increased, the resistance of the coil itself would also increase, and thus add further hardship of reaching the goal. The same is true for the choice of increasing the coil's cross-sectional area of the windings. The larger this area is, the more wire would be required for each winding, and so the resistance of the coil increases yet again. Should the major radius of the coil decrease much more, it would soon not be able to encircle the conductor through which the fault current flows.

For example, even if the resistance of the coil itself would not increase with the area of the coil's windings, and the area of the windings can be stretched out along the conductor endlessly, it would require an area of:

$$A = \frac{I 2\pi r(R+2)}{\mu_0 n}\frac{dt}{di} \qquad \text{(A1-7)}$$

in order to achieve the desired current of 3 A. Here, this area would be roughly 60 cm^2, which would result in a coil that is not practical. This increase in area would also increase the length of the coil's wire from about 4 cm per winding to 122 cm per winding, if the cross-sectional area of the coil is built like a rectangular shape instead of a circle for the purpose of more easily estimating the wire's length when the windings are no longer circular. This is also without taking any consideration to the wire's increased resistance, which would be about 30 times larger than originally, making the total resistance of the circuit closer to 3 ohm, than the original ~2 ohm when the PSSs resistance was dominating. With an increased resistance, the area would have to increase even further, and would in turn once again increase the coil's resistance.

It is evident that a coil cannot trigger a PSS on its own.

Appendix 2

Appendix 2 holds calculations of values of the construction option 2 and 3.

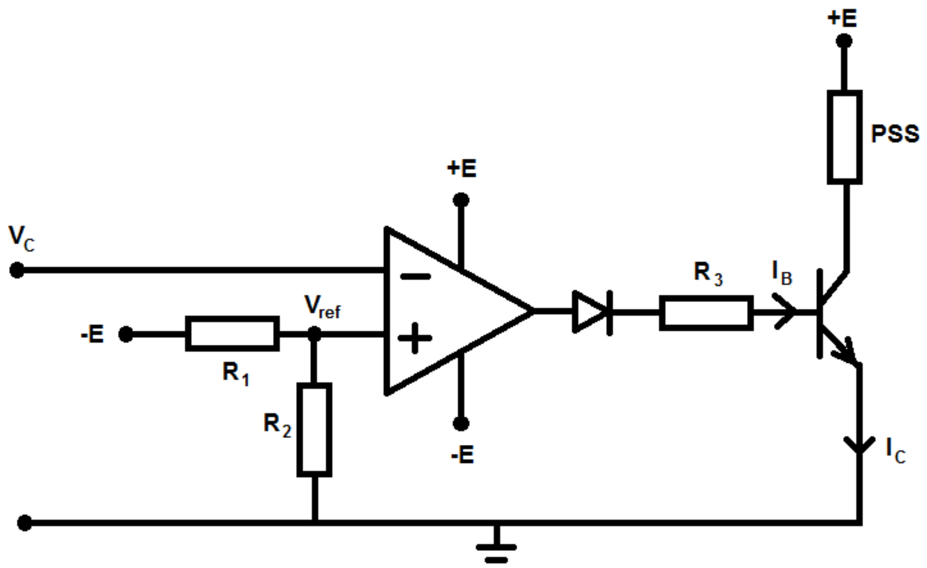

Figure A1, additional circuitry for the coil to trigger one PSS.

With the additional circuit to support the Rogowski coil, the coil itself does not have to be able to output a current that is strong enough to trigger the PSS. Thus, a conveniently sized coil can be used, with the following parameters for example:
A cross-sectional area A of: 1 cm^2-
A major radius r of: 1,5 cm.
A number of windings n of: 62.
And the rate of change of the fault current to be: 1,4 *10^6 A/s.

The number of windings is the highest amount possible that can fit on the coil if the wire has a diameter of one millimeter.

With the equation for the voltage output from a Rogowski coil:

$$v_c = -\frac{\mu_0 nA}{2\pi r}\frac{di}{dt} \qquad \text{(A2-1)}$$

and the parameters given above, a voltage output of 0,116 V is achieved.

0,116 V would thus be the reference voltage the coil has to overcome in order for the circuit to trigger the PSS.

To obtain the desired reference voltage, since the exact value probably is not trivially accessible, two resistors are used to split a more likely available voltage. Since this is an EV, a 12 V battery is probably present, so *E* is logically set to 12 V. Using the following equation, and deciding R_2 to be 1000 ohm:

$$R_1 = \frac{ER_2 - R_2 V_{ref}}{V_{ref}} \qquad \text{(A2-2)}$$

R_1 is found to be 102,4 * 10^3 ohm.

Further, in order to obtain the suitable current I_B for the transistor to pass 3 A through the PSS, I_C, R3 is dimensioned with the example of a transistor with a h_{FE} of 1000. The output of the comparator is 12 V, and the voltage drop over the diode and the transistor are both 0,7 V for a total of 1,4 V.

$$I_C = h_{FE} I_B \quad \text{(A2-3)}$$

$$I_B = \frac{E - V_D - V_t}{R_3} \quad \text{(A2-4)}$$

$$R_3 = \frac{E - V_D - V_t}{I_B} \quad \text{(A2-5)}$$

(A2-4) gives an I_B of 3 mA, and subsequently (A2-5) gives 3,53 kohm for R_3.

The same method for determining the resistor value prior to the transistor is used in construction option 3 (the one with a digital IC), where the output of the IC is connected to the diode rather than a comparator. In this case, the collector current should be 1,75 A instead. The voltage drop over the diode and transistor remain the same, but the output voltage of the IC might vary, depending on what exact IC is used.

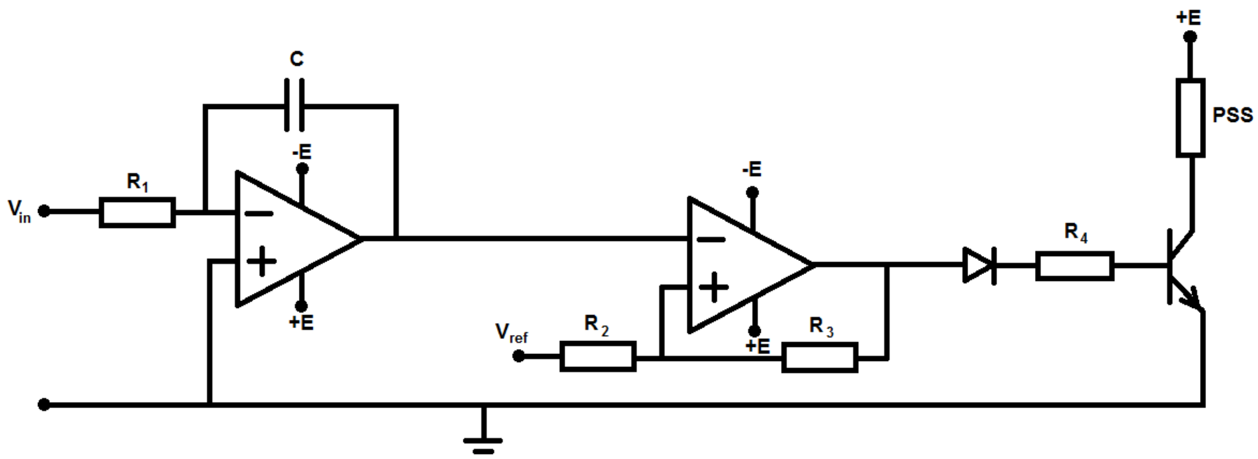

Figure A2. Delay circuit to trigger the second PSS.

In order to trigger the second PSS of the system a bit later than the first one, the circuit above is added to the original one, where V_{in} is connected directly to the output of the operational amplifier of the original triggering design.

The first operational amplifier in the circuit above is coupled to function as an integrator. That is, it will output the integral of the input. When this voltage is low enough, the second operational amplifier here - coupled as a Schmitt trigger - will output the voltage to trigger the second PSS.

With the characteristics of a fault current, the first comparator will give an output for about 0,3 ms. This is the amount of time for which the integrator will move towards a more negative output. When the 0,3 ms are past, the integrator will again move towards its higher supply voltage value.

The integrator is dimensioned according to the equation:

$$\frac{V_{in}}{R} = -C\frac{dV_{out}}{dt} \qquad \text{(A2-6)}$$

The time duration dt is given, so is the input voltage. Left to decide is the desired output at the end of the 0,3 ms, then the resistor and capacitor can be picked accordingly. An output change of 12 V could be achieved with a resistance of 20 kohm, and a capacitor of 150 nF.

In an extreme case, the Schmitt trigger's threshold values could be set to be the absolute ends of the integrator's output, and thus yield a delay of a whole 0,3 ms. This would however not give any space for fault-tolerance, and so other threshold voltages ought to be chosen.

The threshold voltages could for example be 4 V and 8 V. This would give a delay of 0,2 ms, while still offering some resistance to having a too short pulse from the first comparator, and letting the Schmitt trigger output a pulse identical to the one from the first comparator, since the rate of change of the integrator's output is 12 V / 0,3 ms.

It would take 0,2 ms to reach 4 V. 0,1 ms later, the integrator's output begins to increase, and after another 0,2 ms it will have reached 8 V, letting the Schmitt trigger give a high output for 0,3 ms.

From the following equations, the values of the resistors R2 and R3 can be found. V_{ref} can be acquired similarly to how the reference voltage to the first comparator is achieved, by splitting the supply voltage over two resistors. How to calculate the value of these are done in the same manner as presented earlier.

$$V_{Tmid} = V_{ref}\frac{R_3}{R_2+R_3} \qquad \text{(A2-7)}$$

$$V_{Twidth} = 2E\frac{R_2}{R_2+R_3} \qquad \text{(A2-8)}$$

To get a span between 4 V and 8 V, a middle of 6 V is desired, and a width of 4 V. E is given to be 12, and one resistor can be chosen freely, the second one and the reference voltage being deducted from the other parameters.

For example, the resistor could be 1 kohm for R2, and 5 khom for R3. This would give a required Vref of 7,2 V.

The final resistor R4 is chosen to be the same as the resistor prior to the transistor in the original triggering circuit, if an identical transistor is used in the delay circuit since the triggering currents of the PSSs are to be the same.

Appendix 3

Example of program-function for the IC in construction option 3:

```
If input = 1{
        output1 =1;
        wait 0,5ms;
        output1 = 0;
        output2 = 1;
        wait 0,5 ms;
        output2 = 0;}
Else {
        output1 = 0;
        output2 = 0;}
```