

Low-voltage fuses and circuit breakers, comparison of operation in conditions of high short-circuit currents

Summary:

The paper is attempting to describe in a simple way the physical background of low-voltage fuses and circuit breakers operation in conditions of high short-circuit currents. Further, it attempts to draw some conclusions from their operational peculiarities, that substantially influence the practical application of fuses and circuit breakers.

1. INTRODUCTION

Under the slogan “Safety First” are presented in the following discussion low-voltage fuses and circuit breakers as the most important and most frequent protection elements in electrical engineering, viz. electrical installations.

The basic physical and electrical processes in short-circuit conditions are shown. The paper attempts, on the one hand, to demonstrate the advantages and drawbacks of both protection elements, and, on the other hand, to indicate the way of their interaction, with particular emphasis on their operation in the domain of high short-circuit currents.

First of all, the following criteria have to be observed when selecting the protection elements:

- Safety
- Reliability
- Quality
- Diversity
- Economy

An electrical installation has to be designed and manufactured in such a manner to allow the protection device to cut an electric circuit only when it is really necessary. But at that time with an absolute reliability! When a fault arises, the protection device, whether a fuse or a circuit breaker, must disconnect an electric circuit before a damage on installation, power source or consumer occurs.

Advantages and drawbacks of fusible cut-outs - fuses

As said above, when evaluating advantages and drawbacks of an individual protection element, the above mentioned criteria have to be observed:

- **Safety:**
 - o High degree of current limitation,
 - o Low values of transient integrals,
 - o No leaking out ionizing gases,
 - o Low power losses.

- **Reliability:**
 - After the cut-out the fuse cartridge is replaced, the properties of the new one are fully available,
 - Aging resistance,
 - Simple use.
- **Quality:**
 - Today's production is highly automated, which ensures small deviations in technical characteristics of the whole quantity of products from the regular production.
- **Diversity:**
 - Use in low- and high-voltage networks,
 - Protection of electronic apparatuses and devices.
- **Economy:**
 - In comparison with its capabilities and dimensions as well as price, this is the most economic solution.

The drawbacks of the fusible cut-outs are mainly due to the following facts:

- They have to be replaced when a fault occurs, which usually means a specific time without power;
- More difficult setting of the I-t overload characteristic, which depends on the physical processes in the fusible element.

Advantages and drawbacks of the circuit breakers

Comparison of circuit breakers by the same criteria:

- **Safety:**
 - Possibility of exact setting of the current-time characteristic;
 - Otherwise large enough degree of the current limitation, still on account of economy.
- **Reliability:**
 - The truth is that modern design solutions ensure a high degree of reliability, but with time, or with the number of cut-offs the characteristics of each circuit breaker are gradually being deteriorated.
- **Quality:**
 - The same applies to quality.
- **Diversity:**
 - Very wide possibility of use, at NN, SN and VN levels;
 - The use of electronic in tripping circuits increases the applicability.
- **Economy:**
 - The economy appears primarily in short reconnecting times;
 - The power circuit breakers involve a big difference in the product price.

The weakness of circuit breakers appears primarily through the following facts:

- At disconnection an exhaust of ionizing gases appears, that can cause various consequences in the switch cabinet;
- With the number of short-circuit disconnections a circuit breaker gradually loses its technical properties.

2. OPERATION OF FUSES IN SHORT CIRCUIT

The operation of fuses in short circuit can be illustrated with the current-time characteristic. The range from a rated current I_n up to 4-8 times multiple of the rated current is called overload range. The area of higher short-circuit current is called short-circuit area. (Figure 1)

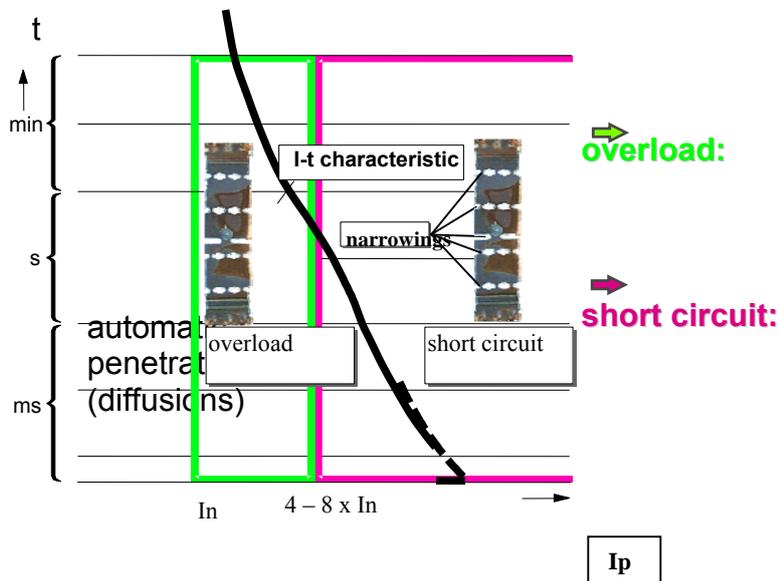


Figure 1

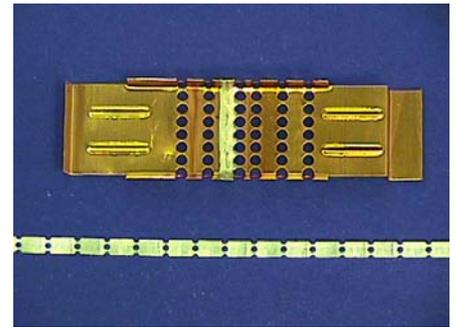


Figure 2

For melting the weakened portions of a fusible element (Figure 2), an adequately high current is required, that will convey enough energy for liquefaction and vaporization in specific time interval (according to the characteristic) of the metal at the weakened portions.

The denotation I_p designates the expected short-circuit current, i.e. the current that would flow through an electric circuit if the fuse were bridged short. Very important specification for each fuse is its breaking capacity.

What does the term »breaking capacity« mean?

This is the property of a fuse to interrupt (cut off) an electric circuit that exactly meet specific conditions, always and correctly, without other consequences. These exactly defined specific conditions are described with the following limit values:

- the highest and the lowest expected short-circuit current
- waveform and frequency of the current
- $\cos\phi$ (for AC), time constant L/R (for DC)
- return voltage value

What does the term »current limitation« mean?

A fuse fulfils its current limiting function then, when at short circuit occurrence it substantially limits the rise of current up to its peak value, viz. it must interrupt the current before its instantaneous value reaches the maximum peak value.

This is graphically shown in Figure 3. The effect of short-circuit current limitation will occur then, when the arcing voltage exceeds the mains voltage, whereby the instantaneous current value starts rapidly dropping down towards zero value. The highest instantaneous (momentary) value of the current is called cut-off current (also is used the term: transitional current).

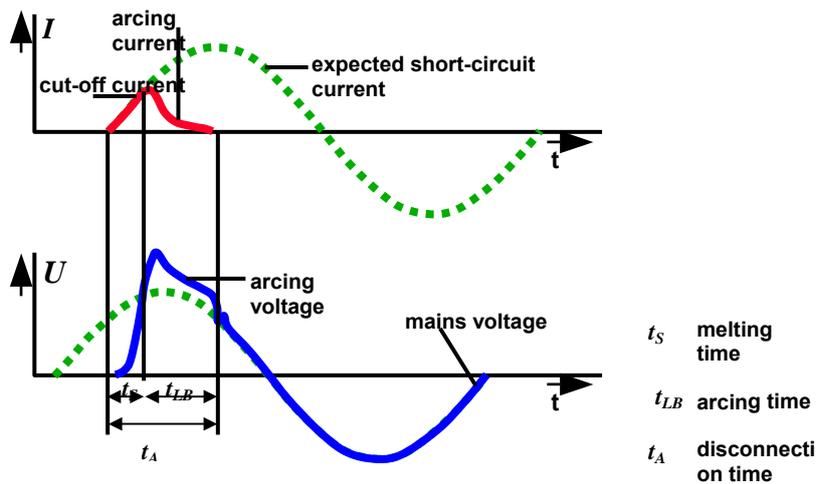


Figure 3

The entire disconnection phase can be divided into the phase of melting or melting phase, and the phase of arc or arcing phase.

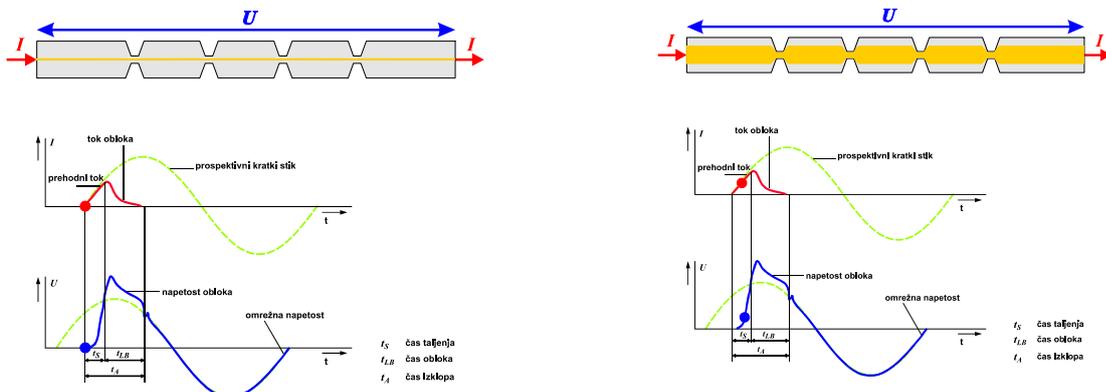
The figures below (from 4 to 8) show the flow of voltage from the beginning of the short circuit occurrence to the final interruption of current.

Melting phase:

- Figure 4: Beginning of short circuit, the current intensity is illustrated with the yellow line width;
- Figure 5: The instantaneous short-circuit current value is rising, but the energy conveyed is not yet high enough for melting the weakened portions of the fusible element;
- Figure 6: The current reaches the value when the conveyed energy is high enough for melting the weakened portions, the melting phase is concluded, starting the

Arcing phase: The characteristic of the arcing phase is a fast voltage rise at the fusible element (indicated with blue colour), that occurs in arcs at individual weakened portions.

- Figure 7: The arcing phase is in full swing, individual arcs are being cooled in the quartz sand, and the instantaneous current value is dropping down towards zero value;
- Figure 8: The current is interrupted, the arcs are extinguished, the return voltage that equals the mains voltage is established. The view of the interrupted fusible element is shown in figures 9 and 10.



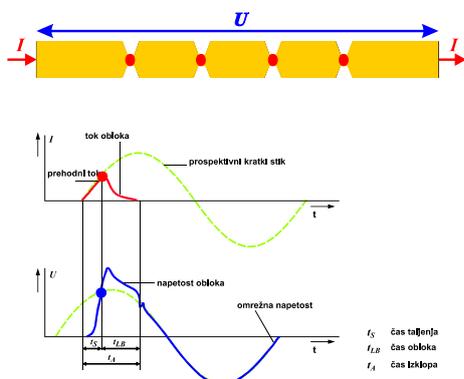


Figure 6

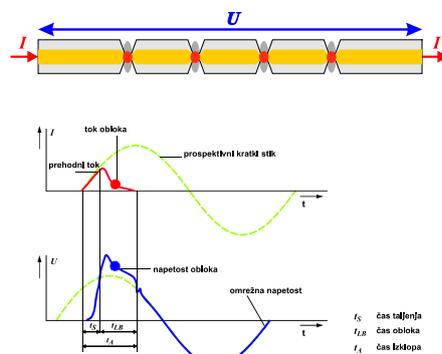


Figure 7

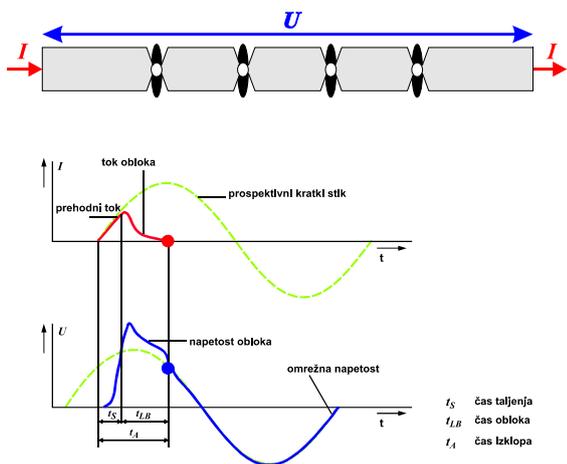


Figure 8



Figure 9



Figure 10

For rather simplified understanding of the fuse operation in short circuit, it is useful to know two current values:

I1: maximum breaking capacity (for NV fusible cartridges 120kA)

I2: critical current (for NV fusible cartridges 1kA and 5kA)

Cut-off at the current I1:

All the weakened portions will be cut off instantaneously ("primary decay").

There appear so called partial arcs in length of the entire weakened portion; at each weakened portion an arcing voltage of 150-200 V arises.

The level of arcing voltage depends on:

- conditions of heat dissipation onto surrounding quartz sand: better conditions, lower arc temperature, higher arcing voltage;
- current intensity: higher the current, higher arcing voltage;

- the length of arcing channel: longer its length, higher arcing voltage;
- arcing channel cross-section: narrower the channel, higher arcing voltage;

The oscillogram of current and voltage at cut-off with I1 is shown in the following Figure 11.

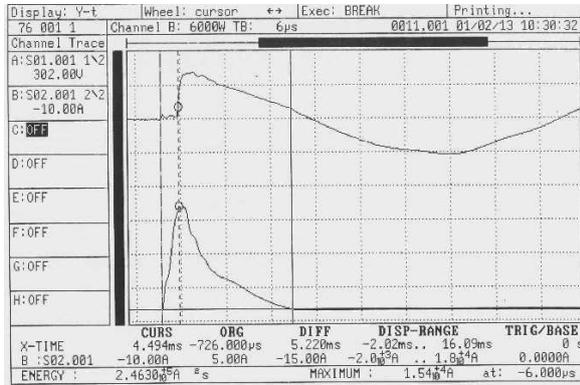


Figure 11

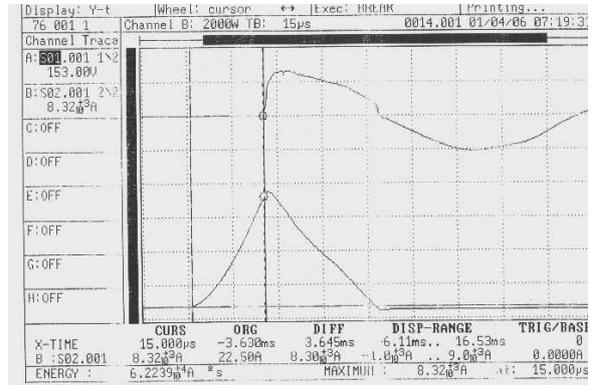


Figure 12

Value of the integral $I^2t = 24.630 \text{ A}^2\text{s}$ (the whole integral, heat pulse). The phenomenon is characterized by a very short melting phase, and fast rise of the arcing voltage.

Cut-off at the current I2:

The weakened portions are disrupted singly, and namely in only one single point (“decay due to electrodes burn-off”).

At each weakened portion arises first a very short partial arc, that subsequently burns off at both electrodes, the arc spreads with constant speed.

The vaporization speed of the fusible element is 10 to 1000 times lower than with primary decay.

The oscillogram of cut-off with the current I2 is shown in Figure 12.

The maximum arcing voltage is higher than the peak value of the mains voltage, and the rise of the arcing voltage is essentially slower. Value of the integral $I^2t = 62.239 \text{ A}^2\text{s}$, melting phase is longer, arcing phase is longer.

3. SELECTIVITY OF SERIALLY CONNECTED FUSES:

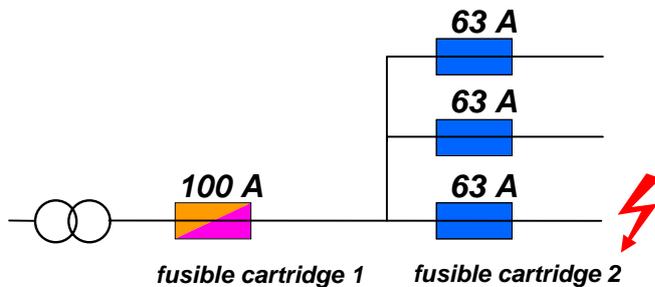


Figure 13

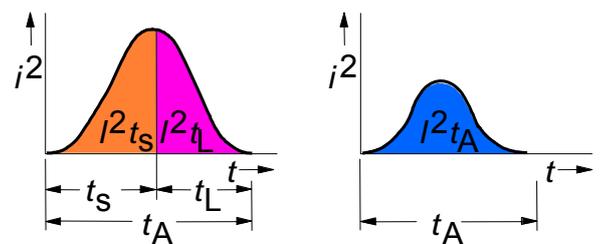


Figure 14

The selectivity is guaranteed when the orange surface is larger than the blue one. Accordingly, when the melting integral of the previous fuse is bigger than the overall integral of a subsequently built-in fuse. The fact is, that fuses are selective if the ratio of the rated currents is larger than 1:1.6.

Example: 100A 63A

$$I^2t_s = 7700A^2s$$

$$I^2t_{tb} = 10300 A^2s$$

$$I^2t_s = 24000A^2s > I^2t_A = 18000 A^2s$$

3.1. Breaking work

The breaking work is represented by the electric energy arising in electric circuit that is transformed in an arc into heat energy (absorbed by the quartz sand).

$$W_a = \int_{ts}^{ta} u_{LB} i_d dt = W_m + W_c \quad (\text{product of current and voltage in the arcing phase})$$

$$W_m = \frac{1}{2} L_c I_m^2 \quad \text{potential electromagnetic energy in electric circuit}$$

$I_m =$ value of current at the moment of cut-off

$L_c =$ inductivity of electric circuit

$$W_c = \int_{ts}^{ta} u_c i_d dt \quad \text{energy supplied from the source over duration of the arc}$$

The breaking work equals at least the potential electromagnetic energy. It is increased in proportion with the ratio *arcing time : melting time*.

3.2. Breaking pulse, melting pulse, arcing pulse

1. **Melting pulse:** the value indicated by the manufacturer, and meaning the energy required for melting the weakened portions of the fusible element.

$$\Delta K_m = \int_0^{ts} i dt$$

2. **Arcing pulse:** $K_a = \int_{ts}^{ta} i^2 dt$

3. **Breaking pulse:** $\Delta K_m + K_a = \int_0^{ta} i^2 dt$

The breaking pulse designates the entire heat energy, transferred into an electric circuit. There are also some »domesticated terms« of it: melting integral, arcing integral, overall integral.

4. OPERATION OF CIRCUIT BREAKER IN SHORT CIRCUIT

In the figures below is shown a schematically represented circuit breaker, and the corresponding oscillogram of the current and voltage flow. A contact arcing system is represented only schematically, i.e. through a model, that is by its form and execution similar

to real circuit breakers. The releasing (tripping) system is represented in the form of a coil of an electromagnetic tripping device, acting with a force F on a movable contact in the opening direction.

Figure 15: **Time t_0** : time of mechanical delay: Short-circuit current starts flowing, but the force F is still too weak to start the process of opening the contacts, voltage at the circuit breaker U is very low, and equals the voltage drop across the resistance between terminals, the buckling system is already released, but due to mechanical delays the contacts are still closed.

Figure 16: **Time t_1** : start of the arcing phase between contacts: The current attains the value when the force F already starts opening the movable contact.

Figure 17: **Time t_r** : end of the arcing phase between contacts: The contacts are opened to such an extent, that an arc appears exactly between the contact spots, the actual distance between contacts is 1-2mm, the voltage at the terminals is increased by the value of the arcing voltage that is still very low and amounts to 10-20V.

Figure: 18: **Time t_f** : the arc under the influence of the Lorentz force starts moving in the direction of the arc chamber, the lower points of the arc start moving both on the movable contact and on the fixed contact, which is extended into the arcing strip. The arcing voltage increases.

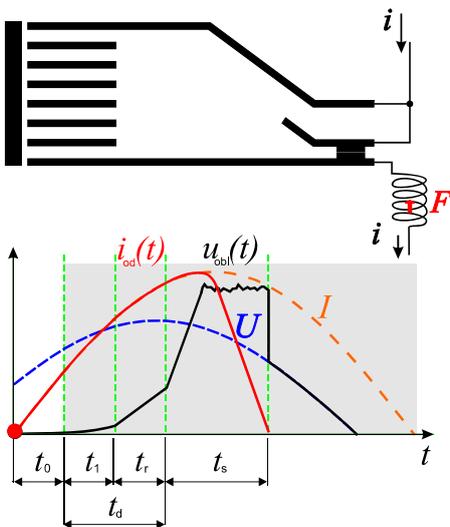


Figure 15

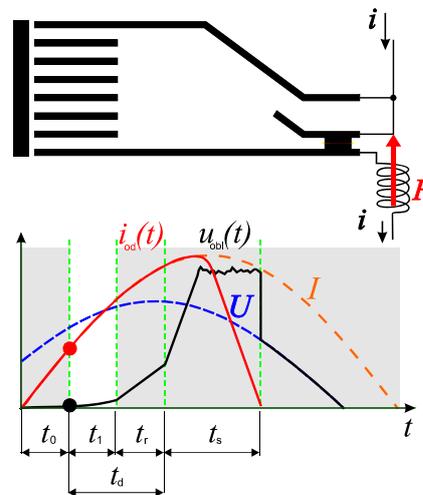


Figure 16

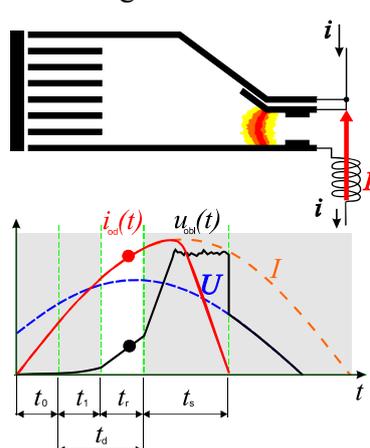
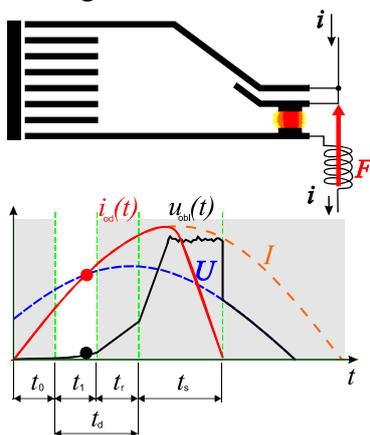


Figure 17

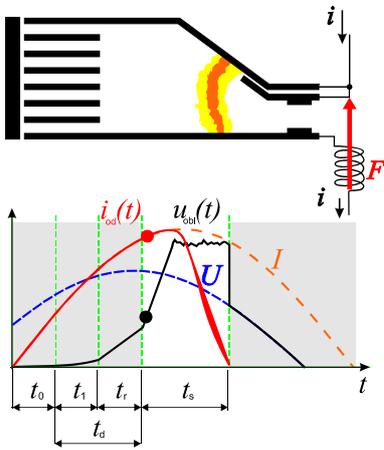


Figure 19

Figure 19: At the end of phase t_r the lower side of the arc jumps to other arcing strip, thus starting the travelling phase to the arcing chamber. Arcing voltage increases very rapidly.

Figure 18

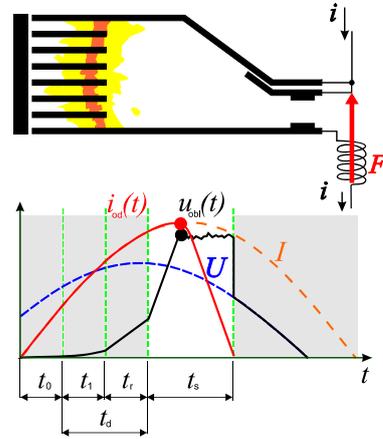


Figure 20

Figure 20: The phase of arc distribution between the arcing chamber plates. The arcing voltage exceeds the mains voltage, starting the current limitation phase.

Figure 21: The phase of high arcing voltage maintenance, and thereby of short-circuit current limitation. Individual partial arcs are maintained between the arcing chamber plates. The level of arcing voltage depends on the number of plates in the arcing chamber. The mechanism of establishing the arcing voltage in the package of plates is described below.

Figure 22: The moment of arc extinction and of current cut-off.

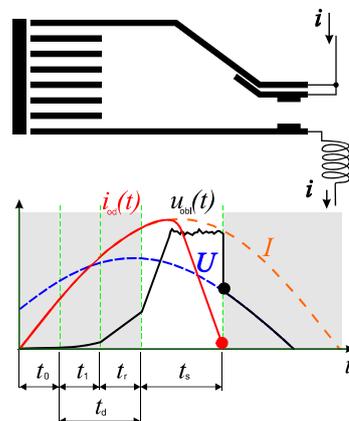
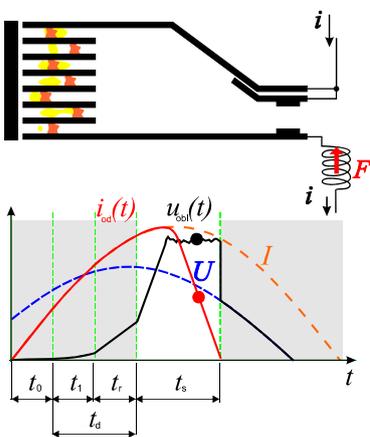


Figure 21

Figure 22

The mechanism of establishing arcing voltage in circuit breakers

An (electric) arc is an independent, thermal gas discharge, arising at the opening of contacts through which current flows. It consists of a plasma column, and cathode and anode drops. (Rieder: Plasma und Lichtbogen, 1967) Figure 23 shows a very idealized representation of arc

U_a : anode voltage drop
 U_k : cathode voltage drop
 U_s : arcing column voltage
 U_{obl} (U_{lb})(U_b): arcing voltage

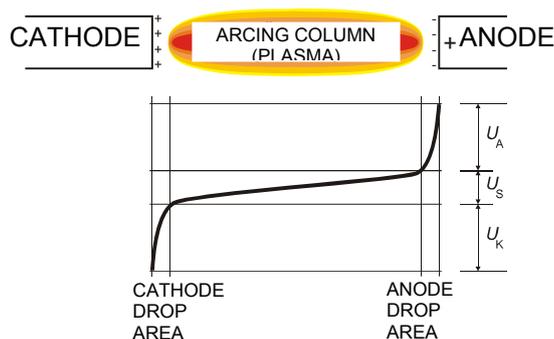


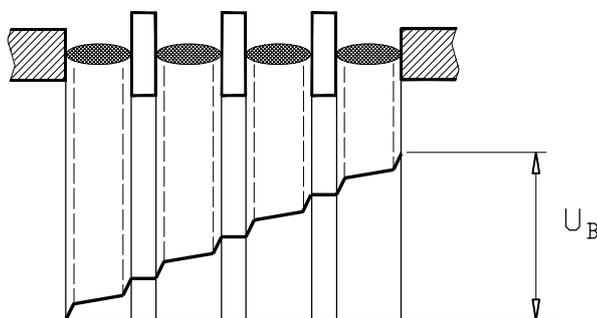
Figure 23

An arcing column, burning in casing of switches, where several kinds of gases or vapours under pressure are present, is actually plasma in thermal equilibrium. This means that the temperatures of electrons, ions and neutral particles are approximately equal. The main share of the current carriers represent electrons which are more agile than ions.

The cathode produces electrons needed for current through the arc. And in the area of anode ions are produced. So the distribution of voltages between both electrodes is not linear, but so called anode and cathode voltage drops arise in vicinity of both electrodes. To the arcing column itself comes smaller voltage portion. The sum of all three values is called arcing voltage that amounts to 20V.

The actual form of the arc is to a large extent defined by the design characteristics of the switching device, and as a rule it significantly differs from the described idealized form.

In what way is a high arcing voltage built up?



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By dividing an electric arc into several so called »partial« arcs, it comes to the summation of individual arcing voltages, and to the necessary level of the arcing voltage, that together with the voltage drop at the circuit breaker represents sufficiently high voltage value at the circuit breaker terminals, to ensure the function of short-circuit current limitation.

In practice there are used arcing chambers having 12-13 (sheet metal) plates, which means that 13-14 partial arcs are generated in it. Consequently, arcing voltage in the chamber decisively contributes to the short-circuit current limitation.

Now, if we go back to the current and voltage oscillogram, we shall see that the level of arcing voltage is mainly independent of the expected short-circuit current intensity, which means, that with increasing of the short-circuit current the overall integral will be increased, too.

On the other hand the overall integral depends very much on the duration of delay times. In sum, the sooner high enough arcing voltage is established, the smaller is the overall integral. This means that the size of overall integral in the circuit breaker in large extent depends on mechanical capabilities of the mechanism, as well as on the design of the arcing chamber with its contacts.

5. OPERATION OF SERIALY CONNECTED FUSES AND CIRCUIT BREAKERS

The comparison of operation of fuses and circuit breakers in short circuit, especially in conditions of rising expected short-circuit current, indicates the following characteristics:

- Fuse:
 - o The value of integral diminishes from the value at the critical current I_2 up to the value at I_1
- Circuit breaker:
 - o The value of overall integral rises linearly up to the maximum current of the breaking capacity.

This becomes evident from the following diagram in Figure 25, where comparison between a fuse and a circuit breaker is shown.

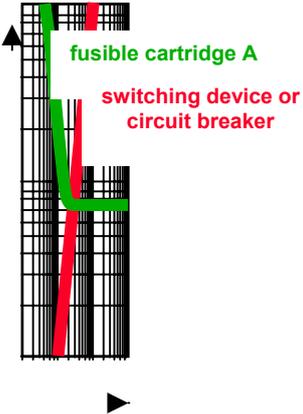


Figure 25

6. SELECTIVITY OF FUSIBLES AND CIRCUIT BREAKERS

The following figure shows an example (Figure 26) of a scheme with a series fuse of 100A and subsequently built-in installation circuit breaker with a rated current of 63A. In order to

establish the conditions of selectivity, we need data on integrals of fusibles and circuit breakers, that have to be entered in a diagram, similar to that in Figure 25.

Breaking work: the same definitions applies as for the fuses from the paragraph 3.1., so the point is thermal energy released in the circuit breaker.

Breaking pulse: with the installation circuit breakers the term »melting integral« is unknown, there only exists an overall integral.

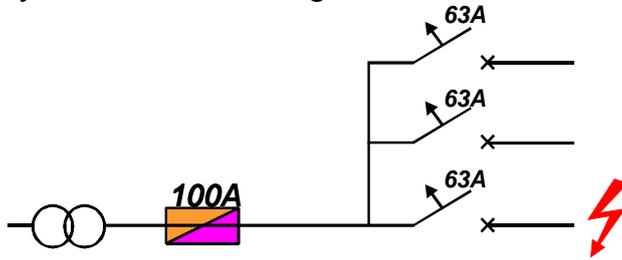


Figure 26

In Figure 26 other appropriate values can be imagined as well, e.g. rated current of the series fuse gG 50A and rated current of the installation circuit breaker B20A.

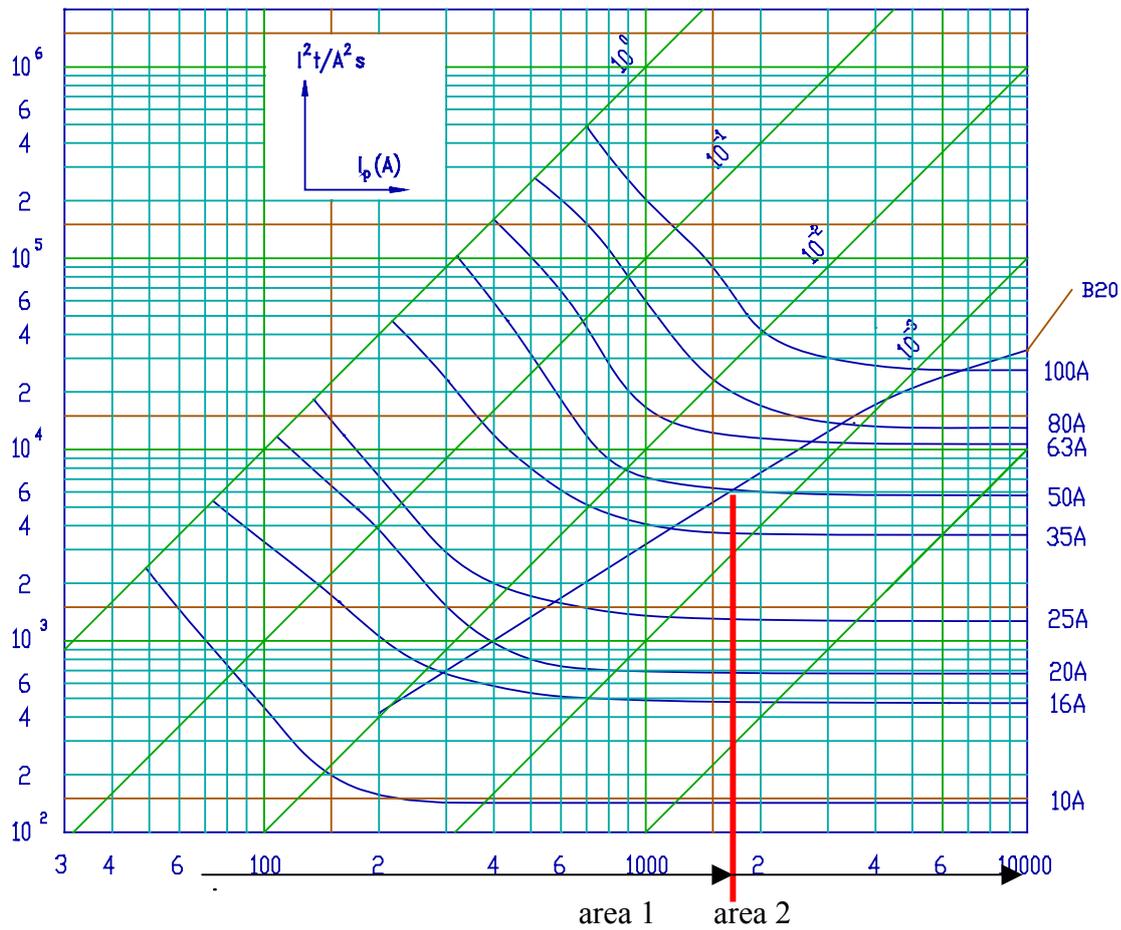


Figure 27

How the selectivity conditions can be read?

Firstly, we must find the intersection of the melting integral curve for the selected fusible, and the curve of the overall integral for the installation circuit breaker. By connecting the intersection point and the axis of the expected short-circuit current, we obtain two areas.

- Area 1: the overall integral for the installation circuit breaker is smaller than the melting integral for the fusible – selectivity is ensured;
- Area 2: the overall integral for the installation circuit breaker is larger than the melting integral for the fusible. The selectivity is not absolutely ensured, in the given example both protection elements will cut off.

7. DIAGRAM OF CUT-OFF CURRENTS

The fact is that both fuses and circuit breakers have the capability of limiting short-circuit current even before the latter has reached its peak value, thus causing a damage in an installation. The following Figure 28 illustrates a diagram of cut-off currents as a way of providing these data.

Why is it important to limit as much as possible the short-circuit-current?

Because an excessive value of cut-off (transient) current provokes excessive dynamic efforts of all the installation elements through which that current flows. Figure 28 shows an example for the fuses (fusibles) of NV type, and similar diagrams also exist for installation circuit breakers, only with different values.

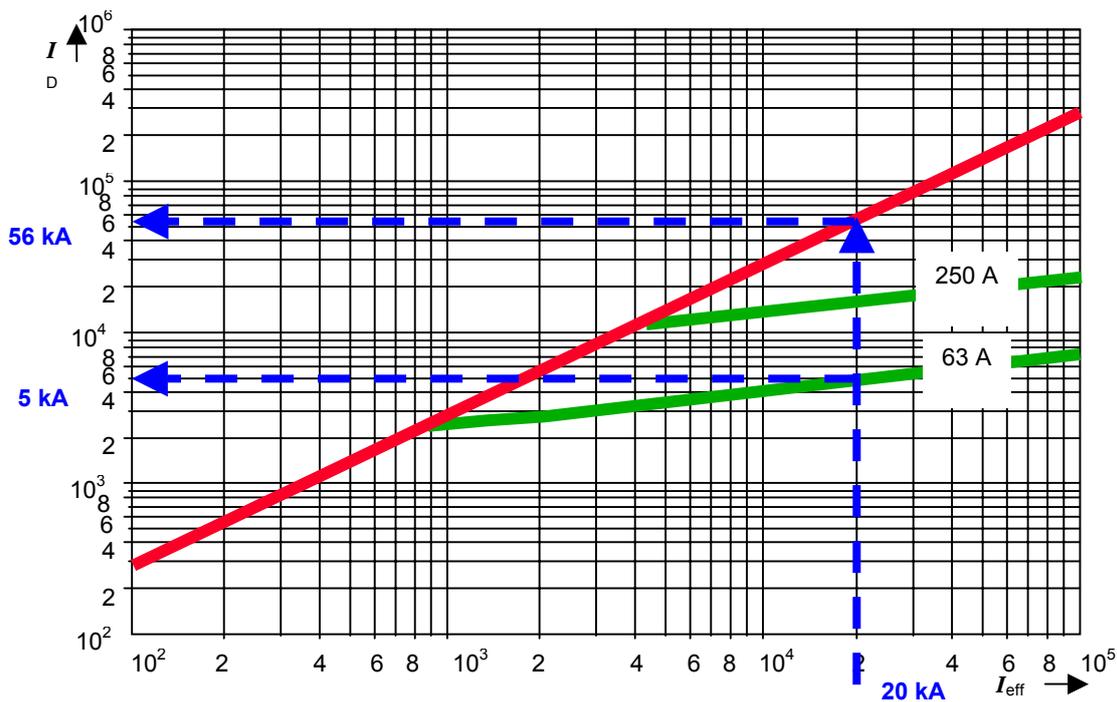


Figure 28

From the diagram we can make out the value of the cut-off current at an expected short-circuit current having effective (r.m.s.) value of 20kA. The maximum value of the cut-off current amounts to 5kA when NV fuse cartridge with rated current of 63A is used.

Equally can be used also the diagram for installation circuit breakers.

8. CONCLUSION

On the basis of findings in this paper we can conclude, that for an optimum protection in conditions of high short-circuit currents in installations, it is necessary to make use of all good properties of both fuses (fusible cut-outs) and circuit breakers.

In addition, it is very important to know the right specifications for individual circuit breakers that can be, in spite of standardization in this field, very different from manufacturer to manufacturer. From the both protection devices (fuses and circuit breakers) the following is expected:

- as low overall integral as possible, which reduces thermal loads of an installation;
- as low cut-off currents as possible, which reduces dynamic loads of an installation.

9. SOURCES:

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