# Fuse Operation under DC Conditions

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**Points of interest:**

- The Underwriters Laboratories (UL 248) and the International Electro technical Commission (IEC 60269) describe standard tests conditions for fuses under DC voltage. These are applied to industrial fuses, semi conductor protection fuses and special DC rated fuses as well.
- The curve giving maximum L/R values as a function of the DC working voltage U is an essential characteristic for the selection of fuses in DC applications

## 1. Introduction

The absence of natural voltage zero makes the interruption of DC faults more difficult than the interruption of AC faults as only the fuse arc will force the current to decrease to zero. Moreover when the time constant L/R of a DC circuit is large the interruption of a fault is much more difficult. Another arduous operating condition is the interruption of a low over current.

In trains fed by a DC voltage (metros and railways) there is wide range of L/R values and over current levels. Consequently special DC rated fuses with fully enclosed operation are used in order to ensure people safety and protection of the equipments.

Mersen has developed and designed such fuses for voltages up to 4000 V DC (as required by Italian and Belgian railways), as other fuses would be unsuitable. DC rated fuses must have passed specific tests in order to publish all necessary information on the DC capabilities of the fuse. Specific data are essential in order to safely apply fuses in DC circuits.

However some applications are easier and do not require fuses with a special design for DC interruption. In such cases AC rated fuses can be used providing the fuse manufacturer publishes the DC capabilities of the fuse.

## 2. DC Circuit, Current and Time Constant

When a fault occurs in a DC circuit (*figure 1*) the current rises with an exponential component towards (*figure 2*) the value of the available current (also named prospective current) as follows:

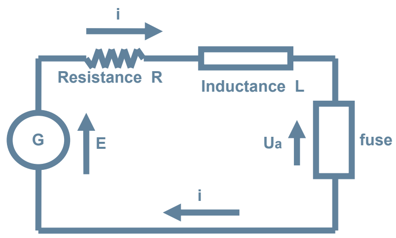


*Figure 1: Fault circuit*

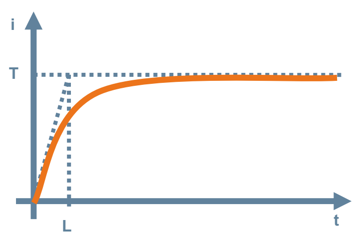


*Figure 2: Fault current*




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$$i = I_A * \left(1 - e^{-\frac{R}{L}t}\right) \qquad I_A = \frac{E}{R}$$

and

$$\tau = \frac{L}{R} = \text{time constant}$$

The equation of the current i shows the L/R influence on the fuse prearcing time (or melting time) since the di/dt at the origin is :

$$\frac{di}{dt} = \frac{E}{L} = \frac{I_A}{\tau}$$

Therefore the larger is L/R, the smaller is the di/dt and longer is the prearcing duration of the fuse for the same value of  (as illustrated by *figures 3 and 4*).

The arcing duration and arcing $I^2t$ depend upon the energy dissipated inside the fuse during this period of time.

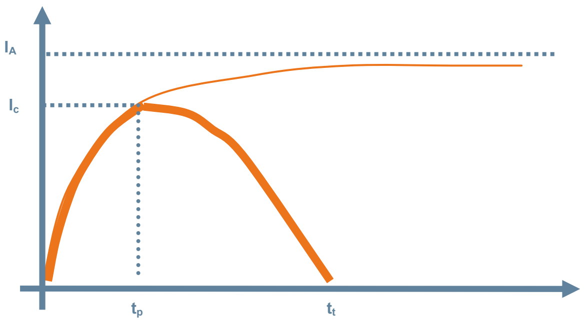


*Figure 3*

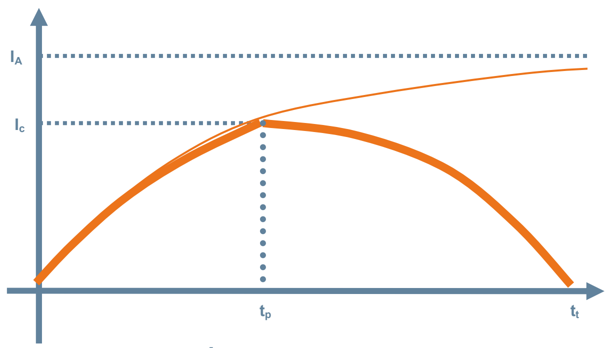


*Figure 4*

## 3. Interrupting Energy

The interrupting energy dissipated inside the fuse is the energy produced during the arcing period. The arc energy $W_a$ is :

$$W_a = W_L + W_S - W_R$$

- $W_a = \int_{t_p}^{t_t} u_a \, i \, dt$ :

Arc energy ( $u_a$ is the arc voltage of the fuse)

- $W_L = \frac{1}{2} L I_C^2$ :

Energy stored in the inductance at the end of the prearcing period

- $W_S = \int_{t_p}^{t_t} E \, i \, dt$ :

Energy provided by the generator during the arc time

- $W_R = \int_{t_p}^{t_t} R \, i^2 \, dt$ :

Energy lost in the circuit resistance




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## 4. Main interrupting tests

The Underwriters Laboratories (UL 248) and the International Electro technical Commission (IEC 60269) describe standard tests conditions for fuses under DC voltage. These are applied to industrial fuses, semi conductor protection fuses and special DC rated fuses as well.

As for the testing under AC voltage there are 3 typical tests :

- Maximum energy test (also named critical current)
- Breaking capacity test (or maximum interrupting ability)
- Overload test (or minimum interrupting capacity)

L/R values recommended by the standards are:

- UL 248: 10 milliseconds or more for the maximum energy test and all higher currents and .5 * ( IA ).3 ms for low current tests
- IEC 60269: 10 to 12 ms when IA > 20 KA and .5 * (IA).3 ms when IA 20 KA (note that when IA = 20 KA it gives 9.76 ms) with 0 to +20% tolerance

Since L/R values in traction applications can reach 100 ms, it is the fuse manufacturer responsibility to test fuses under such conditions in order to provide a suitable fuse to achieve the required protection. It means all above tests must be performed with various values of L/R.

The tests required by the standards are giving essential information on the fuse DC capability. However it is necessary to provide more information and more specifically the curve giving maximum L/R values as a function of the DC working voltage U (see examples in *figure 6 and 7*). This curve is an essential characteristic for the selection of fuses in DC applications.

### 4.1. The maximum energy test

As shown earlier the arc energy depends upon a great extent on the energy WL stored in the inductance. It has been demonstrated that the arc energy in the fuse is maximum when WL is maximum as well.
A study of the energy WL stored in the inductance L shows that a maximum is reached when the preacing time tp of the fuse is about equal to the time constant L/R of the circuit (*figure 5*).

Then

$$I_c = I_a \left(1 - e^{-1}\right)$$

IC = .632 IA

More studies have established that the energy in the inductance WL remains close to its maximum when the ratio IC/IA is between .50 and .80 .

IEC 60269-4 specifies IC must be between .5 and .8 IA
UL 248-1 specifies IC must be between .6 and .8 IA

Therefore a simple definition of the maximum energy test is that the fuse must have a prearcing duration equal to the time constant L/R .

Then

$$\frac{I_C}{I_A} = .632$$

In this case the energy in the inductance is :

$$WL = \frac{1}{2} L I_C^2 = \frac{1}{2} L I_A^2 \, (.632)^2$$

This can be transformed as follows :

$$WL = \frac{1}{5} \frac{L}{R} \frac{E^2}{R} \quad \text{or} \quad WL = \frac{1}{5} \frac{L}{R} E I_A$$

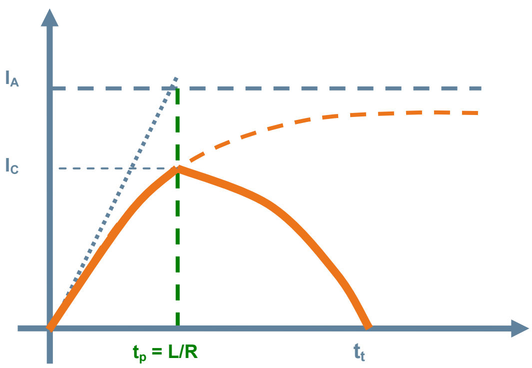


*Figure 5*




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Once more the large influence of L/R on the fuse behaviour is demonstrated. This test tremendously stresses the fuse and consequently determines the maximum L/R value for a given working voltage.

The L/R = f(U) curve is plotted according to the maximum energy test results at various voltage values. It means larger values of L/R are acceptable when the prearcing time is much smaller than L/R.

### 4.2. Breaking capacity test

When a fuse has passed the maximum energy test for given values of the time constant L/R and the working voltage U it usually interrupts successfully much larger fault currents under same values of U and L/R. As a matter of fact greater values of L/R are easily accepted by the fuse when the fault current IA is very large.
It must be noted that unfortunately the published breaking capacity of fuses are not large values because they are only the maximum current values the test circuit could supply.

### 4.3. Minimum interrupting capability (or overload test)

In the electric traction it is possible to get low over current faults that impose to the fuse a difficult operation under a DC voltage. The fuse may not be able to interrupt low overloads for the same reasons as in AC conditions.
Document EduPack 201 «Behaviour and operation of the fuse» explain the two main problems met when the prearc time is too long:

- The fuse body is damaged
- The arc goes out of the fuse through the terminals

## 5. Comment on the Fuse Rated Voltage, Practical Values of L/R

These three fundamental tests and the curve in *figure 6* show that it is not possible to select the DC voltage rating of a fuse purely on the basis of the working voltage value of the DC circuit to be protected.

It is absolutely necessary to plot the curve L/R = f(U)

This curve is plotted from the maximum energy tests results. Larger values of L/R are acceptable when the prearcing time is much smaller than L/R.

A L/R value must always be associated to the voltage and the range of possible fault current levels.

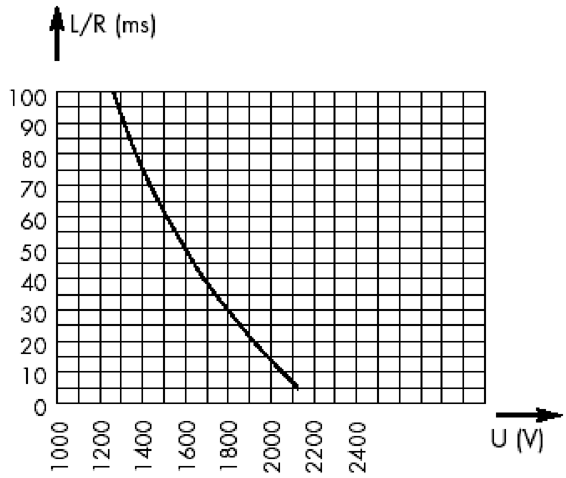


*Figure 6: L/R = f(U) of the 2000 V DC SRD fuses*

It is often difficult to obtain a precise value for L/R in practice. In the absence of better information the following table gives some typical guideline values.

| Equipment | L/R in ms |
|---|---|
| Capacitor bank | < 1 |
| Battery | < 10 |
| Output of a three phase bride feeding a main DC bus bar | < 25 |
| DC motor armature | 20 - 60 |
| DC traction systems | 40 - 100 |
| Continuous excitation of rotating machines* | 1000 |

* It is not recommended to fuse a DC motor field circuit.




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## 6. Exemple of DC capabilities for an AC Rated Fuse Range

### Maximum L /R of the fault path versus the DC working voltage U

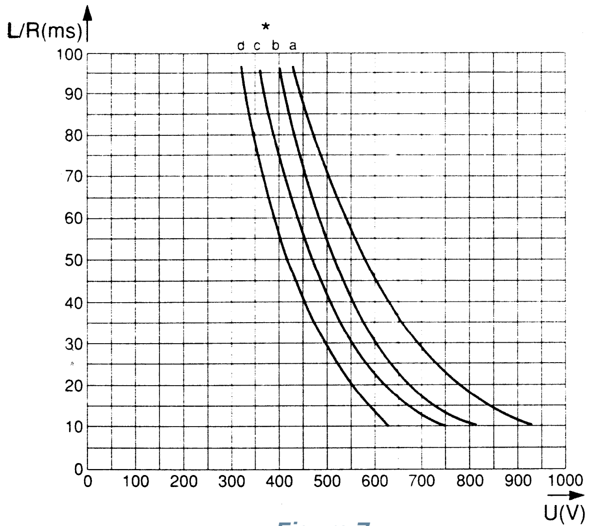


*Figure 7*

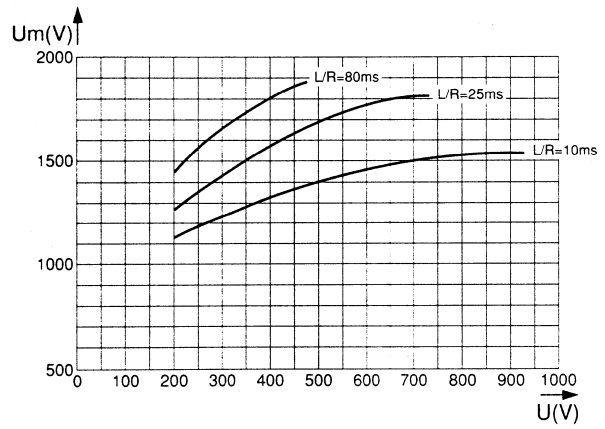


*Figure 9*

**Peak arc voltage $U_m$ of the fuse versus the DC working voltage U for three values of the time constant L/R**

Body size

Letters a , b, c and d indicates the L/R curve to use in *figure 7*

$I_{pm}$ is the minimum breaking current of each fuse

| | 70 * Ipm (A) | 71 * Ipm (A) | 72 * Ipm (A) | 73 * Ipm (A) | 2x72 * Ipm (A) | 2x73 * Ipm (A) |
|---|---|---|---|---|---|---|
| 63 | a 270 | | | | | |
| 80 | a 400 | | | | | |
| 100 | a 520 | | | | | |
| 125 | a 700 | | | | | |
| 160 | a 950 | a 950 | | | | |
| 200 | a 1300 | a 1300 | | | | |
| 250 | a 1800 | a 1800 | | | | |
| 280 | b 2200 | a 2000 | a 1800 | | | |
| 315 | b 2600 | a 2300 | a 2200 | a 2000 | | |
| 350 | c 3000 | a 2700 | a 2600 | a 2400 | | |
| 400 | | b 3500 | a 3200 | a 3000 | | |
| 450 | | b 4000 | a 3800 | a 3500 | | |
| 500 | | c 4800 | a 4600 | a 3900 | | |
| 550 | | c 5200 | b 5000 | a 4400 | | |
| 630 | | c 6400 | b 6200 | a 5300 | a 4400 | |
| 700 | | | c 6800 | a 6000 | a 5200 | |
| 800 | | | c 8000 | b 8000 | a 6400 | a 6000 |
| 900 | | | | b 9000 | a 7600 | a 7000 |
| 1000 | | | | c 11000 | a 9200 | a 7800 |
| 1100 | | | | c 12000 | b 10000 | a 8800 |
| 1250 | | | | c 13500 | b 12400 | a 10600 |
| 1400 | | | | c 15000 | c 13600 | a 12000 |
| 1600 | | | | | c 16000 | b 16000 |
| 1800 | | | | | | b 18000 |
| 2000 | | | | | | c 22000 |
| 2200 | | | | | | c 24000 |
| 2500 | | | | | | d 27000 |
| 2800 | | | | | | d 30000 |

*Figure 8*




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## 7. Curves

### 7.1. Time current curve (prearc time versus RMS value of the prearc current):

The curve plotted with AC or DC tests is the same because of the use of the RMS value of the prearc current (see § 3.4.2. in document EduPack 201-Behaviour and operation of the fuse). This curve allows to calculate the prearc time as a function of the fault current IA and the time constant L/R as well as to calculate the peak let through current and the prearc I²t.

### 7.2. Peak let through current versus short circuit current

There is a different curve for each different value of the time constant L/R. There is an unlimited number of curves and for this reason there is no published curve. It is possible to calculate the peak current from the time current curve as shown in § 8 example.

### 7.3. I²t versus short circuit current

There is a different curve for each different value of the time constant L/R. There is an unlimited number of curves and for this reason there is no published curve. It is possible to calculate the prearc I²t from the time current curve as shown in § 8 example but there is no simple formula for the calculation of the arc I²t and the total clearing I²t.
It is necessary to contact Mersen Technical Support.

### 7.4. Arc voltage

There is a specific curve for each value of the time constant L/R as shown in the *figure 9*.

## 8. Calculation of the Fuse Operation

The prearc time is given by the crossing point of the 2 following curves (see example in *figure 12*):

- The time current curve giving the real prearc time versus the RMS value of the prearc current
- The curve giving the real prearc time versus the RMS value of the fault current

$$I_{RMS} = \left(\frac{1}{t}\int_0^t i^2\,dt\right)^{\frac{1}{2}} = I_A\sqrt{\left(1+\frac{\tau}{2t}\left(4e^{-\frac{t}{\tau}} - e^{-\frac{2t}{\tau}} - 3\right)\right)}$$

The RMS value of he fault current is given by:

$$\tau = \frac{L}{R}$$

Example :
Fuse rated 600 V DC 500 A gRB type in body size 73
Fault: 10 KA under 500 V DC and L/R = t = 25 milliseconds

Fault equations:

$$i = 10000\ (1 - e^{-\frac{t}{25}})$$

and

$$I_{RMS} = 10000\sqrt{\left(1+\frac{25}{2t}\left(4e^{-\frac{t}{25}} - e^{-\frac{2t}{25}} - 3\right)\right)}$$

with **t** in milliseconds.

The selected fuse is suitable because U = f(L/R) (this is another presentation of the curve L/R = f(U) ) shows L/R =

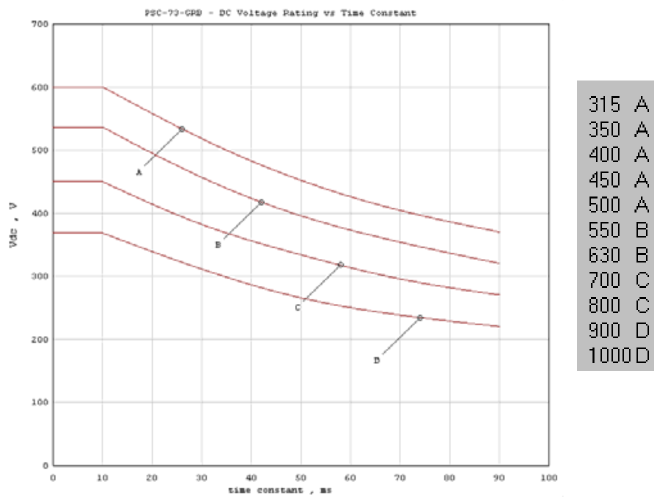


*Figure 10: U = f(L/R) of the GRB 600 V DC size 73*




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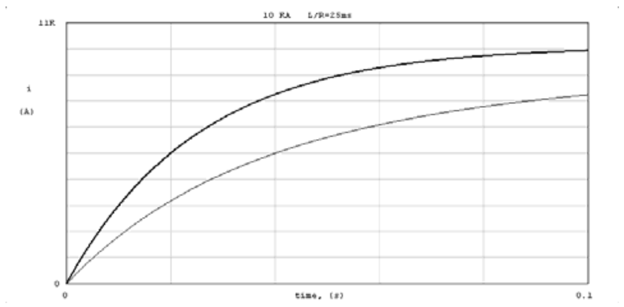


*Figure 11: i and IRMS of the fault*

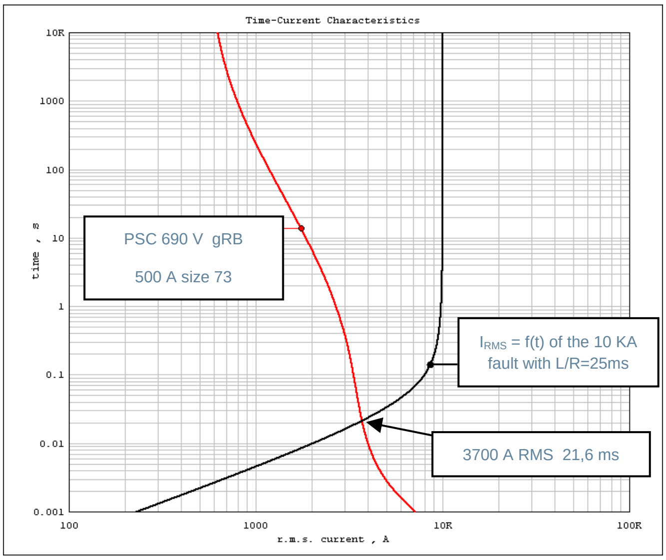


*Figure 12: Determination of the melting point of the fuse*

Results:

- Prearc time: 21,6 ms
- Peak let through current: 5785 A (calculated with the equation of i at time 21.6 ms)
- Estimated arc time : 25 ms to 30 ms
- Total clearing time: 50 ms
- Prearc i²t: 295 700 A²S

Note : prearc i²t can be calculated as follows
prearc i²t = 3700²x 0,0216 = 295 700

Or prearc i²t = $I_{EFF}^2 * t_P$ with $t_P = 0{,}0216$ seconde

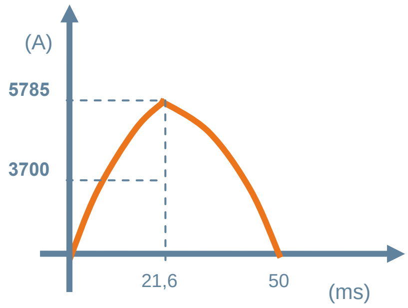


*Figure 13: fuse operation*

## 9. Conclusion

For all DC applications it is absolutely necessary to define the fuse with:

- The voltage
- The time constant of the circuit
- The fault currents

It is required as well to get all necessary information about the rated current passing in the fuse as well as the load cycles and overloads to withstand in order to calculate the current rating of the fuse so that its life time fits with the life time of the equipment it must protect.




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