

Characterization of fuses for applications under high di/dt's

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Power-electronic converters are very reliable equipment and are widely used in many activities including industries, services and even residential. However, there is a non-negligible risk of failure of a semi-conductor acting to commutate in a leg. In that case, the semi-conductor will short-circuit and all the available source energy will pass through the leg in question. There is then a very high risk of the semi-conductor exploding, with occurrence of an electric arc inside the converter and even outside. During the arc, current is carried by ionized vapors and a huge amount of energy is dissipated. Not only will the converter and its components be affected and even destroyed, but also fragments will be ejected, intensive radiation emitted, toxic gases produced and a pressure wave propagated. All these dangers fly in the face of the safety requirements in the industrial field. Moreover, designers of equipment for the general public – think automotive, railways, aeronautics – will be especially concerned by this issue. For more than fifty years, MERSEN has built up very significant core-knowledge and -business in the design and manufacturing of fuses, and particularly in ultra-fast fuses. Nowadays, MERSEN is making a strong commitment to the protection of VSI. That involves research studies with university labs and private companies as well as investments in new test equipment and modeling tools.

The aim of this paper is to present in more detail the protection of these VSI-converters under high di/dt's.

Fuse protection for VSI converters

When the first semi-conductor components came out, at the end of the 50's, they were built into converters as simple as diode-rectifiers, and 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 sides of the Atlantic Ocean, companies that would merge years later and be the origin of today's 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 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 essential 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-converter in Technical Leaflet SC 120.

It 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 , and based on the here-under restrictive hypothesis:

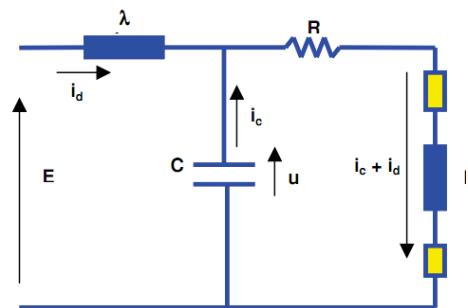


Fig. 1. Typical diagram of a VSI-inverter's leg.

- Inductance λ of the upstream circuit is large versus the inductance L of the discharge circuit of the capacitor C ($\lambda \gg L$)
- Discharge current of C is highly oscillatory
- Oscillation period T of the discharge current is less than 10 ms
- 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 $\cos \omega t$ and $\cos \omega T/6 = 1/2$.

MERSEN's engineers defined and calculated specific characteristics for the protection fuse:

- U_{pm} , the maximum value of U_p that the fuse can accept, U_p being the voltage across the capacitor at the end of the fuse prearcing-time
- E_m , the maximum value of E that the fuse can accept, E_m being the initial voltage across the capacitor
- The pre-arcing I^2t

And also:

- G , a coefficient depending on the reduced section $G = 1000/(I^2tp)^{0,5}$
- A characteristic $K=f(U)$
- A characteristic $U_m=f(U_p)$
- Characteristic lines $t = f(G.di/dt)$ rated according to U_p

Fuse selection procedure

A fuse voltage rating is selected by checking that:

- the value E of the DC power supply is lower than or equal to the Em value given by MERSEN for the fuse;
- the voltage across the capacitor at the end of the fuse prearcing-time is lower than or equal to the Upm value given by MERSEN;
- The pre-arcing time tp is calculated from the characteristic line $t = f(G \cdot di/dt)$ under 0V. G is given for each current rating and di/dt is calculated from $di/dt = E/L$

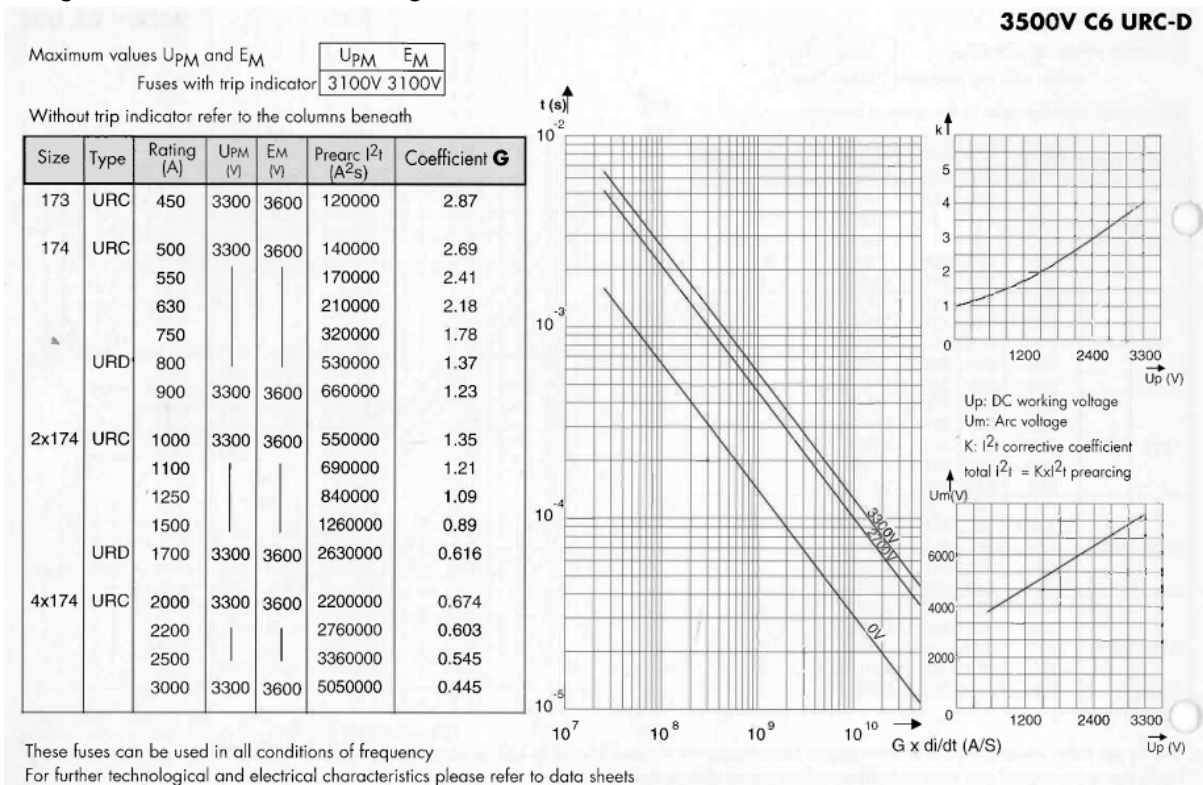


Fig. 2. Data sheet of a MERSEN fuse, with Upm, Em, G and characteristic curves

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 to check 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).

Nevertheless, the breaking capacity tests required by the IEC standard are slightly different from actual operation 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 , U_p is at the level of the DC power supply voltage, including ripple factor¹.

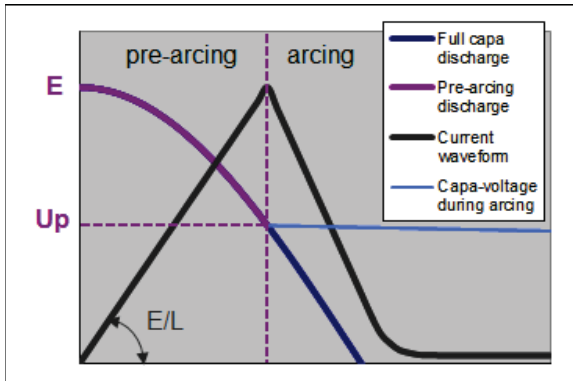


Fig.

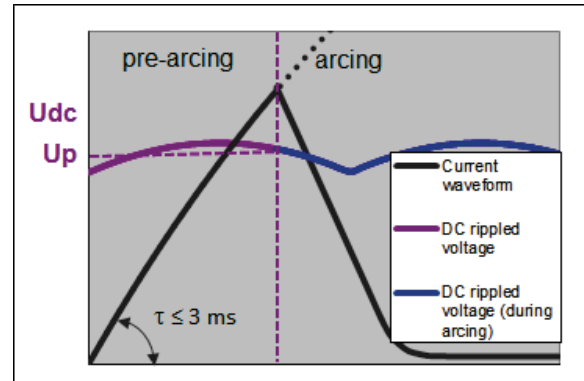


Fig. 4. Operation under DC conditions with $\tau=L/R$

Fig. 3. Operation under VSI conditions: capacitor discharge

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 is why MERSEN proposed the two voltages U_{pm} and E_m .

U_{pm} is defined as recommended by IEC standard 269-4, from DC tests under time constant less than 3 ms and current leading to a melting time lower than 1 ms.

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/ μ s
4 kV	7.8 mF	5000 A/ μ s



Fig. 5. General overview of the high di/dt test bench at Mersen's Saint-Bonnet de Mure lab (France)

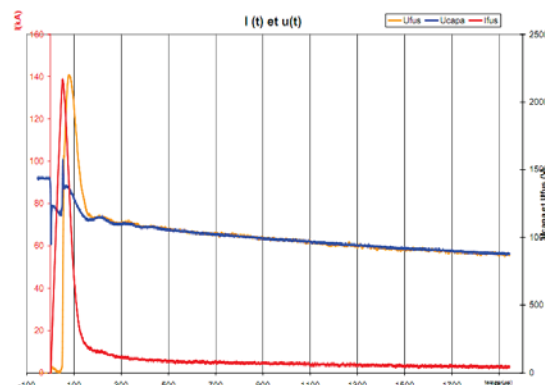


Fig. 6. Typical oscillogram of fuse operation under VSI conditions

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

Determination of E_m

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.1.) The more the capacitor is discharged during the short circuit, the more the voltage across it will be high.

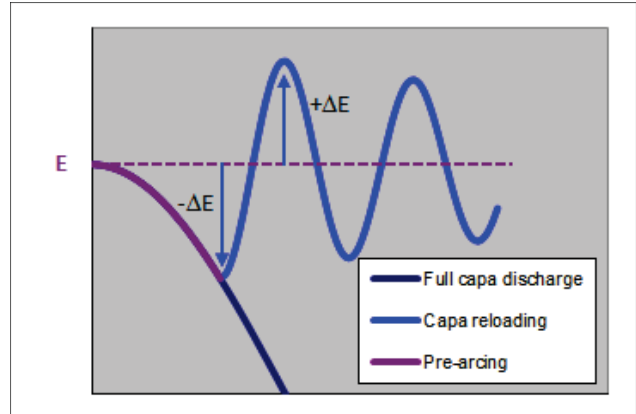


Fig. 7. The voltage across the capacitor can increase up to $E + \Delta E$

In order to define the value of E_m , a first hypothesis is to consider the rated voltage of the fuse under AC conditions. The value has to be expressed as a peak value, i.e. $\sqrt{2}U_N$.

This hypothesis is probably pessimistic because, as shown in Fig. 8., the peak voltage during capacitor recharge is maintained for a time much shorter than it should be under AC conditions.

Another hypothesis should be to consider the RMS value of the voltage across the capacitor during recharge. This case could be not conservative enough because of voltage-peaks overstepping the RMS value.

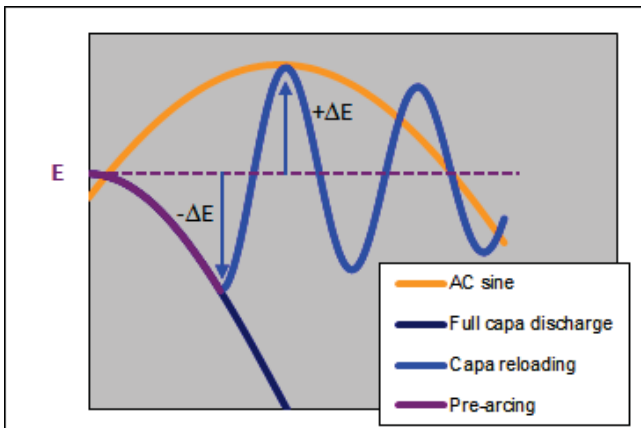


Fig. 8. The first hypothesis is to consider that the peak voltage in AC is "equivalent" to the peak voltage during capacitor-recharge

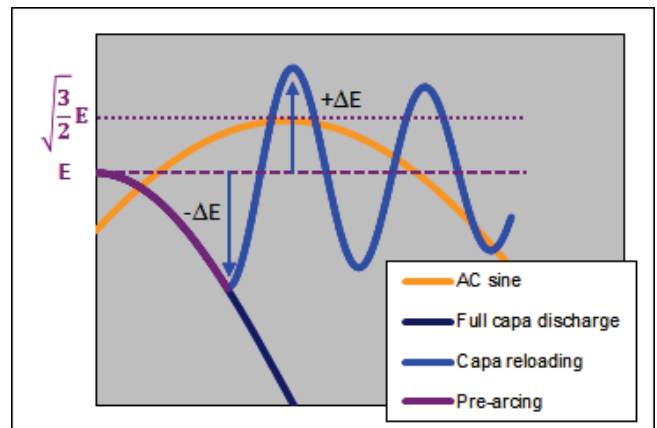


Fig. 9. The second hypothesis is to consider that the peak voltage in AC is "equivalent" to the RMS voltage during capacitor-recharge.

Due to the fact that in Technical Leaflet SC 120 MERSEN limits prearcing-time at less than $T/6$, the voltage across the capacitor doesn't go under the half of the initial voltage ($\Delta E \leq \frac{1}{2}E$) and the maximum voltage in case of capacitor recharge will not exceed $E + \frac{1}{2}E$.

So the first hypothesis leads to

$$E + \frac{1}{2}E = \sqrt{2}U_N(\text{AC}), \text{ i.e. } E = 1.061 U_N(\text{AC})$$

And the second hypothesis to

$$\sqrt{\frac{3}{2}} E = \sqrt{2}U_N(\text{AC}), \text{ i.e. } E = 1.155 U_N(\text{AC})$$

Risk of re-arcing

MERSEN Technical Leaflet SC 120 foresees that inductance λ of the upstream circuit is large versus the inductance L of the discharge-circuit of the capacitor C ($\lambda \gg L$). This should avoid any need to consider the possibilities of re-arcing of the fuse. This is probably realistic as it is proven by years of experience.

Over this restrictive but realistic hypothesis, it is to be considered that nowadays more and more applications are based on the principle of a DC-bus feeding a number of inverters in parallel. Inside these topologies, the inductance ℓ between 2 (or more) inverters is much lower than λ .

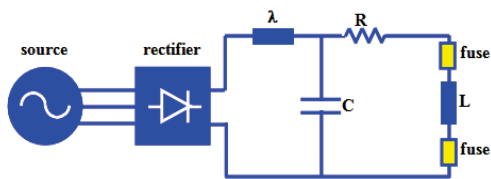


Fig. 10. Risk of re-arcing coming from recharge of the Capacitor C by upstream source through inductance λ

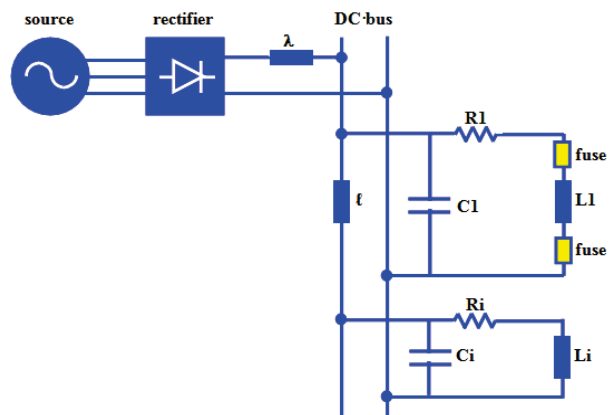


Fig. 11. Risk of re-arcing coming from recharge of capacitor $C1$ by parallel inverters-capacities through inductance ℓ .

Up to now, in this paper, the matter of the protection of VSI from short-circuits has been approached from the electrical point of view. It is also interesting to deal with materials properties and behaviours. In principle, re-arcing will occur when the insulation is not sufficient. And insulation is not sufficient when:

- a) the amount of insulating material is not large enough,
- b) the electrical resistivity of the material is not high enough.

The amount of insulating material will depend on the arc-energy during operation of the fuse. The higher is the energy, the larger will be the amount of melted material around the necks in the fuse-element-neck. And the energy depends directly on the voltage after the pre-arcing-time.

The electrical resistivity of the material will depend on its thermal and electrical activities. The higher is the temperature, the higher will be the electrical conductivity and conversely the lower the

resistivity. And temperature will be directly linked to the energy, which depends on the voltage after pre-arcing-time.

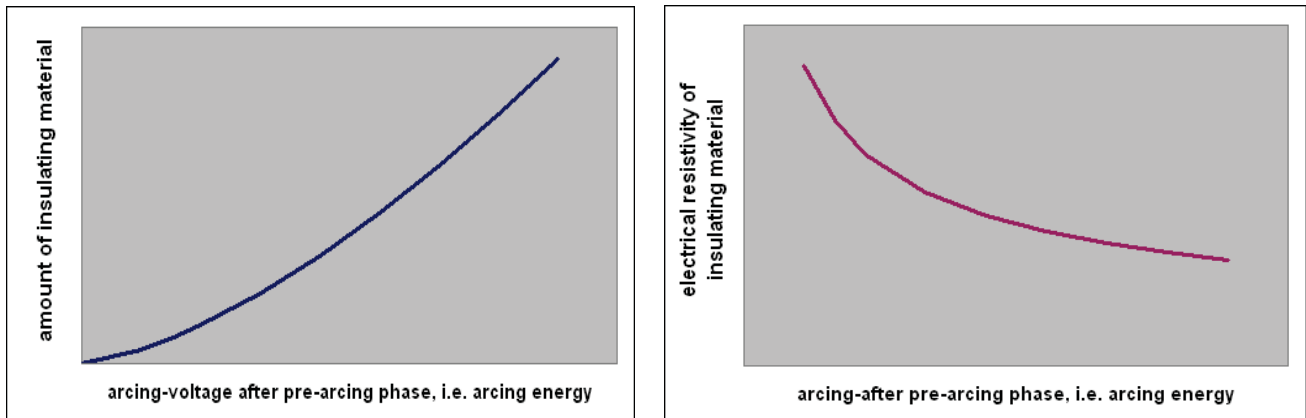


Fig. 12. Amount of insulating material and resistance of this amount vs. arcing energy

In addition, electrical resistivity, as depending on the temperature, will also depend on the time after arcing. If time is sufficient, temperature will be lowered enough to ensure a high resistivity, hence lowering the risk of re-ignition.

Re-arcing when re-applying voltage will depend on the energy brought by the arc and also the time during which arc-energy is dissipated.

Conclusion

Engineers are developing more and more VSI-inverters using IGBT, IGCT, MOSFET, etc. In case of fault, i.e. short circuits, currents with very high di/dt , typically reaching $5 \text{ kA}/\mu\text{s}$ but even more (10 to $20 \text{ kA}/\mu\text{s}$), occur. For many years, MERSEN has proposed a method in order to select the best fuse to use in this kind of equipment. Nevertheless, this method restrains the scope of its application and especially doesn't take into account topologies with multiple inverters plugged on the same DC-bus which would also have to be protected.

In fact, neither manufacturing technologies nor understanding-approach derogate from standards. First investigations show that extrapolation from usual skills is not so easy and the problem has to be re-considered *ab initio*. A more appropriate knowledge of the electrical phenomena occurring during operation under high di/dt is essential for innovating technological solutions. Main questions will relate to short duration arc, pressures and temperature of the gases, and interactions with the surrounding medium. Moreover combining all these physics will need to couple their relative equations within modelling.

Conference: 10th International Conference on Electric Fuses and their Applications

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