E-Vehicle Safety – Pyro Switch as High Voltage Circuit Breaker & Bypass

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ABSTRACT

An E-Vehicle (i.e. electrified vehicle such as EV and HEV) is often equipped with a traction battery with voltage of as high as 200 to 600 Volt dc. It is critical that such voltage shall not be put in circuiting contact with any person at any point – workshop, crash or post-crash rescue. NHTSA have defined testing procedures in FMVSS 305 so as to assure that a basic level of safe guard systems shall be utilized by conventional E-Vehicles. The paragraph S5.3 (b) demands that the traction battery shall present an external voltage <60 Volt dc after crash. This is commonly solved with relays and melting fuses which have their Pros and Cons. Relays/contactors have the benefit of being a reversible active component but are limited to operative currents and are prone to switching bounces and they are relatively heavy, large and expensive. A melting fuse is a passive component that can operate at extreme currents but is irreversible and their cutting speed is dependent on the magnitude of the fault-current.

In this paper Autoliv will present a methodology on how to disconnect a faulty battery unit rapidly (in milliseconds) regardless of the magnitude of the fault-current. This methodology can also be used to divide a traction battery down to minor units of <60 Volt dc or even bypass and disconnect a faulty battery module with maintained power electronics in order to retain mobility as well as adding the option of discharge the disconnected module so as to prevent stranded energy.

Autoliv has investigated how to use pyrotechnic switches for disruption of over-currents in a traction system with battery packs of about 300-400 Volt dc. Those tests, aiming at safe disconnection without lasting arcs, included static faulty-current tests and tests simulating an E-Vehicle traveling 50-70 km/h on a horizontal surface. Autoliv's Pyro Safety Switch (PSS) arrangement proved capable to safely disconnect both a complete battery pack (ranging from 300 to 400 Volt dc) and the intended battery module (30-60 Volt dc) in less than 0.5 milliseconds.

INTRODUCTION

While the number of E-Vehicles on our roads is steadily increasing, new safe guard systems are continuously being developed in order to extend their electric range in terms of higher energy density without compromising safety. Safe disconnection of high voltage battery in the event of an error is mandatory and conventionally relays and fuses are used to manage such safety issues. Continuous efforts to reduce component size and weight are challenged by

issues such as arcing and switching bounces as well as unintended division of the electric energy over relays and fuses in case of harmful over-currents. The latter may occur during exposure to high over-currents if relays experience electromagnetic repulsion or bad contacts.
In his article “Hochvolt-Relais von morgen: Sichere Minimalisten” product manager Thomas Merkel of Panasonic Electric Works Europe AG educate the reader on the potential consequences if the interaction between relays and fuses does not work properly. Mr. Merkel offers an illustration to clarify this interaction between relays and fuses in general; hence the lack of definite figures for Current respectively Time in Figure 1. In tests done by Autoliv on fuses the corresponding results to the yellow curve indicate that its delta time to completion of disconnection can vary from tens of milliseconds (at over-currents of several thousands of Amps) to seconds (at lower fault currents).

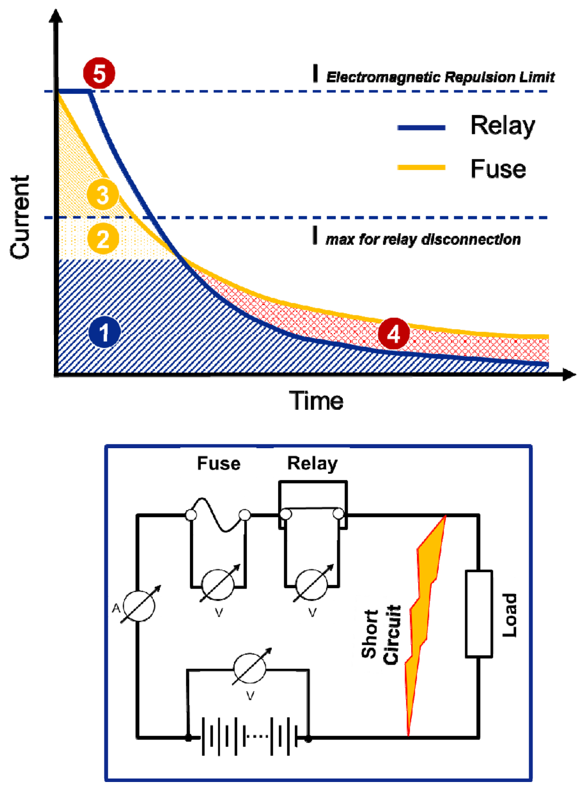

Figure 1. **a) A comparison of characteristics of conventional relays and fuses when circuit disconnect is demanded. b) Simplified representation of the High Voltage circuit. (Merkel, 2014).**

In Figure 1a the blue line represent the maximum current that a relay may carry whereas the yellow line represent the characteristics of a fuse and the condition at which it will disconnect the circuit. The curve of the fuse present the dependence between the magnitude of the over-current and the rate at which the current is reduced when the fuse performs its disconnection. Figure 1b illustrates a simplified representation of a High Voltage circuit related to Figure 1a. The five areas represent the following conditions (Merkel, 2014):

1. This is the area in which a relay can comply with electrical conditions and successfully act upon activation signal.
2. Although relays can operate in this area they are often designed not to disconnect the circuit because the fuse act faster than the relay and thereby protect the relay from potenially harmful exposure to over-currents.
3. Under these conditions the relay must stay closed. Instead, the fuse shall disconnect the circuit as it is faster than a relay at these over-currents. If the relay fail to stay firmly closed and do open, a difference in

potential will be established across the contacts of the relay and the electric energy required for disconnection by the fuse will not be sufficient. A risk of severe damage to electrical components in the circuit will be imminent.

4. In this region, the system is exposed to an unacceptably long-lasting faulty-current. The fault current is not high enough for the fuse to disconnect the circuit before the relay is damaged. The system must rapidly regulate down the power in order to avoid harming the relay.
5. Fault/over-currents above the Electromagnetic Repulsion limit cannot be safely handled by neither fuse nor relay. Electrical components in the circuit will be severely damaged.

Permanent damage to the electrical system and/or its safeguard components is commonly related to overheating that is induced by over-currents and/or arcing. The time to successfully complete a disconnection of a circuit that is experiencing an over-current must be minimized in order to assure that irreversible damage to electrical components in a high voltage system also is minimized.

In contrast to a fuse, the time to achieve a complete disconnection of a circuit by means of a pyrotechnic circuit breaker will not be dependent on the magnitude of the over-current. In general, Autoliv's series of pyrotechnic switches utilizes a miniature guillotine that is propelled by a pyrotechnic charge to achieve the force required to cut through a metallic conductor. The first generation of these PSS devices have been designed for disconnection of 12 Volt batteries in the event of a traffic accident (Autoliv, n.d.) and is widely used by automanufacturers. Later PSS versions address the issue of high voltage disconnection and a methodology for such an action is presented in this article.

In the tests presented in this article, the bypass and disconnection sequence was executed by one PSS that closes a circuit so as to establish the bypass path (i.e. *a PSS which is Normally Open –* ***PSS/NO***), and a second PSS that opens a circuit in order to disconnect the faulty unit (i.e. *a PSS which is Normally Closed –* ***PSS/NC***). In later versions those two types of PSS:s are combined into one unit. By the use of Autoliv's pyrotechnic switches this bypass and disconnection sequence offers an safe high voltage disconnection with minimized risk of arcing and an extraordinary short delta time to complete the disconnection of less than 0.5 ms. The pyrotechnic switch design assure that the delta time of bypass and disconnection is kept to a minimum. This is of most importance since it will provide that the heat generated by a fault current and its harmful effects on electrical components are also put at a minimum.

METHOD

The fundamental idea is to "redirect" the main current so as to bypass the "faulty battery unit(s)" before it is to be disconnected. At that point an extreme over-current will develop through the faulty battery unit and therefore rapid disconnection is of vital importance. Moreover, the load applied need to take into account the range of inductance that is experienced by an E-Vehicle traction system. Preparatory tests (conducted at inductance levels within a range from 0 to 154 μH) proved that when performing a direct cut off to a traction system or sub-units thereof, the higher the inductance is, the greater the propensity is of developing lasting arcs across the gap between the formerly connected conductors. Hence, the key tests (i.e. to measure the performance of the bypass and disconnection methodology) were those with the inductance above 100 μH.

The bypass of the faulty unit is the key of solving the issue with the risk of harmful arcing when cutting off an inductive circuit. A simplified explanation for this is that the circuit with inductive current is reluctant to change. This reluctance causes a harmful arc to develop between two formerly connected conductors at the moment of disconnection. In contrast to the type of "soft" arc that appear anytime when a circuit with no inductance (i.e. a capacitive circuit) is disconnected, an arc under influence of inductance will not be easily extinguished. By first establishing the bypass path, the influence on the faulty unit by the inductance from the electric traction system will be greatly reduced. Thereafter, a rapid disconnection of the faulty unit can be achieved with minimum risk for harmful arcing.

This PSS arrangement was tested in two major setups – Complete High Voltage Disconnection and Partial High Voltage Disconnection. In the former test series, the tests were performed on a complete battery pack with test voltage ranging from 300 Volt dc up to 400 Volt dc where the arrangement replaced a Main Fuse. The latter test series were conducted on the same battery pack but the arrangement acted as a pack-internal bypass and disconnection device that allow a "faulty battery module" to be selectively disconnected while retaining operative conditions for the remaining traction system.

Complete High Voltage Disconnection

The diagram and photographs in Figure 2 present the test setup and the key equipment. In order to substitute a Main Fuse the PSS arrangement, i.e. a bypass switch (PSS/NO) and disconnection switch (PSS/NC), was located outside the battery pack. The intention with this test was to expose this "main fuse substitute" to an extreme condition of 5000 Amp of short circuit current carrying an inductance of 154 µH. A coil was used as static load and all power was supplied by the battery pack after a contactor (i.e. an ASEA EG315 that normally operate for steady three-phase current up to 690 Volt ac and present a very low resistance) had established the short circuit across the coil. In order to assure that the circuit carried 154 µH of inductance the short circuit was allowed to prolong for about 20 ms before the PSS/NO and PSS/NC arrangement was activated (i.e. time 0 ms). The bypass and disconnection sequence was performed in less than 0.5 ms. An additional 20 ms of data was acquired in order to visualize the relaxation of the system after the short circuit had been eliminated.

Three shunts (60 mV @ 400 Amp) measured currents as experienced by the battery pack (I_{Batt} Battery Current), by the bypass circuit (I_{BP} Bypass Current), and through the load (I_L Load Current). All data was acquired by use of a data acquisition unit with a sampling rate of 100 kHz.

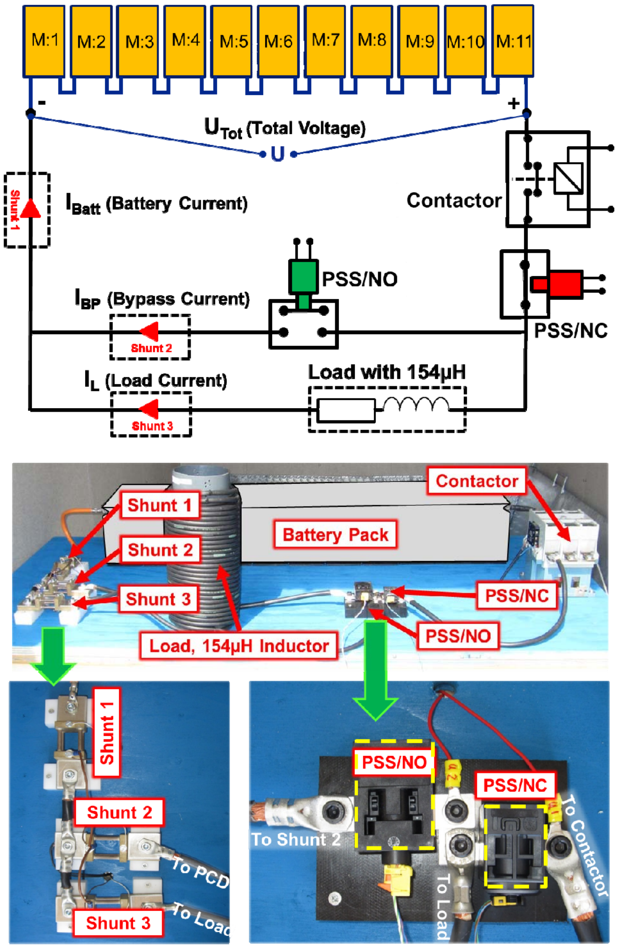

Figure 2. **Complete HV disconnection. Diagram on test setup, and picture of the physical test setup.**

Partial High Voltage Disconnection

In Figure 3 a diagram is presented where the PSS arrangement has been mounted inside the battery pack in order to allow the removal of a "faulty battery module" while retaining the main current flow through the neighboring battery modules. A Resistor-Inductor-Capacitor (i.e. RLC) load that provided a load representative for an electric car driving at steady state of 50-70 km/h on a horizontal surface regulated the main current to 25 Amp. The inductance of the system was 108 µH, which is a result of a capacitive impedance of 0.19 Ohm @300 Hz, inductive impedance of 3.4 Ohm, and a resistance of 4.5 Ohm of the RLC load.

The RLC load included a current converter with six silicon-controlled rectifiers (SCR) in bridge feeding the power from the complete battery power pack back to the national power grid. This power electronics had also a capacitor bank on the DC side to simulate the commutation capacitance in the inverter. Between the power grid and the current converter a three phase coil was located to simulate the induction in an automotive traction machine. This three phase coil also ensured that a smooth current was fed to the grid (dI/dt).

The instruments used to observe the wave forms were two Fluke® oscilloscopes of model 199C respectively 99B. Both of these were triggered by a step response, i.e. when a large change in voltage and current were evident in the circuit.

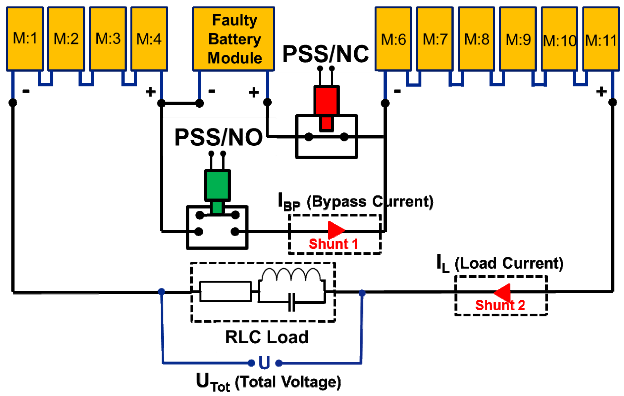

Figure 3. **Partial HV disconnection. Diagram on test setup, and picture of the physical test setup.**

RESULTS

In both test series – i.e. Complete HV Disconnection and Partial HV Disconnection – a battery pack (ranging from 300-400 Volt dc) was used together with a load that was designed to simulate an E-Vehicle electric traction system. Test results showed that breaking the high voltage circuit or isolating a faulty battery subunit, by the use of the PSS arrangement, was successfully achieved without harmful arcing or electrical fluctuations of a magnitude that may damage the surrounding electronics. As can be seen in Figure 4 and Figure 5, this action was performed in less than 0.5 ms and only minor current spikes (i.e. the integral of such a spike represent little electrical energy) and momentarily voltage variations were seen in the traction system. After a test the total battery voltage showed a reduction corresponding to the unit disconnected.

Complete High Voltage Disconnection

At the start of the Complete High Voltage Disconnection test the contactor was closed to create a hard short circuit across the poles of the battery pack. The inductance of the system (i.e. 154 µH) delayed the balancing current conditions, which are presented in Figure 3a (between approximately -10 ms to 0 ms), i.e. the plateau for *Battery Current*, *Load Current* and Total Voltage. Meanwhile the *Bypass Current* is zero since the bypass circuit is not yet connected. See Figure 4a.

Starting at the time of the connection of the bypass circuit (i.e. at 0 ms) and prolonging for 0.5 ms (i.e. throughout the bypass/disconnect delta time) the *Battery Current* experience an even higher extreme current than before, while the *Load Current* only experience very short current spikes at the point in time of disconnection (i.e. at 0.5 ms). See Figure 4b.

After the disconnection of the battery pack the inductive circuit relaxed. This is seen in Figure 4a as the *Bypass Current* (negative direction) and *Load Current* (positive direction) decreased.

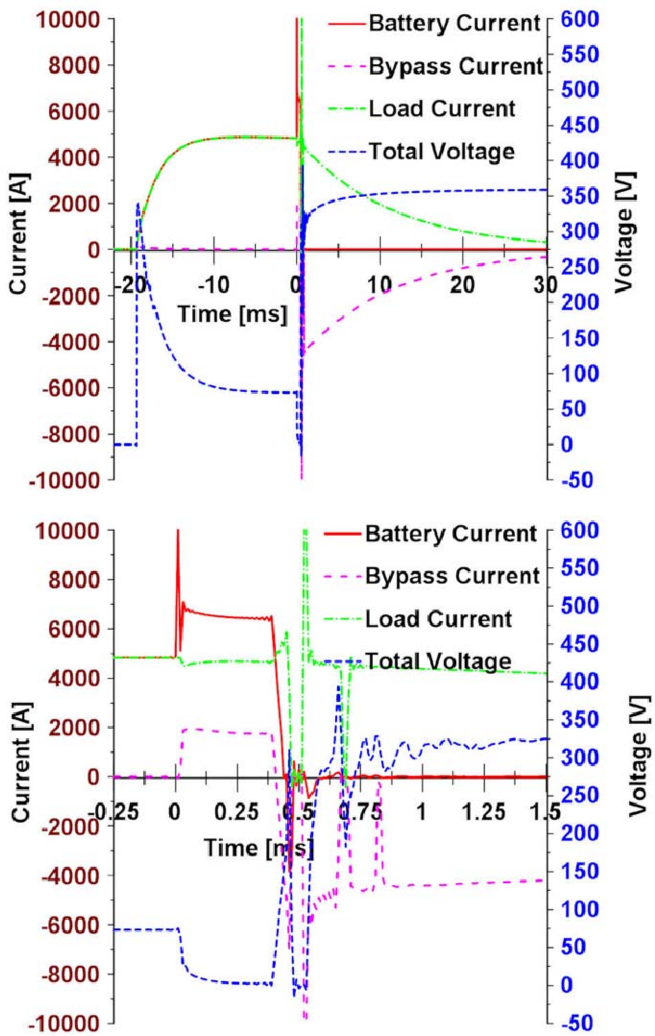

*Figure 4.***Complete HV disconnection. a) Current flow and voltage change during test (range -20 to 30 ms). b) Current flow at time of disconnection (range -0.25 to 1.5 ms).**

Partial High Voltage Disconnection

The delta time for the process of active bypass and disconnection in the Partial HV Disconnection test series was about 0.35 ms. At the time of the activation of the bypass circuit (time 0 ms) a very rapid negative current spike was seen in the main circuit (see Figure 5a), while the battery module to be disconnected experienced an extreme short circuit that rushed to a peak of at above 3000 Amp just before the action of disconnection (see Figure 5b). At the time of disconnection the Load Current experienced one rapid positive spike followed by one rapid negative spike, while the short circuit current across the Bypass path was sharply terminated.

After the completed process of active bypass and disconnection in the Partial HV Disconnection test series the battery pack offered a total voltage equivalent to the original voltage minus the disconnected battery module (see Figure 5a)

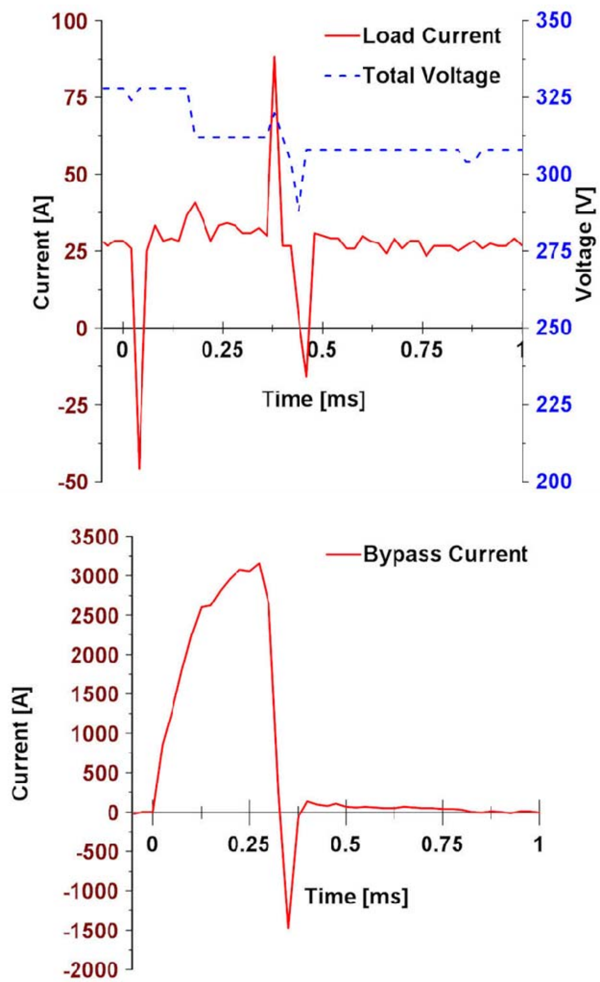

Figure 5. **Partial HV disconnection. a) Main current flow and total voltage change across the bypass and disconnect sequence. b) Short circuit current flow through the bypass path and the faulty module.**

DISCUSSION

The tests series presented in this report were performed on battery packs of ranging from 300 to 400 Volt dc and the disconnected unit was either the complete battery pack or a constituent battery module of the pack. The risk of generating a severe arc when cutting off a complete battery pack of 300-400 Volt dc or disconnecting subunits of such a battery pack, is greatly reduced by the presented methodology. However, this methodology demands a very short delta time between the connection of the bypass circuit and the disconnection of the battery unit. This short delta time is vital in order that the extreme short circuit, which instantaneously develops across the battery unit to be disconnected through the bypass circuit, shall not generate heat or other phenomena that are harmful to the battery system.

Autoliv achieved the required short delta time by using pyrotechnic switches (i.e. the PSS/NO and PSS/NC) which are available in Autoliv's product portfolio. A later version of PSS offers a single unit with those two functionalities combined. Furthermore, in order to deal with the risk of stranded energy of a disconnected battery unit an additional PSS/NO functionality can be incorporated in order to engage a Drain Unit after the sequence of bypass and disconnection has been completed (see Figure 6).

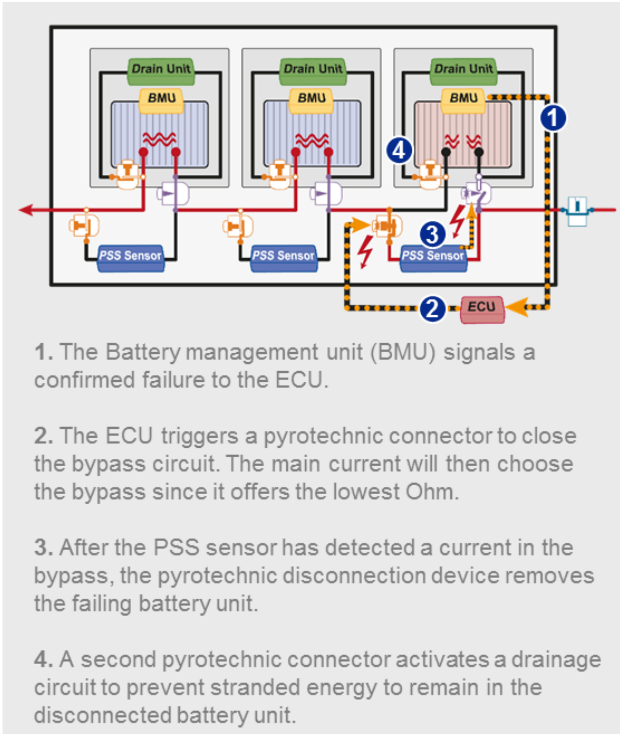

***Figure 6.* Concept sketch with separated PSS/NO and PSS/NC units for clarity. In later PSS version, a single unit of combined functionalities of PSS/NO and PSS/NC offers a multiple connection/disconnection opportunity.**

The Complete HV Disconnection that is achieved with the methodology of Active Bypass & Disconnection can alternatively be achieved with a single ‘one-stage’ pyrotechnic switch that perform a disconnection of the HV battery but no bypass (i.e. a ‘one stage’ PSS/NC). Such a device must be very robustly designed to anticipate the extreme conditions of arcing that evolves within the device when carrying out a disconnection without first diverting the inductive current. This type of device is defined in Autoliv’s product portfolio as PSS/NC High Power. However, it has not been subject to the test series presented in this paper as it is using a different methodology.

CONCLUSIONS

The key feature of the successful disconnection and bypass, seen in the tests presented, is the diversion of the electrical traction system's inductive influence away from a faulty battery pack or battery subunit, right before that unit is disconnected. This diversion of the influence of the inductance on the pyrotechnic circuit breaker prevent the formation of harmful arcs across the divided conductor.

When the bypass has been established it is crucial that the subsequent disconnection of the faulty battery unit (i.e. complete battery pack or a battery subunit) is performed extraordinary quick in order to minimize the effects of the short circuit current that is rushing between the "faulty unit" and the bypass circuit. Autoliv is capable of achieving this by using a pyrotechnic switch sequence with a delta time of less than 0.5 ms between bypass and disconnection. This extraordinary short delta time provides that the otherwise harmful effects of an extreme short circuit remain at a minimum, and therefore damage to the battery system as well as potential repair costs can be kept at a minimum.

Complete High Voltage Disconnection

Autoliv's PSS arrangement can offer an alternative to main fuses and, in contrast to a conventional fuse; it will perform a clean cut-off of the conductor at a speed that is independent of the magnitude of the fault current.

Partial High Voltage Disconnection

Autoliv's PSS arrangement can offer an alternative to relays/contactors when reversibility is less important than speed, physical weight and size as well as cost and the ability to act properly beyond current levels during the E-Vehicle's operational driving conditions. The risk of switching bounces is eliminated when using Autoliv's pyrotechnic switches.

Furthermore, when a faulty battery sub-unit is bypassed and disconnected properly, a "limp-home" ability can be offered since the battery power electronics are remained unharmed due to the extraordinary short delta time and the minimized effects of inherent current spikes during process of the bypass and disconnection.

General

The setup of Pyro Switches for High Voltage Circuit Breaking & Bypass not only prove to assist in solving the acceptance criteria of the FMVSS 305 for E-Vehicle crashes, but also offers a tool to achieve retained mobility after a faulty battery unit(s) have been disconnected. Additionally, by using the Autoliv's PSS arrangement the faulty battery unit(s) will be isolated from the rest of the traction system and thus will not experience further electric exposures that otherwise may cause more damage to such unit(s). Instead, a discharge unit may be connected in order to release stranded energy in a safe manner.

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