Overcurrent protection and electric arc mitigation
in
800Vdc circuit of battery electric vehicles

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ABSTRACT: This paper shows the new approach for protection of electric energy storage batteries in order to prevent heavy damage in case of sever electrical fault, e.g. direct short circuit on the battery. Existing solutions with Pyroswitches with parallel Fuses has disadvantages. Proposed paper presents battery over-current protection system with specially designed Pyroswitch and melting Fuse in parallel. This connection can be triggered externally and it is able to cover all time-current circumstances with specialy designed internal self-trigger system. Additionally, it is able to provide the discharging process for DC-link capacitor.

KEY WORDS: electric vehicle, over-current, protection, battery, high-voltage, electric arc, fire.

1. INTRODUCTION

In last few years, the use of DC voltage and current increased tremendously. It started with the use of Photovoltaic power plants as one of the most important renewable recourses of electric energy. Together with electric energy storage system, especially batteries, they are becoming competitive solution against conservative and centralized electric energy distribution systems.

On the other hand, the use of DC current is even more significant in electric vehicles. The batteries as electric energy storage system are becoming more efficient and the range of battery-operated cars is getting longer. The efficiency of electric cars also depends on the capacity of the batteries, which depends, among others on the value of the DC voltage of the main electric power-train system. Thus, the short-circuit capacity and expected short-circuit current are getting higher and safety aspects in case of an electric arc, provoked by the fault on the battery circuit wiring, are becoming more and more important. This paper will propose a very competitive solution for over-current protection in a main High-Voltage DC circuit between battery and powertrain. We speakabot High-Voltage DC system when there is a rated voltage of qt least 300Vdc and up to 1.000Vdc.

The over-current solution is based on specialy designed Pyro-switch, combined with a melting fuse. The triggering solution is based on the use of standard passive components such as Reed-relays and Thermo-sensors with normaly open contacts. Additional function, such as, discharging the DC-link capacitor, helps to prevent futher possible arc with fire and possible touch of danger high-voltage and consequentely electrocution of persons.

2. SAFETY ISSUES

2.1. In case of car crash

This paper would like to emphasize some safety issues in battery electric vehicle, which uses HV battery storage system. It is obviously more than possible that in case of crash of an electric vehicle a fault on the main wiring, e.g. plus and minus cable between the battery and powertrain, can occur. That means direct short circuit of the battery system and high current will appear which will cause electric arc on the spot of the damaged cables. Fig.1 below shoves the photo of such event, described in (1).

Fig.1

In the report of the fire fighters it is clearly seen, that the fire appeared several times after it was already extinguished. The main message from the same report was that the main action to stop the fire in electric vehicle is to provide total disconnection of the battery from the powertrain as quick as possible.

3. EXISTING SOLUTIONS

3.1. Use of melting fuses

The melting fuses are historically recognized as a perfect over-current protection. Yet, it is also well known, that a fuse breaks the current according to time-current characteristics. The modern electric battery storage systems require more than that. They require also opening the circuit at any current condition, usually by using DC contactors, which are often at higher DC voltages and DC currents prone to contact welding. Some other solutions has been proposed in the past, such as “Triggered Fuse” (2),(3), where inside of the fuse there is short-circuit connection, imposed through the third wire into the fuse via voltage dependent resistor. Fig.2 below shows the shematic diagram of battery circuit, protected by triggered battery fuse.

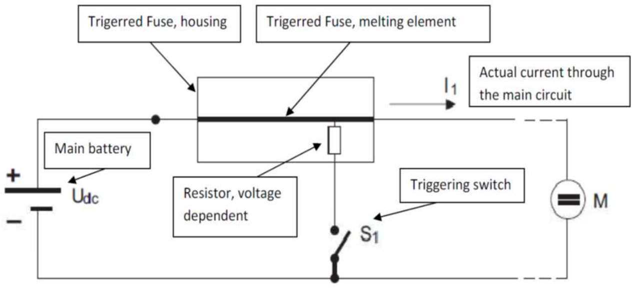


Fig.2

The main disadvantage of such solution is in fact, that the whole concept is based on standard melting fuse, which is sometimes unreliable at high number cycling loads with heavy current profiles.

3.2. Use of Pyroswitch and Fuse

The Pyroswitch is known solution and it is based on piston, driven by gases exposed from chemical filling above the piston. The chemical filling is triggered by electrical impulse. When triggered, the piston cuts the copper conductor and thus cuts the electric current.

Recently, there is some more work done on the parallel connection of Pyroswitch and a DC Fuse, published in (4) and (5). Both sources are dealing with Pyro technology used in combination with melting fuses in order to combine the advantages of Pyro technology on one side and Fuse technology on the other side. In source (5), we can see the parallel connection of Pyroswitch P1 and Fuse F1, as shown on Fig3. The combination is called “PyroFuse”.

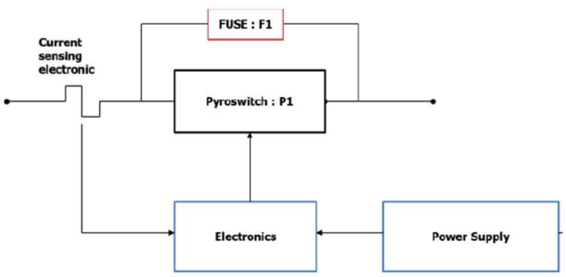


Fig.3

This solution has at least two disadvantages. Fistly, when overcurrent occurs and the level of this faulty overcurrent is just above the rated current of the fuse F1, than is the operating time of the Fuse F1 much longer than it should be in case of severe crash of electric vehicle. Secondly, the solution is rather complex because of separate current sensor and electronic circuit for current measurement and evaluation with separate power supply.

4. NEW SOLUTIONS

New solution in over-current protection in HVDC circuit of electric vehicle is based on special design of PyroSwitch with 3 contacts and not only two like the standard Pyro-switch. Such pyro-switch is combined with a fuse and the whole combination we call it "Triggy-Fuse". This is the first part of the solution.

4.1. "Triggy Fuse"

On the figures Fig.4a and Fig.4b we can see the basic solution with 3-contact Pyro-switch. Before the ignition, as we see on the fig 4a, the contact points Nr.1 and Nr.2 are connected and the main current path is closed and ready to conduct main part of the load current.

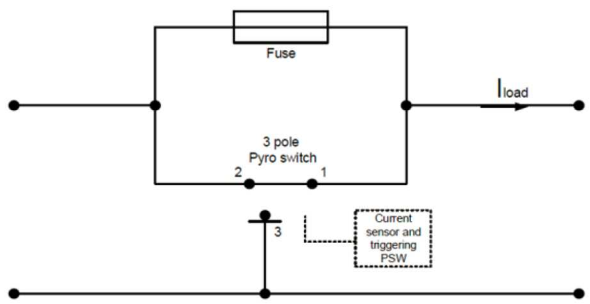


Fig.4a

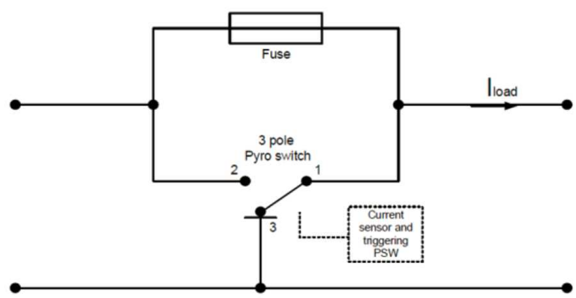


Fig.4b

The ignition impuls comes from current sensor or battery management system. After the ignition, the contact Nr.1 and Nr.3 are closed and thus contact Nr.3 is directly connected with opposite pole of the battery.

4.1.1. How does "TriggyFuse" works?

The current sensing device according to the measurement result sends the triggering impulse to the Pyroswitch, which starts to operate, and physically breaks the copper busbar between point 2 and point 1, as it is shown on the Fig.5

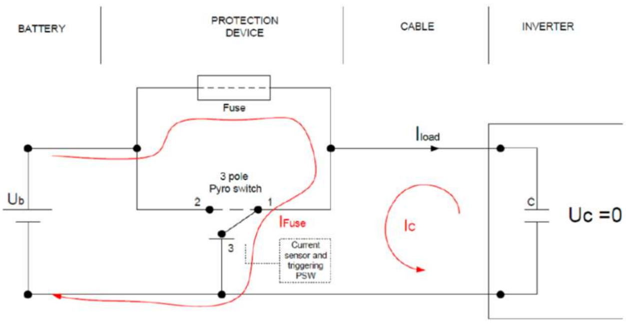


Fig.5

An arc occurs and remains until the moving part of the busbar hits the point 3 and provides the connection between the Point1 and Point2 und thus the short-circuit conditions for the Fuse. Under short-circuit current the Fuse operates immediately and safely breaks the main HVDC circuit independently from the value of actual fault current.

Additionally, this proposed solution gives the conditions for discharging the capacitor in the DC-link of the invertor. This is important safety action after e.g. the car crash, where all sources of electric energy (battery pack, DC-link capacitor) has to be safely disconnected from the rest of the vehicle instantly after the dangerous event.

4.2. Advanced solution in form of a "Self-Triggy-Fuse"

The goal of this solution is, as follows:

-to achieve complete operation without additional electronics,

-to incorporate over-current sensor inside of protection device,

-external triggering has to be possible,

The proposal for solution is shown on the next Fig.6.

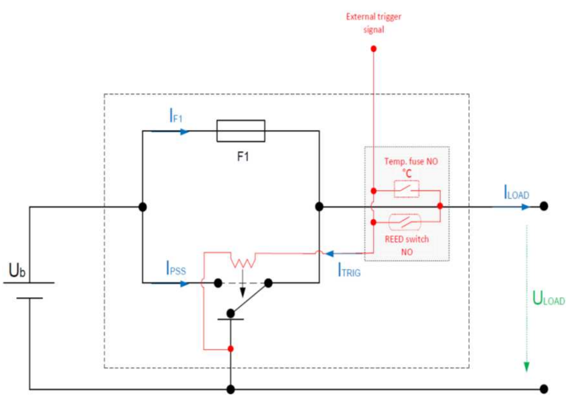


Fig.6

On the Fig.6. we see the self triggering solution with two devices, namely the Reed Relay NO (Normaly Open), and Thermal Fuse NO. Next Fig7 gives more exact explanation about the principle of operation of self triggering.

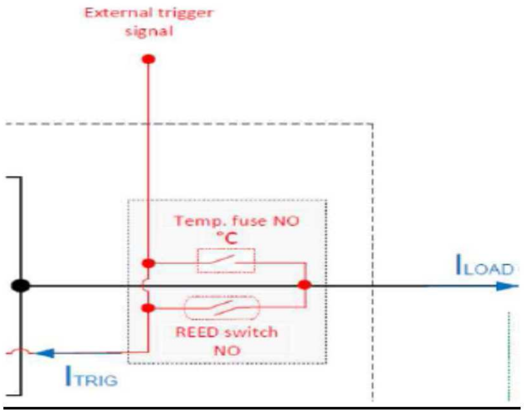


Fig.7

Fig7 gives us more precise explanation of, how self-overcurrent detection works. Thermal Fuse NO is in thermal contact with the outgoing conductive terminal. In case of an overcurrent, the temperature will rise and under specified thermal conditions, the Thermal fuse will react and close the ignition circuit in Pyro-switch to start the operation.

Reed-Switch NO is in a magnetic connection with the outgoing terminal conductor. It is sensitive to the high short-circuit currents. When such high current appears, the Reed switch closes the ignition circuit and Pyro-switch starts the operation.

Thermal Fuse NO is in thermal contact with the outgoing conductive terminal.

How to provide adaptable TIME-CURRENT characteristic in overload area?

-To choose the different type of Thermal fuse

-To dimensionally shape the conductor who provides thermal energy for thermal –fuse operation

Reed-Switch NO is in a magnetic connection with the outgoing terminal conductor.

How to provide adaptable TIME-CURRENT characteristic in high-current short-circuit area?

-To choose the different type of Reed-switch,

-To assure the appropriate distance between Reed-switch and conductor

Below presented Fig. 8. shows the possible Time-Current characteristics in case of "Self-Triggy-Fuse".

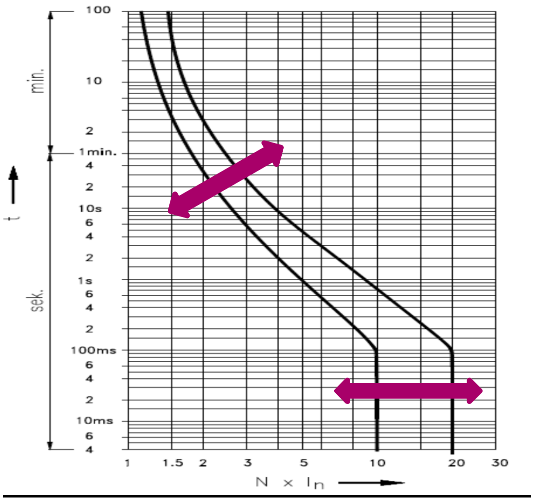


Fig.8

5. TEST RESULTS

First test results has been carried out at two different conditions. DC test generator was set-up on the voltage of 500Vdc and the prospective short-circuit current was 2kA and 15kA.

Next Fig.9 shows the diagram of all electrical values at prospective short-circuit current of 2kA.

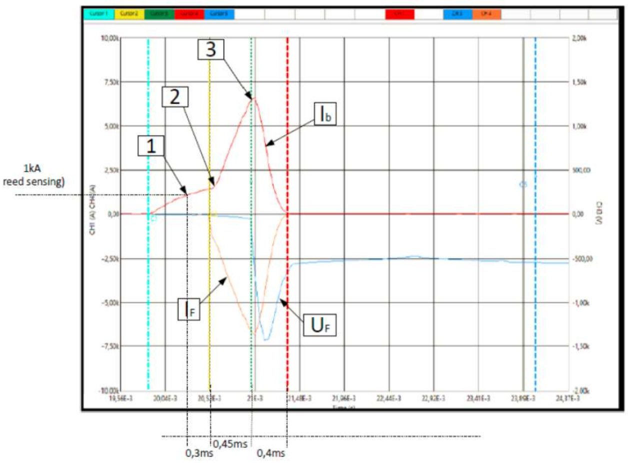
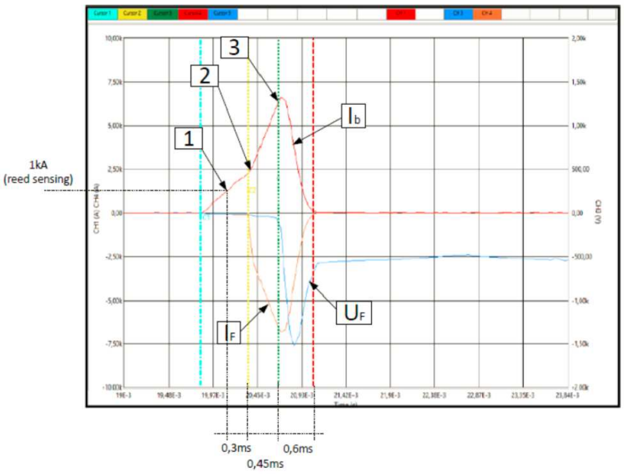


Fig.9

As self triggering unit was used Reed Switch. His distance and position from main current path was set-up to the level of 1kA. Inductivity of the test circuit was low, between 20 µH and 60µH. The operation is divided into three phases.

In 1st. phase the Reed relay at 1kA of actual current, because of his magnetic field, closes the ingintion circuit. Both, Reed relay and Pyro switch reacts in a time of 0,3miliseconds. When the 3rd contact of the Pyroswitch is closed, than the scort-circuit conditions for the fuse are fullfiled, the current is commutated to the fuse and the 2nd phase starts. This is actualy the melting phase of the fuse, which after 0,45 miliseconds ends in 3rd phase, the arcing phase. The duration of arcing phase is 0,4 miliseconds. Total clearing time is thus les than 1,5 miliseconds.

Second test was carried out at the value of prospective short-cisrcuit current of 15kA. Next Fig.10 shows the electrical diagram of all electrical values.



At the first glance, the picture is very similar to those on Fig.9. In fact, the main diference is in steepness of the current ramp from the zero value up to the moment when the magnetic filed around the main conductor reaches the preset value. In both cases this value was set to 1kA. After ignition of Pyroswitch and closing the 3rd contact to opposite pole, the short-circuit conditions are dependent on the electrical conditions in the circuit between the battery and TriggyFuse, while the rest of the circuit after the TriggyFuse is short-circuited and has no influence on the Fuse behavior. Therefore the prearcing and arcing phase of the Fuse are in both cases rather similar, because the short-cisrcuit capability of the DC source was in both cases the same.

In reality we will face different short-circuit conditions of the batteries because of their size, energy density, state of charge and other conditions. Nevertheless, it is known from different sources that the short-circuit capability or better to say, prospective short-circuit current of the battery storage sistems in an electric vehicle could reach even up to 30kA. This value is even mor possible in case of the battery systems with the voltage 800Vdc and more.

3. CONCLUSION

The proposed paper gives several important conclusions: The current breaking time of the device is not dependant from the actual value of the fault current and it depends only from the signal from current sensor and/or from other safety systems in electric vehicle. The device has all advantages given from both, Pyro and Fuse technologies. High safety standards are considered fullfiled and the occurrence of an electric arc and fire is diminished to the lowest possible value. On the other hand, very low operating power loss, high breaking capacity, high operating durability and low product weight and costs are important values for EV manufacturers.

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