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Series Connection of 10 kA Switches with MOSFETs in Avalanche Mode for Short Circuit of Lithium-Ion Batteries Abusive 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. For Lithium-ion batteries, safety is one of the major issues and CEA has abuse tests platforms for the research actions on this subject. In PCIM 2020 a first 10 kA 60 V switch is presented for short circuit tests of Lithium-ion modules. For new tests, higher voltages are necessary. Instead of a new development for twice the voltage, this second version consists in an evolution of the first switch to be adapted for series and/or parallel connections to provide a very versatile solution. For higher voltages, two or more 10 kA switches are used in series and for higher current switches are used in parallel or in matrix. Each switch has hundred MOSFETs in parallel and used voltage clamping by avalanche mode of the MOSFETs.

1 Introduction

During PCIM 2020, we presented the development of an electronic switch for the test of short-circuit of Lithium-ion accumulators, modules or batteries with a maximum voltage of 60 V and a maximum short-circuit current of 10 000 A [1]. This switch, based on hundred MOSFETs in parallel, is designed to create a short-circuit of the device under test (DUT) for shorter times (from 0.2 s to 1 s) than previous mechanicals short circuit tests benches. The main issue to do this is to dissipate the energy of the inductance of the wiring for this level of current. In order to dissipate the energy contained in the wirings inductances when opening the circuit, the switch uses the MOSFETs in avalanche mode, safely thanks to a few simple design rules.

One of the most important things regarding the using of the avalanche mode is the choice of the right technology of MOSFETs. The major criteria is not avalanche maximum energy, but maximum avalanche current [2]. In PCIM 2020, we give some results about the comparison of several MOSFET technologies during avalanche, compare the maximum avalanche current to nominal current, describe how to do tests to evaluate the components easily, and propose a low cost low impedance high frequency voltage probe for voltage measurement.

The switch proves that avalanche is possible with MOSFET in parallel, and the characterization we do allows us to know the clamping voltage, the dynamic series resistance and temperature drifts of these parameters of the MOSFETs in avalanche mode. The dynamic series resistance in avalanche mode is very high compared to the R_{dson} of the component. The consequence of this high value is a good balancing of the avalanche current between all the MOSFETs in parallel.

After tests under real conditions on the dedicated abusive Lithium-ion test platform, the principle of this equipment is fully confirmed and it has become an effective tool in the abusive tests process.

After this first realization, a great interest for short circuit tests with semiconductor appears on the CEA abusive test platforms, with new requests and specifications for higher voltages.

2 Strategy of development for higher voltage short circuit switches

In laboratories, fitting to the voltage, current and power requirements for the power supplies and

loads of test benches for the all cases of tests is a well-known problem.

In CEA, for more than ten years we use the association of 200 V - 200 A power supplies in series and in parallel to provide the energy up to 800 V, or up to 800 A depending of the voltages and currents required for the tests.

This type of modular wiring possibilities is easily possible with power supplies and is an actual commercial offer for electrical loads and reversible power supplies.

For power supplies, the association in series needs mainly a zener diode in parallel with the outputs of the power supply to limit the voltage if one or some power supplies are stopped or in defect, and if the load has an energy storage (capacitor, ultracapacitor, battery) which imposes the total voltage

For electronic loads or reversible power supplies, there is a risk of voltage collapse. If one of the element stops the dissipation or reinjection of energy, an overvoltage may occur on this element. The short-circuit failure of this element may create an overvoltage on the outputs of another one. Because of the energy involved, it's not possible to treat the issue of overvoltage with Zener diodes. Additional drive protections between the elements in series are necessary.

The big interest of electronic loads and bidirectional power supplies in series and parallel is the versatility to adapt the global voltage and current to requirements of the application.

To have the same versatile use for abusive short circuit tests of Lithium-ion accumulators, modules and batteries, we choose to modify your initial design to use the 10 kA switches in series and in parallel instead of a new development for each new voltage specification or the development of a very powerful switch adapted for all the needs.

We develop a second version of the switch adapted for matrix connection of switches to form a more efficient assembly. The development approach was to increase performances through serial/parallel connection of switches designed with small, inexpensive off-the-shelf components instead of designing equipment with more expensive and less available components. The use of a multitude of small components in series or

in parallel is an efficient way to reduce stress on components, cost and to increase modularity [3].

3 Preliminary study and design of the electrical architecture

The first step in the development process was to define the possible architecture of the new version of the equipment. To do this, we decided to reuse the power boards of the previous version (shown in Figure 1) in order to reduce development costs and time.

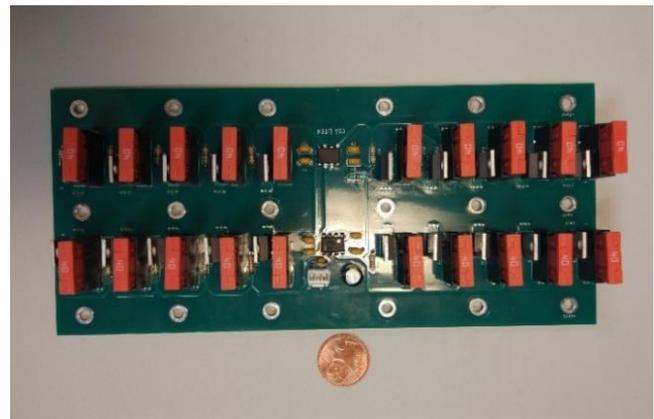


Figure 1: Power card constituted of 20 MOSFETs in parallel with protection fuses

As before, a switch will consist of five power cards in parallel (100 MOSFETs in parallel), i.e. 10 kA maximum short-circuit current under 60 V maximum, and 600 μohm global R_{dson} .

The first objective required by the tests carried out on CEA's abusive test platform is to short-circuit modules of 120 V maximum for currents of 10 kA maximum, for times of up to 5 seconds. In accordance with the work already accomplished [1], it is possible to achieve such performances by serial and parallel connection of existing cards.

It is necessary to adapt the electrical architecture of the version 1 of the switch to make it tolerant to series connection. In this case the main requirements of the application are:

- Manage line and component propagation times to have a sufficient MOSFET switching synchronization
- Design an electrical architecture of the system compatible with series connection: insulated power supply and drivers

- Create a modular system who allow simplified series/parallel connection while being tolerant to wiring/using errors

The technological choices of the development are:

- Make a symmetric wiring for reduce propagation delay
- Optocouplers are used to electrically separate the control from the power part of the switches
- Low capacitance insulated DC/DC converters allow the electrical insulation of each switch from the others
- Logical gate based system protection of the system against wiring errors

When the current circuit opens, the MOSFETs will switch off with voltage clamping and dissipation of the wiring inductance energy by avalanche mode. During this period, it is essential to have homogeneously distribution of the energy contained in the wiring between the MOSFETs in order to limit their stress.

Our previous design presented in 2020 proves the robustness of the design due to:

- the performance in avalanche current of the MOSFET chosen. The IPP023N10N5 is able of conducting during the avalanche phase a current of 630 A, more than 1.3 x the maximal specified pulsed current (480 A), 5x the nominal current (120 A) and 6x the specified avalanche current (100 A).
- the good balancing of avalanche current between MOSFETs in parallel due to the high value of the apparent series resistance

Because of this robustness, we choose to limit the speed of command and the switching time of the switches to avoid CEM issues. In the abusive test platform, the wiring length between monitoring office and switches is some ten meters.

4 Preliminary tests and validation of the concept

One of the first step in the developing process of switches in series is the validation of concept.

In order to validate the fact that the propagation times of the components and lines are not an issue when MOSFETs switch on and off, the realization of a test model on a reduced scale is necessary. For this purpose, we connect two 2kA power cards in series.

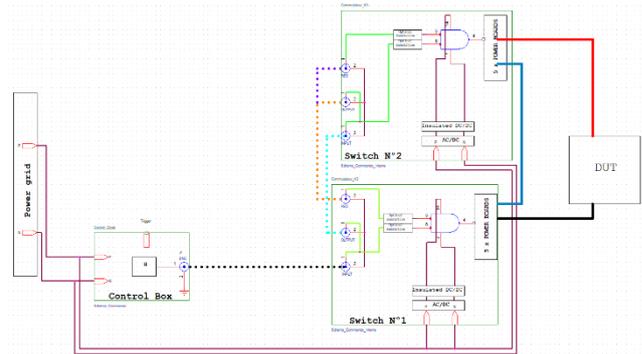


Figure 2: Simplified electric bloc diagram of two 10kA switches in series

For this second version, the evolution of the drive are:

- Internal power supplies are insulated.
- Drives are transmitted by optocouplers.

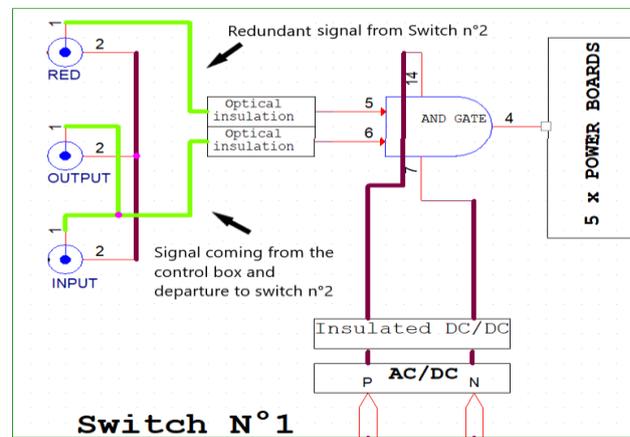


Figure 3: Simplified internal electric bloc diagram of the 10kA switches

- Each switch duplicates the input signal and transmits this duplicated signal to the other switch.
- The AND gate circuit allows the switch-on of the switch only if the two signals are ON. Therefore, the switch-on of the switches are only possible if the two switches inputs are connected correctly.
- The command and the interconnection between the switches are low impedance one's with 50 ohms cables and resistances on the inputs.

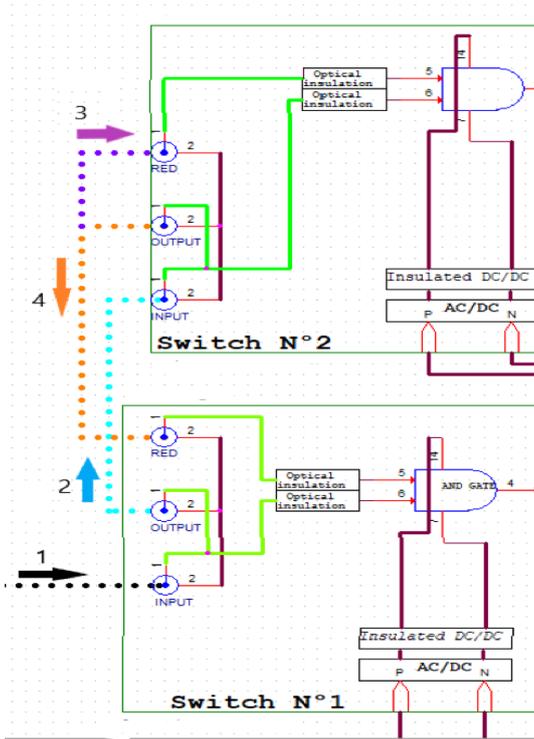


Figure 4: Simplified electric bloc diagram of the drive signal for two 10kA switches in series

The distance between command and switches may be as high as 30 m because of the distance between monitoring office and outdoor test platform. For diagnostics, there are pre-existing 50 ohms cables between them.

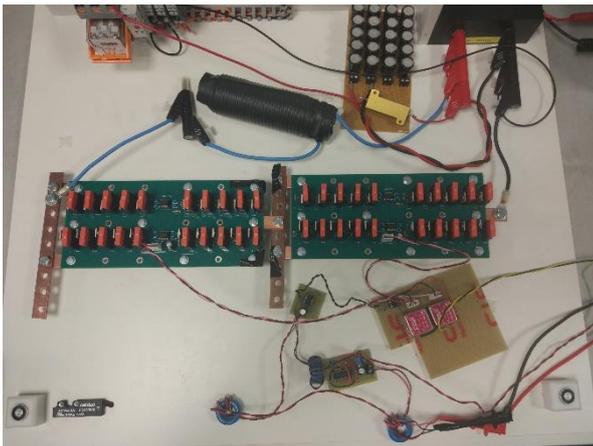


Figure 5: Validation of concept: two power boards in series with insulated power and control short-circuiting a safe capacitive bench

The good synchronization and functioning of the two cards in series are validated in the 2020 summer, without any EMC interferences. For safety reasons, a capacitor bank generates the 2 kA current for this test.

5 10 kA switch adapted for series and matrix connection

For outdoor uses, the switch enclosure provides weather sealing. Coaxial inputs have seals and an additional hood.



Figure 4: Photography of a wired 10 kA switch under test

The optocoupler transmission has a delay of 1.72 μs for switch-on and 2.56 μs for switch off.

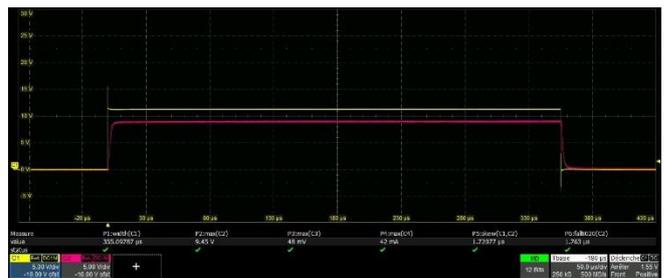


Figure 5: Delay between optocoupler input (yellow) and output (pink)

The two switches are adapted to open the inductive circuit. The global clamping voltage is approximately 220 V.

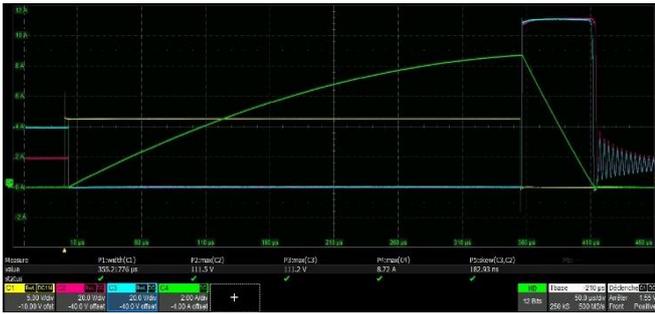


Figure 6: Short-circuit test of two 10 kA switches of a capacitive bank. Yellow -> drive signal; Pink -> bottom switch; Blue -> Top switch; Green -> current

The figure 8 demonstrates the classical scenario of a short-circuit followed by a dissipation of the energy accumulated in the wiring by avalanche effect.

Firstly, when the control signal (in yellow) is received by the boxes, the transistors start to conduct causing the voltage V_{DS} to drop.

Due to the wiring inductance, the current (green) increases slowly until it reaches the value of 8720 A for this test.

When the control signal stops, the two switches in series go into avalanche mode (blue curve => switch 1, pink curve => switch 2). At this moment, they limit the voltage at their terminals to about 112 V each, i.e. 224 V for the series connection.

When the energy is totally dissipated, the transistors clamping by avalanche stops and an oscillation phase between the wiring inductances and the MOSFETs capacitances occurs.

During the tests, we could observe that the avalanche duration was slightly longer (about 1 μ s) on the lowest potential switch. Although the investigations are still in progress, one of the possible hypothesis would be a more important current to be treated by this switch because of the parasitic capacitances present with the ground.

The next steps of the development process and tests of version two of the switch are:

- To increase the size of the capacitor bank to provide 10 kA.
- The voluntary shifting of the control signals on both branches in series. This step will allow to determine the critical delay threshold between the two signals and potentially to define a maximum size of the matrix. This step will be presented in the final paper of PCIM 2021.
- The realization and wiring of the control box.
- The test in real conditions on a sample of a lithium-ion technology module: this step will definitively validate the operation of the assembly.

6 Conclusion

A second version of a 60 V 10 kA short-circuit switch is developed, adapted for series and/or parallel connection to provide a versatile solution for Lithium-ion accumulators, modules and battery short-circuit tests.

The first tests we do are on capacitive test bench up to 8700 A to avoid Lithium-ion batteries risks. After this phase, final tests will be done on real batteries.

7 References:

- [1] D. Chatroux and J. Chauvin, "10kA switch with MOSFET in avalanche for Lithium-ion battery short-circuit test," PCIM2020 Europe Digital Days, Conference Proceedings pp. 1198-1204.
- [2] Power MOSFET Avalanche Design Guidelines, Application Note AN-1005, Vishay Siliconix
- [3] D. Chatroux, Y. Lausenaz, "Small standard components strategy, twenty years later", PCIM Europe 2020, Conference Proceedings 1, pp. 776-780