10 kA switch with MOSFET in avalanche for Lithium-ion battery short-circuit tests

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Abstract

CEA is a technological research center dedicated to nuclear and renewable energies. One department is dedicated to Lithium-ion batteries and fuel cells systems for transportation. Safety is one of the major issue for Lithium-ion batteries and this activity uses abuse test platform for research actions. This presentation focusses on the development of a specific high current switch to short-circuit lithium-ion accumulators or modules and to open the circuit after a 0.2 to 1s duration. The ON resistance is sub-milliohm, the energy to dissipate at turn-off is some tens of Joule because of the stray inductance and the high level of current. This realization use hundred MOSFETs in parallel in avalanche mode to dissipate the stray inductance energy. A second part of the paper presents an avalanche test schematic, a low cost handmade high voltage probe and some first results for avalanche safety area for different technologies of MOSFET.

1 Realization of a 10 kA 60 V switch for Lithium-ion battery short circuit tests

In CEA, in the abuse tests platforms, short-circuit of accumulator, modules or Lithium-ion battery pack is one of the standard abusive tests. With electromechanical parts a low resistance short-circuit switch is possible to switch ON the short circuit but it can be open only after full discharge of the tested device.

For specific characterization and research tests, it is necessary to switch ON the short circuit and to open the circuit after a specified duration between 0.2 and 1 s.

Depending of the parasitic resistance of the Lithium-ion accumulator or module, the level of current is some kilo Amps.

Specifications of the equipment are:

- 60 V maximum voltage for the tested component (accumulator or module),
- 3 kA nominal current, 10 kA maximum current,
- < 1 milliohm ON resistance
- 0.2 to 1 s duration,
- 1.5 m cable length between tested devices and the switch.

The two main difficulties of the application are:

- The very low ON resistance to be negligible compared to the accumulator internal resistance,
- The high level of energy stored in the cables to dissipate at switch off.

The technological choices of the development of our realization are:

- association of small MOSFET in TO220 package in parallel,
- a design adapted to balance the current between the MOSFETs,
- the dissipation of all the parasitic energy of the cables in the MOSFETs in parallel in avalanche mode, without active clamping or external clamping,
- a fuse is in series with each MOSFET to open the circuit in case of the MOSFET failure.

Avalanche mode is the clamping of the voltage by the component due to the maximum electric field limit in the semiconductor. The component clamps the voltage, and the external circuit limits the current.

This phenomena is used in “Zener” diode when the voltage is upper than 6V. A “Zener” diode with a specified voltage higher than 6V works in avalanche mode.

The Zener effect is a low voltage phenomenon, mainly lower than 6V. This clamping effect acts with a soft transition with leakage current under the clamping voltage.
For higher voltage, in a “Zener diode” the clamping is due to avalanche effect with a good transition between none conducting and clamping voltage in avalanche mode, and low leakage current under the clamping voltage
For 5 or 6 Volts voltage, both phenomenon coexist in the “Zener” diode. The advantage is a low temperature coefficient due to compensation of the opposite temperature coefficients of the two effects.

Power avalanche diodes are used for clamping voltage or transient voltage limitation. Different commercial references exists like Transil® for example. The maximum voltage of theses diodes is 200V. Upper voltages exist but with chips in series in the same component.

In the 90’s, for a nuclear research application, high voltage switches were designed with MOSFETs and diodes in avalanche mode. These components were not specified to be used in avalanche but some references were tested and proved a good behavior in avalanche mode [1]. Some realization are still used after twenty years. At PCIM, in 2020, another paper presents this point [2].
These research works indicates that the good avalanche behavior is linked with the conception of the components. One supplier’s reference is qualified by avalanche test, and individual test of each component is not necessary.
Another key point is that the avalanche limitation is maximum current level. The criteria for safety use is avalanche current and not energy as specified by some suppliers. Energy has only a thermal effect as switching losses, with maximum temperature to limit and cycle thermal fatigue.

Now some MOSFETs have some avalanche specifications. For example, the IPP023N10N5 is a 120A MOSFET with a specification for 100A avalanche current and 979mJ of energy for single pulse for this level of current. Some application notes are focus on avalanche current and not only on energy [3].

Nevertheless, avalanche is still considered as dangerous for components, and especially for components in parallel because of the risk of unbalancing of avalanche currents between the components.

For the switch realization, the avalanche was studied for three MOSFETs in parallel, to prove the current balancing efficiency between the MOSFET in parallel.

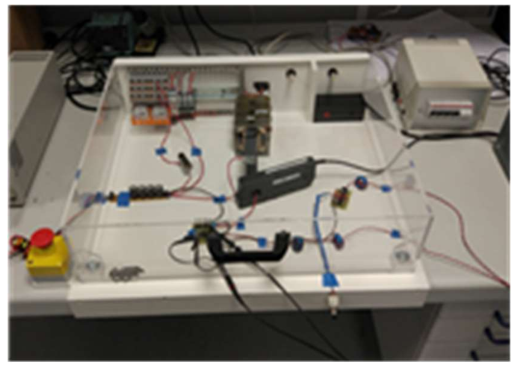


Fig. 1: Test of three MOSFETs in parallel

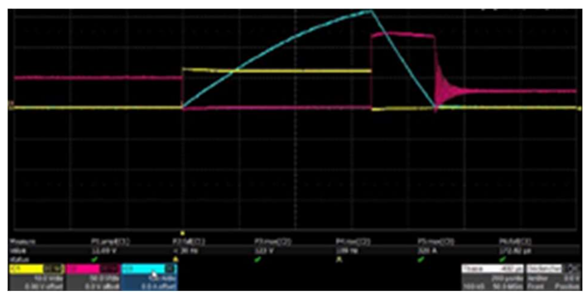


Fig. 2: Avalanche of three MOSFETs in parallel

After the validation with three MOSFETs, a 2kA PCB is designed with 20 MOSFETs in parallel associated with two drivers to provide the total gate current.

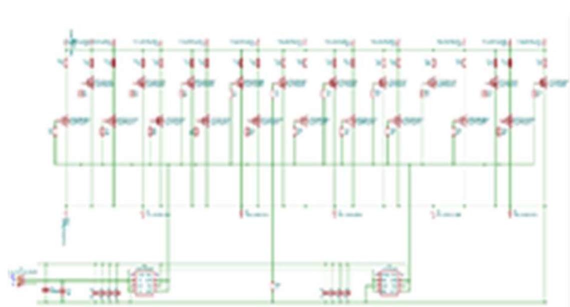


Fig. 3: Power stage and driver for 20 MOSFETs

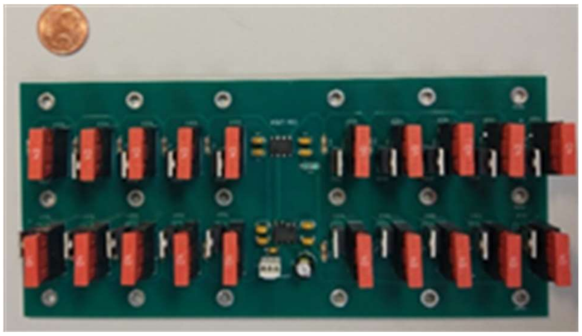


Fig. 4: Twenty MOSFETs PCB

For safety reasons, first tests of the switch uses an electrolytic capacitive bank and not real Lithium-ion accumulators or modules.
The global switch is an association of 100 MOSFETs on five PCB in parallel. Copper busbar provides a low resistance and balances the MOSFET currents.

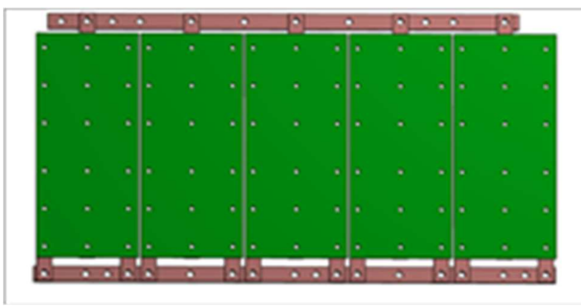


Fig. 5: PCB in parallel top view

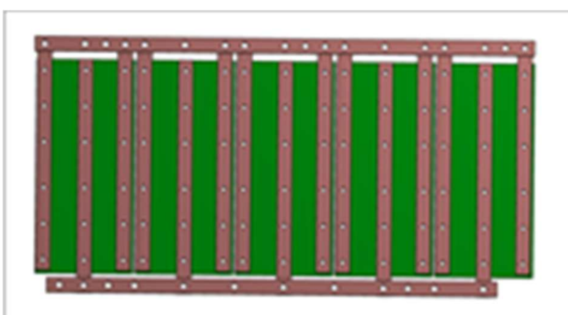


Fig. 6: PCB in parallel bottom view

For current measurement during some hundreds of millisecond, the cascade of a current transformer clamp and Hall Effect one is used. This solution is validated at 500A level by comparison with another probe.

Fig. 7: Current measurement qualification

The final test on the capacitive bank is a maximum current of 10kA delivered by the capacitive bank on the voltage of 55V. The energy dissipated in the hundred MOSFETs in parallel is 48.8J.

The performances of the switch design for Lithium-ion accumulators and modules is conform to specifications. The global resistance of the entire current loop with all the wiring is 600 micro ohm.
The energy stored in the cable is dissipated during avalanche mode in the MOSFETs in parallel with a good balancing.

As describe, for laboratory test, an electrochemical capacitor bank is used to provide the 10 kA current. After this laboratory test, the switch was tested in the abuse test platform on a Lithium-ion module. The current level was 6 kA. Because of higher wire length between module and switch for safety reason in case of fire, the level of current must be reduce to limit the stored energy.

2 Avalanche tests, measurement and probe

For the past two last decades, power MOSFET performances increases continuously on various aspects such as withstand voltage, switching times, Rds_{ON} or internal parasitic capacitances.
The technical progress are in term of semiconductor processing, as new engraving technologies, and the use of new materials such as silicon carbide.
Although each technical advance brings its improvements on certain aspects, what about the avalanche phase?

How a designer can determine, at equivalent datasheet, if a component is able to manage the avalanche?
Finally, which test methods use to judge accurately the observed phenomenon?

Through this part, we are going to see how make a silicon MOSFET transistor benchmark with low prototyping means. Most particularly, the realization and the bandwidth qualification of a handmade 5kΩ oscilloscope probe, which allows performing kilovolts measurements and low-rise time, with low cost and good performances compared to classics oscilloscope probes.
In a second part, we will also deal with an analysis of three different technology of power MOSFET during avalanche phase.

For the purposes of our analysis, we need a prototyping platform that allow us to manage the parameters in term of current and dissipated energy during the avalanche phase. In fact, the aim of the test is to reproduce avalanche phenomenon during opening the current on an inductive load. For this, the use of handmade air inductors of different values is used. The schema of the prototyping benchmark is simple and do not requires specific materials.

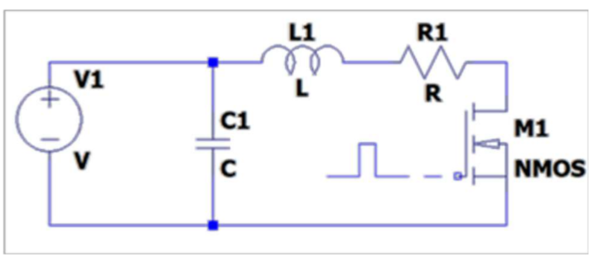


Fig. 8: Benchmark schematic

In the 2000', the avalanche characterization [4] in CEA uses specific avalanche test benches based on high voltage power supply, a resistor and a high voltage switch. This test bench provides constant current pulses for a duration from 200 ns to 2 µs.

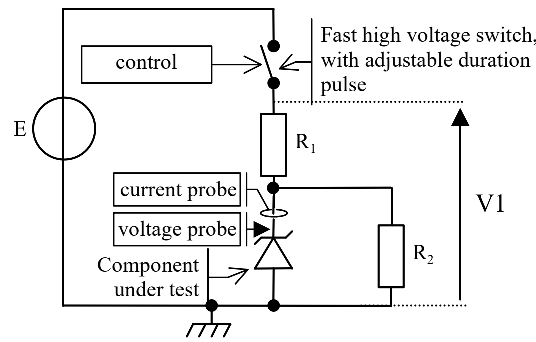


Fig. 9: Benchmark diagram for rectangular avalanche current shape

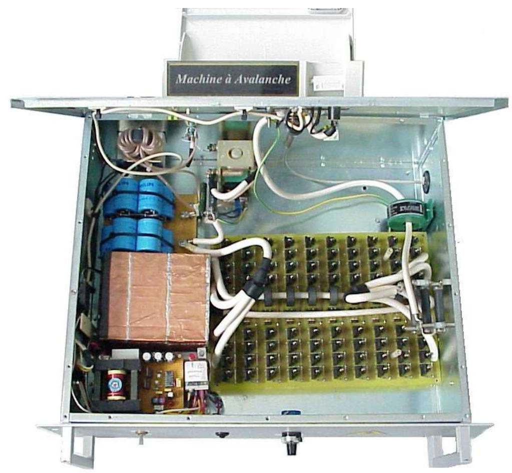


Fig. 10: Avalanche machine with the high voltage switch

With this test bench, the research work proves than some MOSFET of some suppliers have a good behavior in avalanche mode, and so avalanche mode can be used in a design, for example for high voltage switches [1].
For avalanche, energy is not the good criterion. The limiting physic parameter is the avalanche current. Test of components of the same reference have the same level of maximum avalanche current for 200 ns and 2 µs avalanche duration. Energy is ten times higher. It is not the good parameter.
As the good parameter is the avalanche current level and not energy, the shape of the current has no impact, so a very simple test bench as opening the current of an air inductor as Fig. 8 is adapted.

MOSFET suppliers for avalanche MOSFET specification use this diagram. The power supply voltage is 50V for example. This voltage value is interesting because a safe low voltage laboratory power supply can be used. For the human protection, the dangerous zone is limited to the drain of the MOSFET and the connected components. Another advantage of this voltage is the possibility to use a high frequency low impedance probe for voltage measurement.

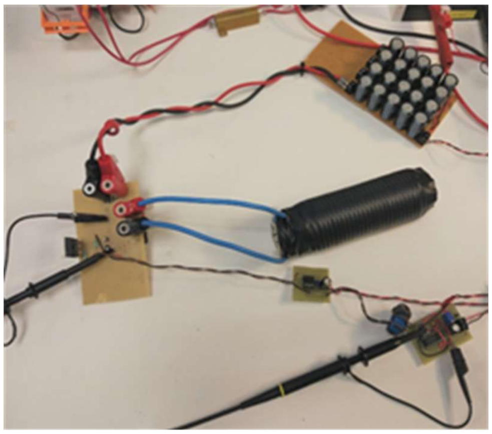


Fig.11: Benchmark realization

On Fig.11, an electrolytic capacitor bank provides the current. Depending of the choose pulse duration, one or more air inductor are used to supply the current to the MOSFET.

Regarding measurement tools, typical high frequency oscilloscope probes are adapted for voltages under 500 V. Above 500 V, voltage probe are specific ones and offers lower bandwidth.

Low impedance handmade voltage probe are a known solution in pulse power application, mainly for high voltage, or for EMC tests. The impedance of the probe is 5 kohm for example. An additional capacitor can cut the continuous or the low frequency voltage level.

The 5 kohm probe is a divider by 100 between a 4950 ohm resistor in series with a adapted 50 ohm cable and a 50 ohm charge on the oscilloscope. Because of the low impedance, and the transmission at the impedance of 50 ohm, a bandwidth of some 100 MHz is possible.

In order to make such probe, it is essential to pay attention to electromagnetic compatibility aspects. Use coaxial cable with a good shielding recovery without useless length; minimize the distance between two resistors while maintaining sufficient insulation distances. Finally, make a precision measurement of your probe including an external 50Ω adapter.

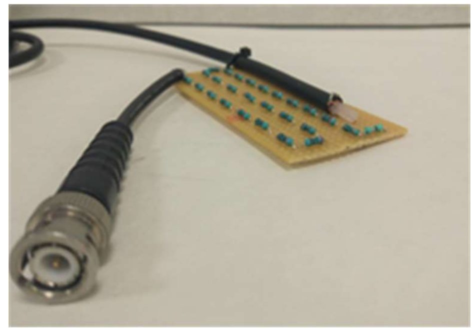


Fig.12: Handmade 5kΩ probe

To qualify the frequency bandwidth of the probe and to optimize the design, a spectrum analyzer is a good tool. Because of the low impedance and the 50 Ohms output adaptation, the probe can be tested between the internal calibration oscillator and the input of the spectrum analyzer. As we can see on the picture above, the bandwidth of the probe is about 200 MHz.

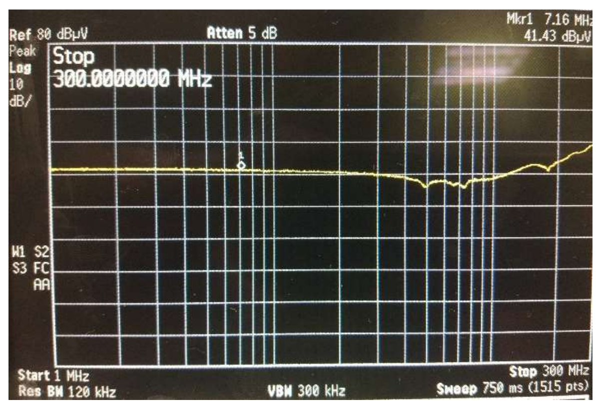


Fig.13: Bandwidth of the 5kΩ probe

With optimization of resistors value, distances between components, and length of the wiring, higher frequency bandwidth are accessible.

3 Benchmark result: comparison of different MOSFET technologies

There are various technologies for the internal conception of silicon transistors. Standard etching usually uses planar engraving, while manufacturers are innovating and offering

different types of vertical etching. Lately, the reliability of SiC transistors also makes it a fully-fledged player on the market.
But what are the performance in avalanche of these three types of component? What is the maximum avalanche current compared to the safe operating area of these three types of component?
We have compared three references of different manufacturers:
- Device (1) is a low voltage transistor use in the 10kA switch (Vds: 100V, Id: 120A)
- Device (2) is a vertical etching transistor (CoolMOS, Vds: 650V, Id: 20.7A)
- Device (3) is a silicon carbide transistor (Vds: 900V, Id: 36A)

The result of these tests are the following:

- As shown on the figure 14, the device N°1 (low voltage MOSFET) has excellent avalanche behavior.

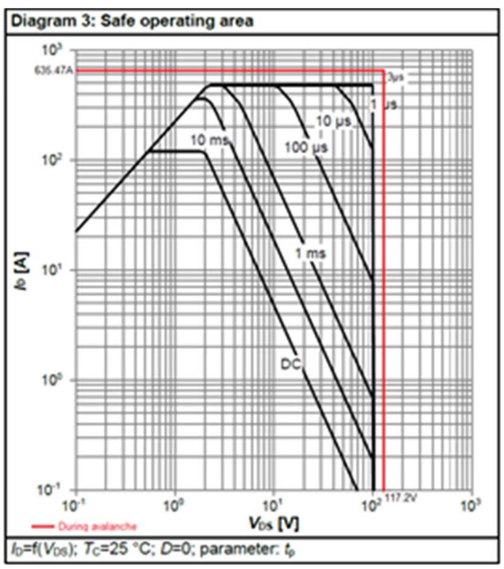


Fig.14: Device n°1 safe operating area during avalanche

In addition to its great stability, the maximum avalanche current before breakage is higher than the datasheet specification. The device n°1 is capable of conducting during the avalanche phase a current of 630A, more than 1.3 x the maximal specified pulsed current (480A), 5x the nominal current (120A) and 6 x the specified avalanche current (100A).

- In comparison, the device n°2 (vertical engraving type MOSFET - CoolMOS), although avalanche specified, has a much unsafe avalanche behavior. Tests have shown that the device n°2 has instability during the avalanche phase and break easily.
The figure 15 shows the maximal current in avalanche mode measured.

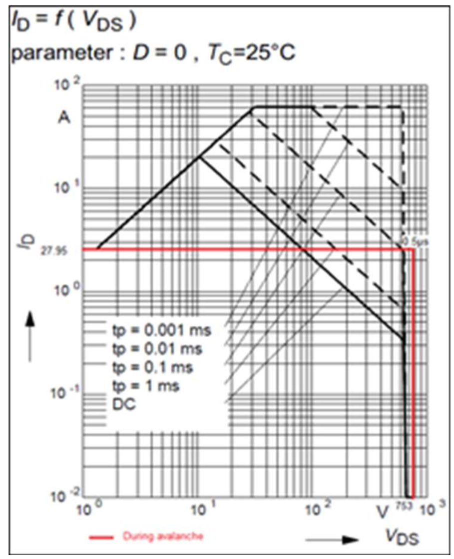


Fig.15: Device n°2 safe operating area during avalanche

The maximum avalanche current for this device is 27 A, compared to its 20.7 A nominal current and 20A specified avalanche current.

Regarding the third component, device n°3 (SiC MOSFET), its avalanche behavior is probably the better in terms of stability for a high voltage component. As shown on the figure 16, the avalanche phase represent a cut-off power about 143kW. The maximum avalanche current (97A) is as high as the specified pulse current (90A), 2.7 times the nominal current (36A). This component is avalanche energy specified for a test current of 22A.

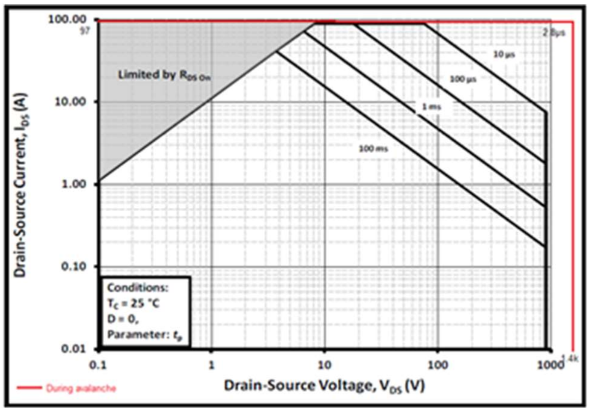
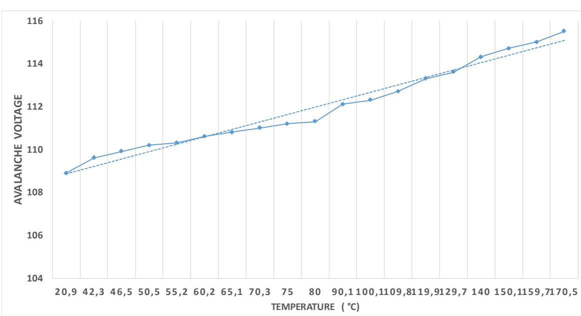


Fig.16: Device n°3 safe operating area during avalanche

The avalanche voltage depends on the current level and on the temperature. The figure 17 is the dependence of the avalanche voltage to the temperature for the 100V MOSFET (device n°1). The MOSFET is positioned on a controlled heating plate for soldering. The avalanche voltage increases from 0.04 V per °C. The equivalent internal resistance of avalanche is near constant from 50 milliohm at 20°C to 60 milliohm at 150°C. This value is 20 times more important as the Rds_{ON} of the MOSFET.



4 Conclusion

This paper describes a specific high current switch with high wiring inductance energy dissipated in the hundred MOSFET in avalanche mode. This proves the good spreading of the avalanche current between the hundred MOSFET in parallel.

Because of the first key parameter for avalanche is the current and not the energy. Very simple test schematic with opening of the current of an inductor is adapted.
For voltage measurement, we propose a low cost high frequency high voltage probe as well as the associated characterization test with a standard spectrum analyzer for CEM tests.

With our very easy test bench, some the maximum avalanche current of different MOSFET of different technologies is presented and compared with the safe operating area specification.

The 100 V tested MOSFET and the SiC one proves a very good of avalanche current and behavior in avalanche mode without oscillation risk. The 100 V MOSFET maximum avalanche current is 5 times the nominal current. The SiC one is 2.7 times the nominal current.

The model of the avalanche is a clamping diode in series with a resistance. For the 100 V MOSFET the dependence between the clamping voltage and the resistance with temperature is measured. The avalanche voltage coefficient is positive. The resistance value is nearly constant from 25°C to 150°C.
These values are the inputs to model the impact of avalanche voltage dispersion on avalanche currents in the case of MOSFET in parallel.

5 References:

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