Low inductance fuses for protection and disconnection in DC networks

Technical session	

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ABSTRACT

Development of renewable energies will be possible because of progress in electrical power converters. But, even if reliability of converters is highly secured, some mis-operations or failures may occur. Generally, these mis-operations and failures lead to a high current short circuit and then, electrical fuses are able to bring an efficient solution to protect equipment and persons.

Unfortunately, fast-acting fuses are components which size depends on rated current (cross section) and voltage (length) they have to cut: higher is the voltage, longer is the fuse. And a longer fuse will increase the inductance of the circuit, and then increases the commutation-time of electronic switches. Engineers are facing the problem of choosing between:

  a) Accept to not protect the equipment
  b) Protect the equipment but reduce its performances
  c) Not develop any converter

Mersen is studying fuses, specifically designed for this kind of converters, both guarantying safety of equipment and keeping the inductance at low values.

Of course, these fuses will not reduce energy consumption by themselves, but they are crucial components for equipment that will reduce energy consumption."

The paper will present the different kinds of faults depending on the source, i.e. internal fault, external fault and up-stream fed fault. It will also describe what will be the specificities needed for a protection device, i.e. fuse. And what is the investigation-plan carried out by Mersen for proposing the right fuse.

KEY WORDS: Inverter, converter, electrical protection, fuse, inductance

Short circuit faults in DC networks

Topologies for electrical equipment are generally organized around a DC bus, fed by one or several sources and supplying power to inverters. In case a semi-conductor in an inverter goes faulty, a short circuit occurs in this inverter fed by the capacitor located ahead of the inverter (so called internal short circuit). Moreover, as the inductances between all the parallel inverters, through the DC bus, are very small, capacitors of these inverters may start to feed the short circuit within a short time (total or external short circuit). Then the fuse in charge of internal protection within the faulty inverter will also have to bear actions from parallel capacitors.
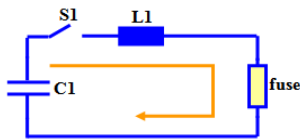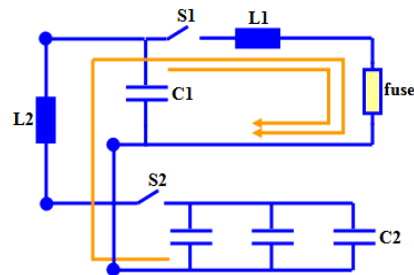

Figure 1: Internal short circuit

Figure 2: Total short circuit

A third case concerns feading by the up-stream side of the bus (up-stream fed short-circuit).
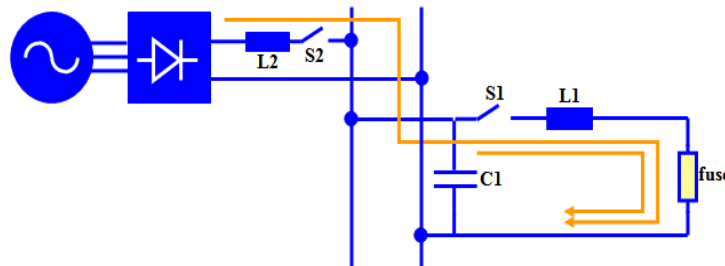

Figure 3: Up-stream fed short circuit

Fuse protection for VSI converters

When the first semi-conductor components came out at the end of the 50's, they were included into converters as simple as diode-bridges. At that time, engineers were confronted with their certain weakness under short-circuit conditions. So they introduced the thermal constraint that semi-conductors must be able to withstand without deterioration:

$$\int I^2.dt$$

On both side of the Atlantic Ocean, companies that would merge years later into MERSEN, developed ultra-fast fuses to stop the current before any damage to the electronic component, i.e. diode or thyristor. Later, during the 80's, new semi-conductors emerged, the most common ones being GTO's and IGBT's. The latter presented the advantage of reducing losses at commutation and on-state voltage and therefore watt-losses. On the other hand, the permitted thermal

constraint of these components was decreased and fuse protection of their junction became difficult.

Nevertheless, even if it is not possible to guarantee full protection of an IGBT under short-circuit, it is absolutely crucial to ensure that its failure will not cause a more dramatic deterioration of the equipment as a whole. Particularly, an explosion of the IGBT-case would damage other components, completely destroy the installation and lead to long downtime, large operating losses, and even more danger to people. Under these conditions, the fuse takes over and ensures excellent protection – providing it is correctly designed and characterized. As early as 1985, MERSEN published a specific method for characterization and selection of fuses for VSI-converters in Technical Leaflet NT SC 120.

The principle of this method is founded on the beside circuit diagram, considering that in case of short-circuit in the downstream leg, and because of the very low inductance l, capacitor C will be discharged very quickly, i.e. with a very high di/dt, MERSEN's engineers defined and calculated specific characteristics for the protection fuse:
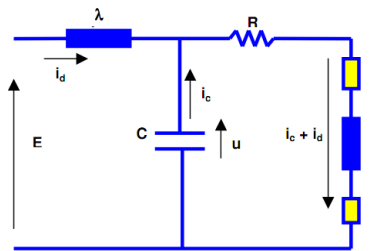

Figure 4: Typical diagram of a VSI-inverter's leg.

- o Upm, the maximum value of Up that the fuse can accept, Up being the voltage across the capacitor at the end of the fuse prearcing-time
- o The pre-arcing I²t

Determination of Upm

Since 2012, IEC-standard 269-4 has introduced the concept of a fuse for VSI applications, i.e. designed for inverters fed by a voltage-controlled source. This standard requires checking the VSI-voltage-rating of these fuses by tests under current I1, in DC conditions, with time constant between 1 and 3 ms (See IEC 269-4, table 106). These conditions required by IEC standard are slightly different from actual conditions in case of fault-current in VSI-inverters. Mainly, in an actual VSI-inverter the value of Up can be much lower than the value E of the DC power supply, whereas in case of operation in DC conditions and low time constant τ, Up is at the level of the DC power supply voltage, including ripple factor[1].
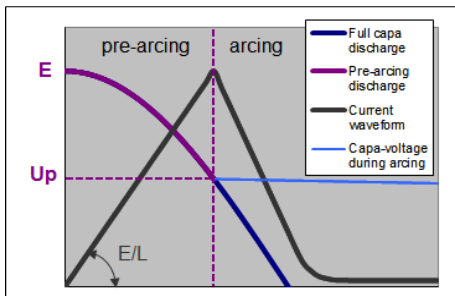

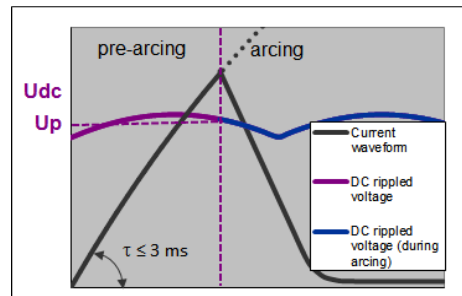**Figure 5: Operation under VSI conditions, i.e. capacitor discharge.**

Figure 6: Operation under DC conditions with τ=L/R

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[1] In order to partly take into account the fact that the given value of the DC-voltage is generally the RMS value of the rippled trace, table 106 of IEC-269-4 requires that the mean value of recovery voltage is in the range 110^{+5}_{-0} % of the rated voltage

Then, considering only the DC power supply voltage can be very pessimistic if prearcing-time is long enough to ensure a high voltage decrease. That leads to choice a higher rated voltage fuse, i.e. geometrically longer than expected and then introducing a high inductance value in the circuit. In order to have a better knowledge, MERSEN developed a specific high di/dt test bench with following performance data:

Table 1 : Characteristics of MERSEN's high di/dt test-bench

Couplings	Capacitances	Available di/dt
2 kV	31.2 mF	4000 A/µs
4 kV	7.8 mF	5000 A/µs

Figure 7: General overview of the high di/dt test bench at MERSEN's Saint-Bonnet de Mure Lab. (France)
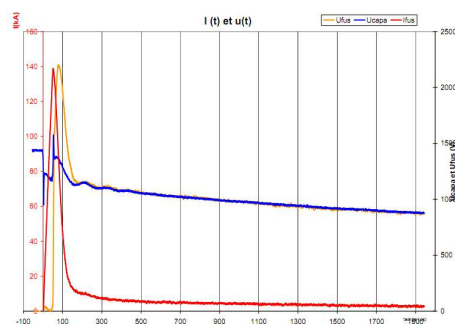

Figure 8: Typical oscillogram of fuse operation under VSI conditions.

Risk of re-ignition – proposal for an additional characteristic Em

It is possible to demonstrate that in case of short-circuit fault within a leg of a VSI-inverter, the capacitor will be re-charged by the upstream source through the inductance λ (see Fig.4.) The more the capacitor is discharged during the short circuit, the more the voltage across it will be high. There is actually a risk of re-ignition of the fuse in operation, depending on many parameters.
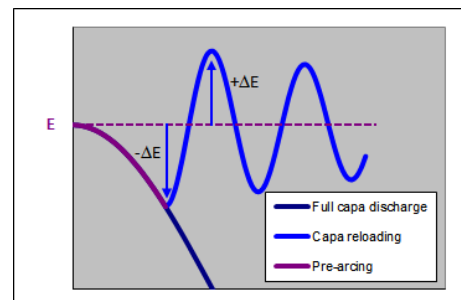

Figure 9: Voltage across the capacitor can increase up to E + ΔE

MERSEN's leaflet NT SC 120 introduced Em, the maximum value of E that the fuse can accept, E being the initial voltage across the capacitor. Some restrictive hypothesis must be respected:

a. Inductance λ of the upstream circuit is large versus the inductance L of the discharge circuit of the capacitor C (λ >> L)
b. Discharge current of C is highly oscillatory
c. Oscillation period T of the discharge current is less than 10 ms
d. Fuse melting occurs after less than T/6, i.e. the voltage at the terminals of the capacitor doesn't go under half of the initial voltage; this is due to the fact that voltage during discharge follows a law in cos ωt and cos ωT/6 = ½.

MERSEN'S research-program

The above hypothesis about inductance λ, pulsation ω and prearcing-time were probably realistic in the past as it is proven by years of experience. They allowed to avoid taking into account the possibilities of re-arcing of the fuse. But, nowadays more and more applications are based on the principle of a DC-bus feeding a number of inverters in parallel. In order to propose solutions for protection against short-circuit with voltage-reapplication, MERSEN's has launched FE2E (Fuse Econom & Ecolog-ically Efficient). FE2E is a collaborative research project, sponsored by BPI-France as FUI after AAP (Call for Project) nr.15, and involving besides MERSEN eight other academic or industrial partners.

At first, MERSEN Electrical Protection has decided to increase the facilities of the test lab at Saint-Bonnet de Mure, in France. Main equipment concerns a new bench consisting of 4 stacks of capacitors. Each one of these stacks can be coupled under 2 and 4 kV. The capacitance of a stack reaches 32 mF under 2 kV and 8 mF under 4 kV. Capacitor stacks can be arranged in parallel, giving up to 126 mF under 2 kV. The very interesting characteristic is that a stack of capacitors can be discharged at controlled time t1 by closing of a switch S1 and others stacks of capacitors can be discharged at controlled time t2=t1+Δt by closing of a switch S2.

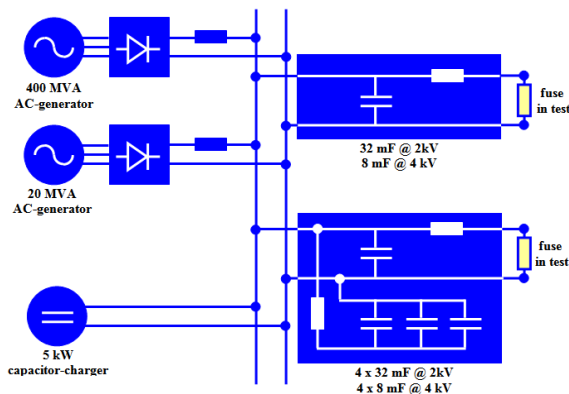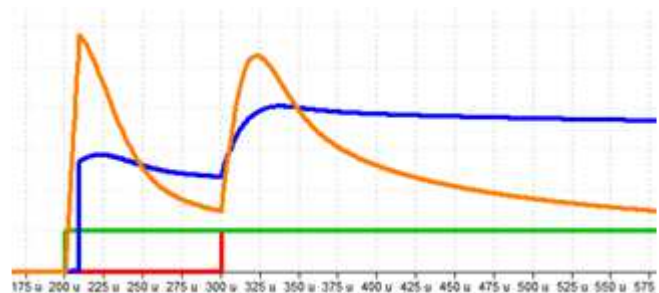**Figure 10: Synopsis of the test facilities at MERSEN - Saint-Bonnet de Mure, in France**.

Figure 11: ■ **State of S1** ■ **State of S2** ■ **Current in the fuse** ■ **Voltage across the fuse**

In addition, MERSEN is also studying the material aspects of the protection by fuse, especially thesis are running about arc electric. The challenge is to understand how the energy of the electrical arc is transmitted to the surrounding medium.
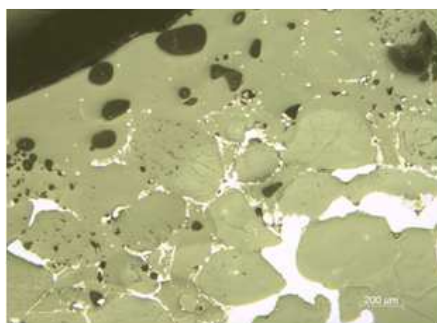

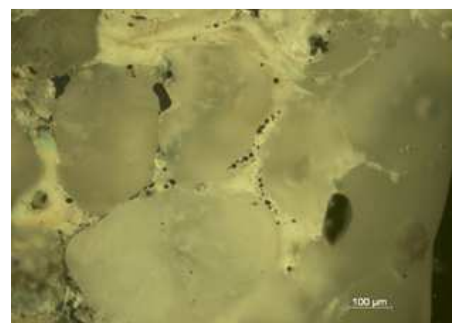**Figure 12: Melted silica grains and re-condensed silver.**

Figure 13: Curls of melted silica pushed by vapor-pressure through not-melted grains.

Also, MERSEN has collaboration with CEDRAT for inductance calculation of fuses, bus-bars and fuses integrated inside bus-bars.
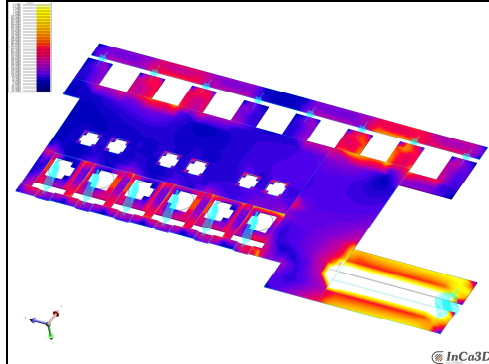

Figure 14: Current distribution in a busbar

InCa3D is a soft-ware developed by CEDRAT in collaboration with G2Elab from Grenoble-INP. It is based on PEEC (Partial Equivalent Element Circuit) – method, in opposition to many soft-wares based on FEM (Finite Element Method). CEDRAT's engineers have implemented a new module for parasitic capacitances calculations. Another challenge is to integrate a coupling with thermal physic, major difficulty being that InCa3D uses PEEC-method with rectangular meshing and thermal solvers refer to FEM with tetrahedral meshing.

Also, calculation of electro-dynamical forces has been run, together with LAEPT at Clermont-Ferrand. These forces should explain decrease of prearcing I^2t of fuses under high di/dt as observed under some test-conditions. Another matter rises concerning the mechanical behavior of silver or copper under high deformation-speed and at high temperature. A specific study is carried out by LAMCOS from INSA-Lyon using Hopkinson's bench.

Conclusion

Since three decades, MERSEN has gained a lot of experience about the protection of inverters. A heavy knowledge is also available about the operation of a fuse, especially concerning the intimacy of arc vs. granular medium and the inductance calculation of conductive elements. Because the energy of a capacitor is much lower than that can deliver a network through a transformer, it is expected that sizes of the fuses will be drastically shrunk, mainly in their length. That will reduce the value of the additional inductance due to the fuse and allow to solve a large quantity of cases of safety. As claims professor Stoke at ICEFA-Conference (International Conference on Electrical Fuses and their Applications) which was hold in Gdansk, in September 2003: "*Modern electric fuses are marvelous devices for protecting life and equipment from potential power of uncontrolled electricity. Since the coming of electricity in the 1870s, they have been in front line for electrical defense. Indeed, it is fair to say that without the virtually fail-safe protection of the electric fuse there would be no modern electrical industry. Electricity would be regarded as far too dangerous for widespread use.*" Once again, that will be confirmed.

Bibliography

MERSEN's technical leaflet NT SC 120.
Alain COULBOIS. *Etude de la transition préarc-arc dans les éléments fusibles.* Thèse pour l'obtention du grade de docteur d'Université. Clermont-Ferrand, 2015.
A.D. STOKES, D. K. SWEETING. *Electric Arcing Burn Hazards.* ICEFA. Gdansk, 2003.
JL. GELET, P. PERBET, K. ALMAKSOUR, P. ANDRE , W. BUSSIERE, S. MEMIAGHE, D. ROCHETTE , E. CLAVEL. *Modelling of electrical fuses by Portunus, InCa3D and a thermal solver.* CEDRAT Flux Users Conference, Chavannes de Bogis, 2010.