

Pyrotechnic Safety Switches for Safe and Quick HV Circuit Disconnection at High Fault-Currents

David Sturk¹, Per Gustafsson², Christian Cavell³, Alf Holgers⁴,
Francois Gaudinat⁵, Etienne Dugast⁵

¹Autoliv Development AB, Wallentinsvagen 22 44783 Vargarda Sweden, david.sturk@autoliv.com;

²Autoliv Development AB, Sweden; ³Autoliv Germany, Germany; ⁴Autoliv Sweden AB, Sweden; ⁵Autoliv NCS, France

Summary

Safe and instantaneous disconnection of a High Voltage Battery Circuit at high fault-currents can be achieved with Pyrotechnic Safety Switches (PSS).

Traditional alternatives are melting fuses and relays. In contrast to those traditional circuit breakers, a PSS offers an instantaneous disconnection within a time range of fractions of milliseconds to a few milliseconds. The speed and high level of safety due to clean disconnection and no bouncing effect is attributed the pyrotechnics that provide a forceful thrust to an insulated guillotine cutting a conductor. Additionally, a PSS consumes no power during ordinary vehicle operations.

Keywords: Lithium battery, Safety, EV, HEV

1 Introduction

An E-Vehicle (i.e. an electrified vehicle such as EV or HEV) commonly utilize a traction battery with voltage between 200-400 Volt dc (VDC). In the event of a traffic incident when the traction battery could be damaged, disconnection of the traction battery is traditionally performed by the use of relays and melting fuses (Figure 1). This shall assure the safety of not only E-Vehicle occupants but also for people in the proximity of such a vehicle, e.g. first responders and other rescue personnel.

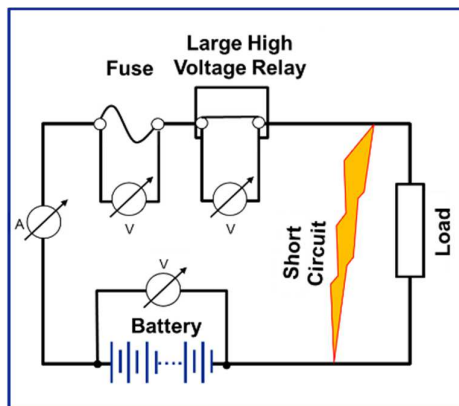
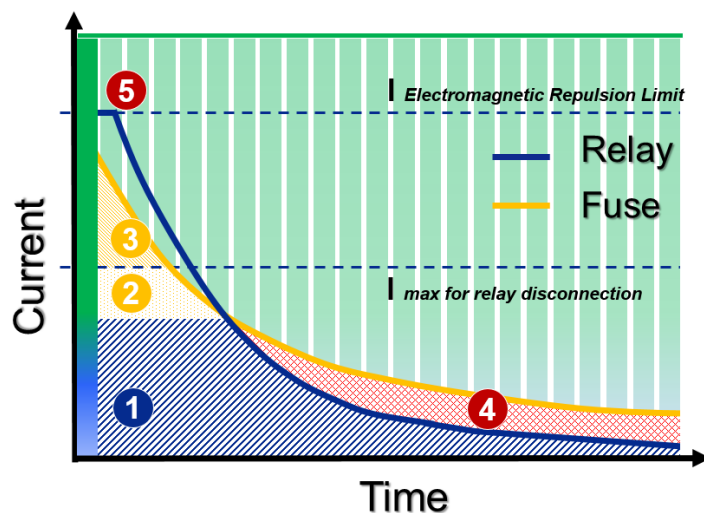


Figure 1 Traditional safeguard management by use of melting fuse and relay

In contrast to melting fuses, a Pyrotechnic Safety Switch (PSS) will offer an instantaneous disconnection as fast as less than a millisecond, and the rate of the circuit breaking action is independent of the magnitude of the fault current; thus minimizing the time of harmful over-current exposure. Additionally, a PSS is activated upon command from an Electric Control Unit (ECU) and thus will act based on a logical decision. PSS will thus be able to act at fault currents that would be too low for a melting fuse if required. [1]

In contrast to a relay, a PSS demands no continuous power during the life of the E-Vehicle until the moment of its activation. The PSS products can offer safe and quick disconnection at a range of fault currents that greatly surpass the available range existing for large automotive HV relays without risk of harmful effects of the electromagnetic repulsion limit (Figure 2). Moreover, at extreme fault currents there is no risk of bouncing effects that otherwise risk to severely harm the circuit breaker and subsequently the battery and/or its power electronics. [1] Additionally, while a relay require power to operate throughout its full lifetime, a PSS only require a short signal for triggering at the point in time of activation and it will not consume energy otherwise.



Autoliv PSS cut-off profile

Figure 2 A comparison of characteristics of conventional relays and fuses when circuit disconnection is demanded. Autoliv PSS units offer a nearly vertical disconnection profile (i.e. the green columns) in contrast to e.g. melting fuse. PSS activation can happen at any level of over-current or time in accordance with specifications; hence, each of the green columns represent a PSS disconnection, and the columns locations on the x-axis illustrates the PSS's time/current-independence.

The PSS series from Autoliv contain three basic types – PSS Normally Closed (PSS/NC), PSS Normally Open (PSS/NO) and PSS Combo. The cutting capacity within the family of PSS/NC range from 12 VDC (Figure 3) up to 600 VDC (Figure 4), and successful quick and clean disconnection has been empirically proven with electrical loads including up to 154 μ H of inductance. The PSS/NO (Figure 5) is rated for a max. short circuit current of 5 kA for 5 ms or 600 A for 60 s, but higher currents is possible at a shorter period of time.

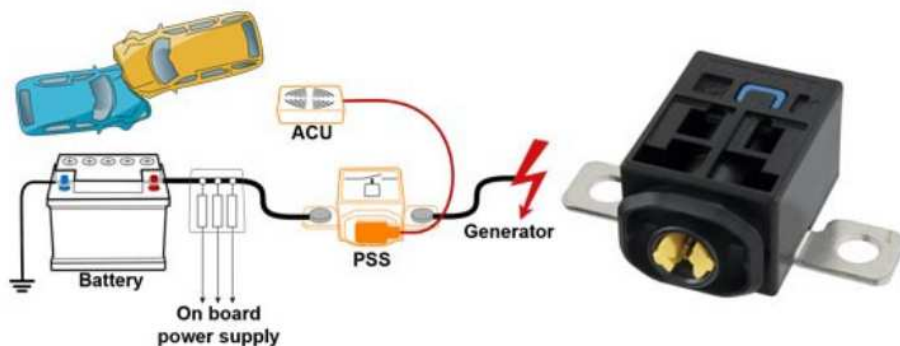


Figure 3 The PSS-1/NC is connected between the power set and the 12 VDC battery [2]



Figure 4 The heavy-duty PSS-4/NC has a max rated voltage capacity of 600 VDC under resistive load, and under inductive load it is specified for a max switching capacity of $8000 \text{ A} / 450 \text{ V} / L/R 0.5 \text{ ms}$ time constant. [3]



Figure 5 The PSS-6/NO circuit connector was originally designed as a safe guard feature of fuel cell stacks for high power drainage of power in the event of an emergency shut down of the fuel cell assembly. [4]

This paper intend to present how Autoliv’s pyrotechnic safety switches can offer successful (safe, clean and quick) disconnection of power systems with voltage ranging from 12 VDC to a max level of more than 950 VDC at system inductance levels of up to $154 \mu\text{H}$ without inducing arcs that prevail (i.e. “lasting arcs”).

2 Methods

This paper will primarily focus on results from tests on the methodology denoted as *PSS Combo 1* where two PSS units are used in correlation to connect a bypass circuit path across the terminals of the battery power source and subsequently disconnect the battery.

However, with intention to provide a contextual background, the following section will present the two major methods for disconnection using PSS units in single as well as in combinations.

2.1 Background

In a worst case scenario a complete battery pack, or failing battery units thereof, must be immediately disconnected from the power circuit. When this is done by traditional circuit breaking methods, there is a serious risk of over-current spikes critically damaging the battery management electronics and thus terminating the future functionality of that battery pack.

PSS units can act as single units or combined units when performing disconnection of high power circuit:

- *Direct disconnection* – one or more PSS units acting in series (only PSS/NC)
- *Combined disconnection* – one or more PSS units offering parallel paths and disconnections (PSS Combo 1 and PSS Combo 2)

Figure 6 illustrates four implementations. In short, when comparing these two solutions the direct disconnection is the fastest and offers the advantage of its simplicity, while the combined disconnection offers an opportunity to minimize the harmful exposure of current spikes (associated with high current switching) to the battery electronics.

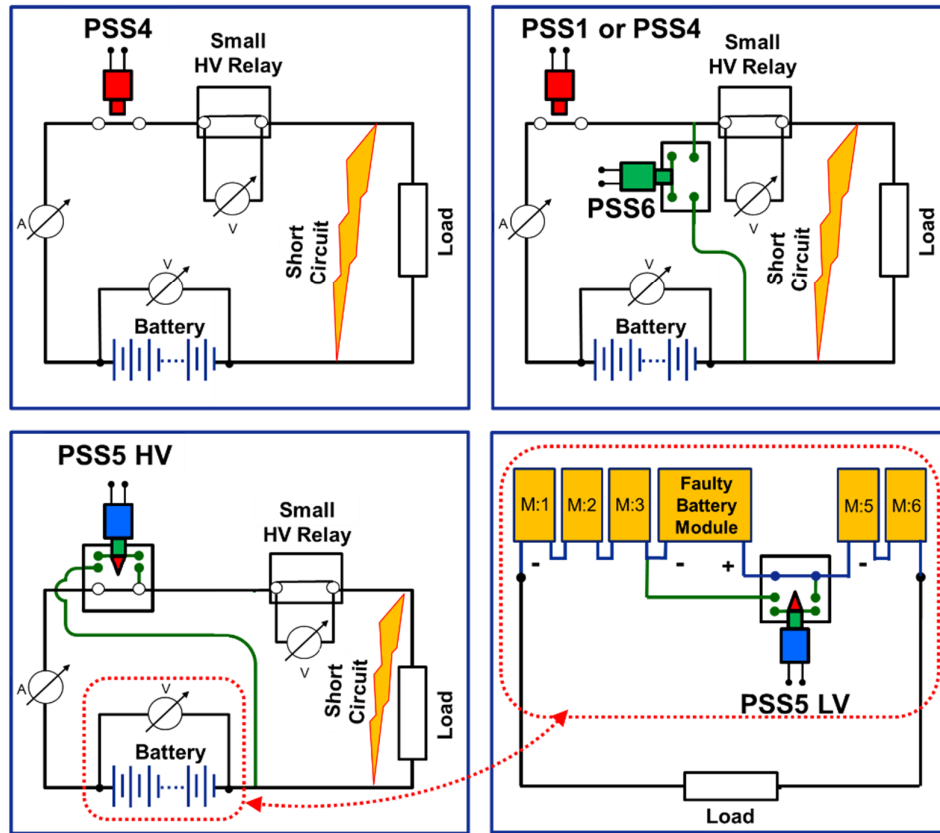


Figure 6 (a) Upper left quadrant presents a Direct Disconnection by PSS-4/NC in series with a small HV relay. (b) Upper right quadrant presents a PSS Combo 1(A or B) setup in series with a Small HV relay. (c) Lower left quadrant presents a PSS Combo 2 (PSS-5 HV) setup in series with a small HV relay. (d) Lower right quadrant presents a PSS Combo 2 (PSS-5 LV) mounted inside a battery pack in order to achieve a "bypass & isolation" of faulty battery module while retaining E-Vehicle mobility.

Moreover, the implementation of the combined disconnection using a bypass path across the terminals of the power electronics circuit provides a safe guard feature that eliminate the risk of remaining capacitive energy in power electronics circuitry or traction machines since such capacitive energy will drain quickly through the bypass path after disconnection of the power source. This will offer a reduction in risk level for professionals that, after a battery failure, may come in contact with live parts. Additionally, combined disconnection offers the concept of isolating a faulty battery module while still retaining E-Vehicle mobility (Figure7). [5]

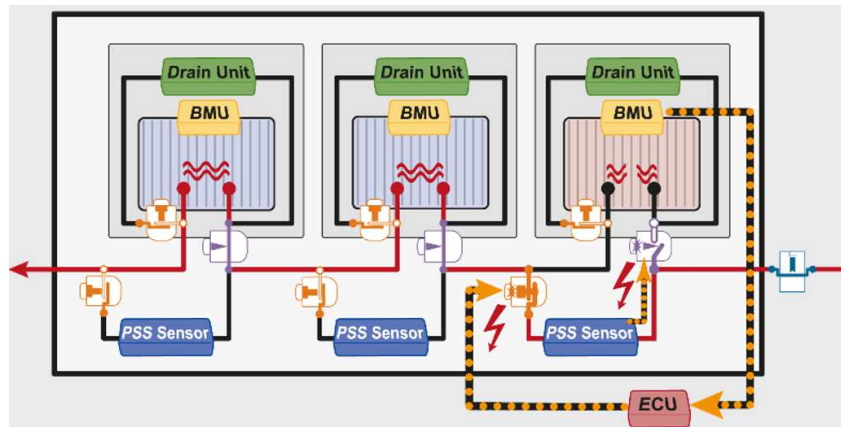


Figure 7 Sketch presenting the inclusion of a Drain Unit to the PSS Combo 1.

2.1.1 Direct disconnection

PSS-1/NC is already a commodity product sold by the millions annually. It was originally designed for direct disconnection of 12 VDC systems [3] [6], but is capable up to 400 VDC resistive load and 150 VDC under inductive load up to 154 μ H when conducting direct disconnection.

PSS-4/NC has been designed for direct disconnection of HV systems up to 600 VDC (resistive load) and 450 VDC under inductive load. It will reach the market in less than 12 months. [3]

Using PSS/NC for direct disconnection offers an immediate substitute to a melting fuse and it is activated upon command signal (Figure 6a). It also offers a reduction in weight when it is combined with smaller HV relays with maximum rated current in accordance with E-Vehicle operative conditions rather than for excess over-currents. Above such over-currents disconnection can be safely handle by PSS, and such a combination will be lighter than large heavy-duty HV relays designed for currents above 1000 A. [7]

2.1.2 Combined disconnection

Acting as a circuit breaker, the methodology of combined disconnection utilized either a PSS/NO device in combination with a PSS/NC device (PSS Combo 1, see Figure 6b) or one device with multiple NO/NC-functions (PSS Combo 2, see Figure 6c). The latter may also be mounted inside a battery assembly or relay assembly in order to bypass and isolate a faulty battery unit (Figure 6d) and an additional drain unit can be added for safe discharge of stranded energy (Figure 7).

2.2 Methodology for HV circuit breaking using PSS Combo 1

The methodology of combined disconnection that was investigated offers a clean millisecond disconnection with minimum exposure to electronics due to the introduction of the bypass circuit providing an alternative current path. However, at the time of PSS/NO activation the battery pack terminals are short circuited and it is therefore crucial that its duration is kept at a minimum. This is assured by correlating the PSS/NO activation with the subsequent triggering of a PSS/NC which disconnects and thereby isolates the battery unit within a delta time of less than 1.0 ms.

By establishing this bypass path, an additional safety feature is achieved; i.e. the potential differences across power electronics and electrical machines throughout the power system are terminated. This will eliminate the risk of residual capacitive energies in the power circuitry after a vehicle crash. Consequently, this will inhibit lingering hazardous voltages in the power electronics and traction machines that otherwise may present risks to e.g. first responders, towing professionals or workshop personnel which might approach an E-Vehicle with a damaged electric traction system in their professional roles.

2.3 Test Procedure

In the present test series, the tests begun at about $t = -70$ ms when a heavy-duty contactor creates a hard short through a circuit that included a battery of 490 VDC or 965 VDC connected to an resistive and inductive (RL) load (simulating the characteristics of an E-Vehicle power system) of up to 154 μ H. During those first 70 ms, an inductive short circuit current of 3000 to 4 500 A “plateaued” which allowed the test scenario to start at $t = 0$ ms; i.e. the point in time when the bypass circuit was established by the PSS/NO. (Figure 8) After less than 0.5 ms the PSS/NC disconnection occur and the battery unit is isolated from the RL load. After disconnection the inductive current relaxation will take place in the RL load.

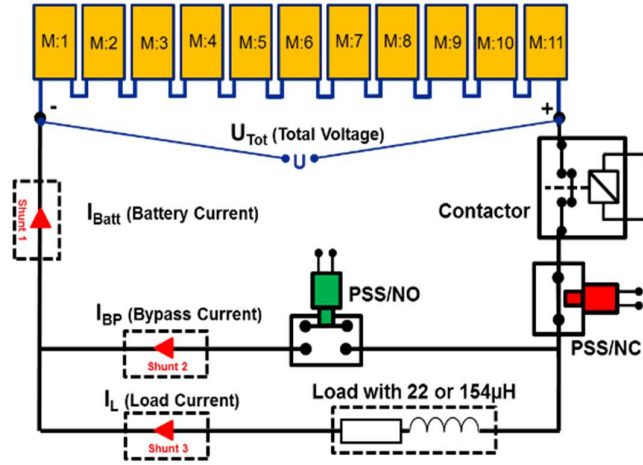


Figure 8 Test setup for Combined Disconnection of a complete HV battery pack using PSS/NO and PSS/NC

The sample frequency was 20 kHz, and the tests were conducted in test chamber temperature of about 17 °C. The heavy-duty contactor was designed for disconnection of circuits with continuously currents up to 315 A at 660 V and 10 times higher currents for instantaneous surges; however, as the contactor was only used for circuit contacting its functionality and durability was not affected during these tests. The contactor's influence on the characteristics of the tested circuit was estimated as negligible.

3 Results

The test results illustrate how quickly and clean the PSS units manage to disconnect and isolate the battery unit before time 0.5 ms. The over-current through the battery rapidly drops to zero as in a capacitive circuit. In contrast, after 0.5 ms, the influence of the inductance of the RL load force the current through the bypass path in negative direction while relaxing relatively slowly down to 0 A. In accordance with expectations, no bouncing effects could be identified through the resulting data series.

Figure 9 presents the results from tests on the PSS Combo 1A setup (i.e. PSS-6/NO in combination with PSS-1/NC). Only limited current fluctuations occur during the 0.5 ms delta-time between PSS/NO connection of bypass path and PSS/NC disconnection of battery unit.

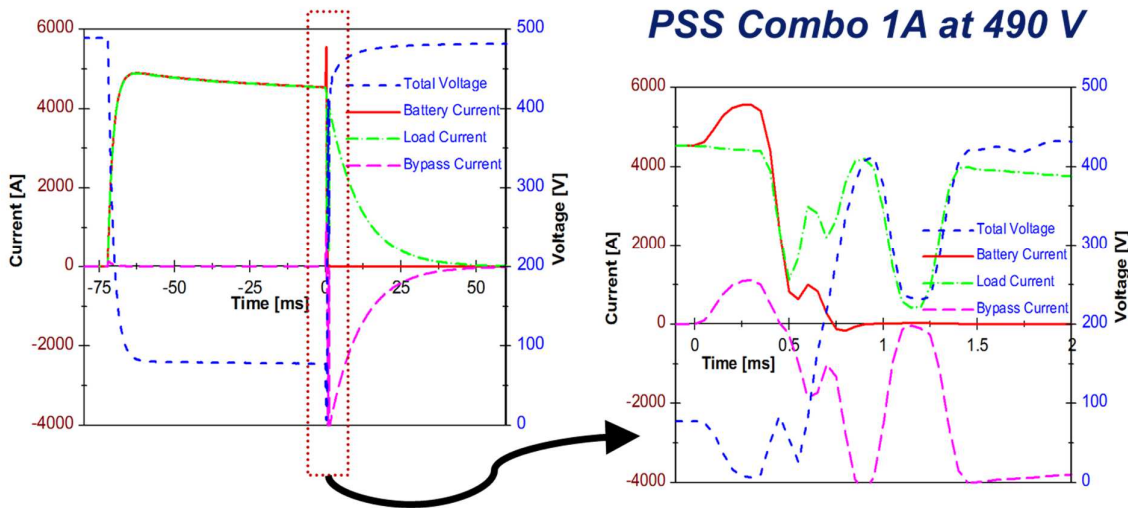


Figure 9 Results from successful, quick and clean disconnection using PSS Combo1A (i.e. PSS-6 in combination with PSS-1). The test system constitutes of a 490 VDC battery together with a RL Load with 154 μH of inductance besides the tested circuit breakers. Left (a) presents the complete test time frame. Right (b) present the currents and voltage profiles during 2 ms after bypass connection at $t = 0$ ms.

Figure 10 and Figure 11 show the results from tests on the PSS Combo 1B setup (i.e. PSS-6/NO in combination with PSS-4/NC). No current fluctuations did occur during the 0.5 ms delta-time in these tests.

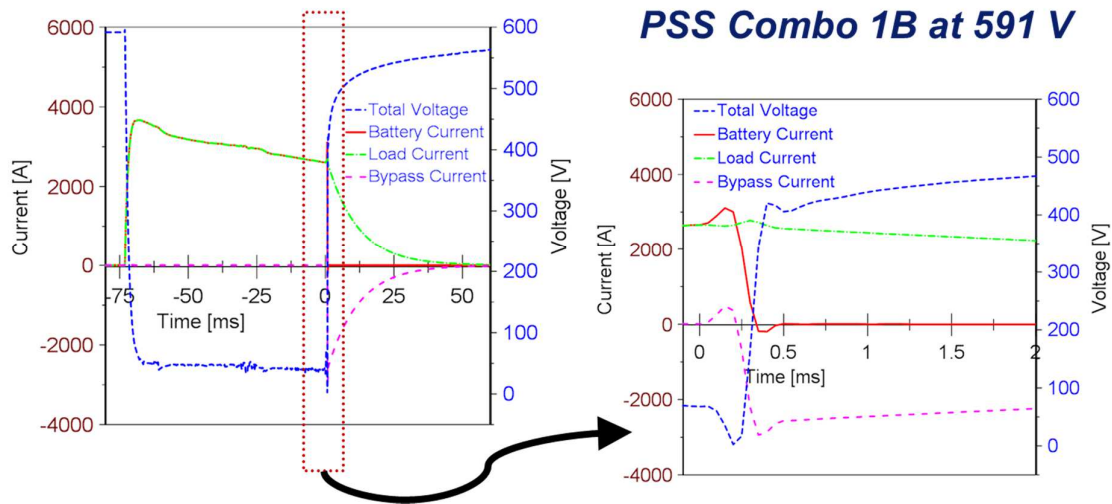


Figure 10 Results from successful, quick and clean disconnection using PSS Combo1B (i.e. PSS-6/NO in combination with PSS-4/NC). The test system constitutes of a 591 VDC battery together with a RL Load with 154 μ H of inductance besides the tested circuit breakers. Left (a) presents the complete test time frame. Right (b) present the currents and voltage profiles during 2 ms after bypass connection at $t = 0$ ms.

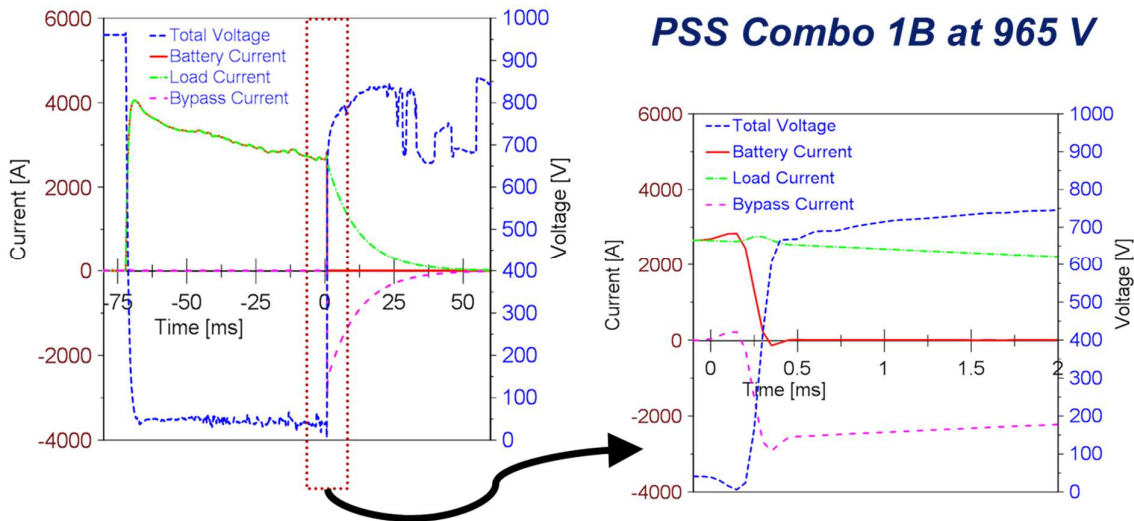


Figure 11 Results from successful, quick and clean disconnection using PSS Combo1B (i.e. PSS-6/NO in combination with PSS-4/NC). The test system constitutes of a 965 VDC battery together with a RL Load with 154 μ H of inductance besides the tested circuit breakers. Left (a) presents the complete test time frame. Right (b) present the currents and voltage profiles during 2 ms after bypass connection at $t = 0$ ms.

Unexpectedly, during the tests of PSS Combo 1B, the curve of Total Voltage before time 0 ms carry some minor ripples, and in Figure 11 there is an unanticipated drop in voltage starting at about 25 ms after the successful disconnection. This behaviour stems from electromotive forces in the cabling, between one battery terminal and the heavy-duty contactor, yanking the fixation of that terminal which caused a fatigue failure. However, this mechanical failure did not influence the successful test results as the time frame of the PSS Combo 1B disconnection was close to 100 times shorter than the duration time frame of those ripples.

4 Discussion and Limitations

The technical solution of Combined Disconnection using the PSS Combo 1A/B concept has been empirically verified in terms of its capability to increase the disconnection rate and significantly reduce the risk of harmful current spikes and lasting arcs in the circuit breaker in comparison to traditional circuit breakers such as relays and melting fuses. Circuit disconnection using relays at excessive over-currents involves the risk of bouncing effects. That risk is terminated by using PSS.

As this methodology significantly reduces the risk of harmful current spikes and achieves extraordinary quick isolation of the battery unit, the battery's management electronics will have a greater probability to survive unharmed when utilizing this type of emergency disconnection than when being disconnected by traditional circuit breakers. Consequently, the cost of repair may be limited to the replacement of the PSS Combo units, rather than otherwise more expensive battery components.

In comparison to traditional circuit breakers, the methodology of PSS Combo permits quicker and gentler disconnection/isolation of the battery unit while also eliminating the risk that residual capacitive energies remains in the power circuitry after vehicle crash or other scenario concerning damaged battery units. Consequently, this method significantly reduce the risk for first responders, towing professionals or workshop personnel to come in contact with harmful residual capacitive energies lingering in the power circuitry of a damaged E-Vehicle.

It is evident that PSS switches are irreversible and will best work in correlation with other reversible circuit breakers that are designed for the operative conditions in an E-Vehicle. Nevertheless, by using pyrotechnic switches, such as the family of PSS Combo, in series with a small HV relay (i.e. with moderate maximum current rating), the weight of the safeguard disconnection system can be reduced in comparison with heavy-duty HV relays. Thus, PSS units shall be used for emergency disconnection while relays can be reduced in size to fit the electrical characteristics of operative conditions in an E-Vehicle. Additionally, as mentioned, in contrast to relays the PSS does not consume any power during the operative life of the electrical system that it is protecting.

References

1. *Hochvolt-Relais von morgen: Sichere Minimalisten*. **Merkel, Thomas**. s.l. : Hanser-Automotive, 2014, OEM Supplier 2014, pp. 106-108.
2. **Autoliv**. PSS - Pyrotechnic Safety Switch - Reliable safeguard against motor vehicle fires and electric shock. *pyroswitch.com*. [Online] Autoliv. [Cited: Nov 09, 2016.] http://www.pyroswitch.com/fileadmin/user_upload/Pyroswitch/PSS_Product_Data_Sheet_engl-Vers0515.pdf.
3. **Autoliv**. Battery Pyrotechnic Switch PSS-4. *Automotive Switch - High Current Device*. [Online] Autoliv. [Cited: Nov 09, 2015.] http://www.pyroswitch.com/fileadmin/user_upload/Pyroswitch/PSS_4_Technical_Data_Sheet__5_2015.pdf.
4. **Autoliv**. Battery Pyrotechnic Switch PSS-6. *Automotive Switch - High Current Device*. [Online] Autoliv. [Cited: Nov 09, 2015.] http://www.pyroswitch.com/fileadmin/user_upload/Pyroswitch/PSS-6_Technical_Data_Sheet_5_2015.pdf.
5. *E-Vehicle Safety - Pyro Switch as High Voltage Circuit Breaker & Bypass*. **Sturk, David, o.a.** Gothenburg : 24 ESV Conference, 2015. 15-0163.
6. **Autoliv**. Battery Disconnect Switch PSS-1. *pyroswitch.com*. [Online] Autoliv. [Cited: March 17, 2016.] http://www.pyroswitch.com/fileadmin/user_upload/Pyroswitch/PSS-1_Technical_Data_Sheet_5_2015.pdf.
7. **Panasonic**. EP Relays. *EP Relays Download*. [Online] [Cited: Nov 10, 2015.] https://www3.panasonic.biz/ac/e_download/control/relay/interception/catalog/mech_eng_ep.pdf?f_cd=300022.

Authors



David Sturk has a Master's degree in Chemical Science and Engineering with focus on Electrochemistry. He is currently employed by Autoliv Development AB as Autoliv's global research specialist on Safety and Risk Analysis on automotive HV batteries and he has been managing this research within Autoliv since 2011.



Per Gustafsson has a Master's degree in Automotive Engineering. He is employed as a research engineer by Autoliv Development AB since 2013 where he currently develops advanced test equipment and methods for vehicle safety testing.

Christian Cavell has a Master's degree in Mechanical Science from the University in Munich. He is currently employed as a Global technical Sales Director for special products and is based in Germany. His career at Autoliv started in 1999 and has been in various positions before he took over the sales for special product.

Alf Holgers is a degree in Mechanical Engineering within the Automotive Industry since 1976. He is currently employed by Autoliv Sweden AB as Manager for Special Projects / Business Development and he has been managing this System project within Autoliv since 2013.

Francois Gaudinat has a Master's degree in Electronic Engineering. He is employed by Autoliv NCS in France since 1999. He is part of the Autoliv NCS D&E team and specially design engineer for Pyro-mechanisms

Etienne Dugast has a Master's degree in Electrical Engineering. He is employed by Autoliv NCS in France since 2003. He is part of the Autoliv NCS D&E team and specially design engineer for Pyromechanisms and PSS products development manager.