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TECHNICAL GUIDELINES

Ultra-Rapid Fuse-links for the protection of semiconductor-rectifiers

1. General

Design of rectifier equipment especially requires provision of switchgear to protect the power semiconductors. Semiconductor components have low thermal capacity so that the requirements for the planned protective device exceed the normal conditions for protection of standard devices. Both rated current and rated voltage as sole criteria for the selection are no longer sufficient and the following has to be considered additionally:

- High speed of response in the overload range
- Operating integrals adjusted to the limited load integrals of the semiconductor cell
- Low switching voltages values during breaking process
- Low temperature rise and power loss of the protective device under operating conditions

Further important design aspects are the price of the protection device in relation to the total costs of the equipment as well as breakdown time after a fault. SIBA ultra-rapid fuse-links meet the mentioned requirements and efficient protection is provided.

Remarkable features are:

- Extreme fast time/current behaviour and low operating integral values
- Low temperatures at the insulating body due to excellent temperature conductivity of the special ceramic
- Low power loss under rated conditions
- Free of ageing; pure silver elements are used
- Low switching respectively arc voltage due to special element design

The present technical information is intended to be used as a design basis and shall offer all basics necessary for selection of maximum protection of rectifier devices. First, the fuse specific data are explained in detail that renders the basis for the physical contemplation of the breaking process treated in the following chapters.

SIBA data sheets include characteristic curves that are described in this documentation and completed by examples.

Subsequently the most commonly used rectifier circuits are shown in tabular form, properties of parallel and series connection of fuse-links are mentioned and possible faults in circuits are treated.

Thermal influences, alternating load operation and shock load are considered by conversion coefficients described in the following chapter.

Finally, in the last chapter criteria for dimensioning the optimum fuse-link as well as a flow diagram for an easy overview are shown.

2.Characteristic values of fuse-links

Rated voltage U_N

The rated voltage of a semiconductor fuse-link is the RMS-value of a sinusoidal a.c. voltage. All test conditions and the operating voltage limit are stipulated on that basis. The fuse-link rated voltage has to be determined in order to be higher than the voltage causing the short-circuit current.

Rated current I_N
The rated current of a fuse-link is the RMS-value of a sinusoidal a.c. current at a frequency of 45 to 62 Hz. It is the current of which the fuse-link can be loaded continuously under determined conditions without changing its characteristics.

Provided by the standards the conditions are:

- Ambient temperature (20 ± 5) °C
- No external cooling
- Connecting cross section specified
- Fuse-links are mounted in an open test rigs while testing

Applications normally are not covered under these conditions. For that reason additional calculations are necessary, which may result in decreasing the fuse-links rated current.

Power dissipation P_V
The power dissipation (or power loss) of fuse-links results from multiplying the rated current by the value of the voltage drop measured over the fuse-link after loading with rated current up to final steady temperature rise under the conditions described above.

Initial short-circuit alternating current $I_{K''}$
The effective value of the short-circuit current at the beginning of the short-circuit which would flow if the short-circuit would occur directly behind the fuse-link and if the fuse-link would be replaced by a member of negligible impedance.

Cut-off current I_D
Peak of the short-circuit current limited by the fuse. Highest momentary value of the current during the breaking process.

Melting time t_S
Period between the start of the fault current and the melting of all elements.

Arcing time respectively extinguishing time t_L
Period between the melting of the elements and the definite arc extinction.

Operating time t_A
Total of the melting time t_S and the arcing time t_L.

Switching voltage, arc voltage U_L
Maximum value (peak value) of the voltage occurring at the terminals of the fuse-link during the breaking process.

Melting integral I^2t_s
Integral of the current square above the melting time. Among others, the value of the melting integral depends on the construction of the fuse elements and the ambient temperature.

$$I^2t_S = \int_0^{ts} i^2\,dt$$

Arc integral I^2t_L
Integral of the current square above the arcing time. The value of the arc integral depends on the system voltage, the short-circuit current or respectively current rise rate di/dt and the short-circuit impedances R_K and Z_K.

$$I^2t_L = \int_{ts}^{ta} i^2\,dt$$

Operating integral $I^2 t_A$
Total of the melting integral and the arc integral

$$I^2 t_A = I^2 t_S + I^2 t_L$$

3. The breaking process

3.1 Breaking at low and medium overload

The load current flowing through a fuse-link results in a voltage drop according to its resistance. Multiplication of the voltage drop with the load current designates a power loss, which in form of temperature is passed to the environment, the terminals and the cables. At load currents above the rated current high temperature rise develops at the melting element notches inside the fuse-link so that in dependence on the time these notches can melt. At these interrupting spots individual arcs occur allow the current to flow until the arc is extinguished.

In the range of low and medium fault currents where the melting time has the duration of some current half waves an arcing time of less than 5 ms can be regarded as negligible. This melting time then corresponds to the total breaking time.

3.2 Breaking at short-circuit currents

In the short-circuit range the melting element notches melt and evaporate in ranges to nearly one millisecond due to the steep current rise. At the melted notches arcs occur which remain active as long as sufficient number of insulating bridges are created by the surrounding quenching medium. The arising arc voltage exceeds the value of the operating voltage, however it is limited by a special SIBA-design of the melting element. The arcing time in this case cannot be regarded as negligible any longer, because the arcing time takes longer than the melting time.

Addition of melting time and arcing time results in the operating time. For protection of semiconductor components in this range the operating integral $I2t_A$ is decisive, that means the total of melting integral and arc integral. It must always be smaller than the limited load integral of the semiconductor element to be protected.

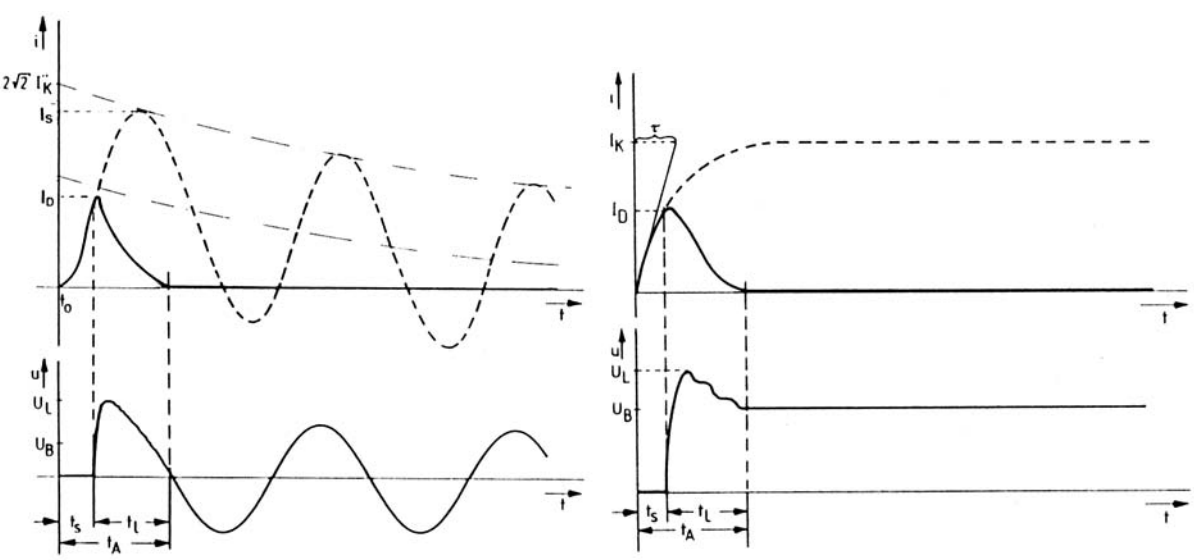


Fig. 3.3 Short-circuit interruption at A.C. and D.C. currents

3.3 Voltage and current development at short-circuit currents

Figure 3.3 shows the temporal development of a short-circuit current at alternating and direct voltage. The voltage existing across the fuse-link during the breaking process is indicated simultaneously with the current with regard to time. The time t_0 is the beginning of the short-circuit; a peak value as maximum asymmetric short-circuit current can be reached. After the time t_s has passed, the fuse-link limits the current to the value of the cut-off current I_D.

A breaking arc occurs, but is decreased rapidly during time t_L by the influencing quartz sand. The breaking process is finished after the time t_A.

4. Graphic presentation of the fuse-link operation behaviour

4.1 Time-current curves

Time-current curves demonstrate the dependence of the melting time on the fault-current flowing though the fuse-link. The curves are a result of testing the melting time of non-preloaded fuse-links. The individual measured points are the arithmetic average value of at least three melting tests. If not otherwise noted, the tolerance of the time-current curve is about ± 7 % in direction of the current.

The limited operating ranges of ultra-rapid fuse-links are indicated by a dotted part of the curve. It is the range of load currents, where the melting elements react, but the fuse-links may not interrupt due to thermal reasons. From these broken line curves it is obvious that this group belongs to back-up fuses of operating class aR.

Due to a self-heating of semiconductor fuses at currents with melting times higher than 30 seconds, these over currents have to be limited with preconnected protection devices. A parallel curve of 80 % the dotted one indicates the maximum acceptable interrupting current and time of each protecting device. This is to limit the contact- and insulation- temperature of the cable and the fuse-holder if fitted.

4.2 Cut-off current diagram

The current-limitation diagram is provided to determine the cut-off current I_D and the maximum asymmetric short-circuit current I_s in dependence of the initial short-circuit alternating current $I_{k''}$ to be expected.

The diagonal line drawn in the diagram is the graphic expression for the possible peak value of the short-circuit current to be expected according to the simple relation: $I_s = I_{k''} * \sqrt{2}$ in case a fuse-link is not used.

Of higher importance for the user are the individual current limitation curves of the fuse-link rated current. The value of the cut-off current in respect of the dynamic load in case of short-circuit is an in important figure for the design of the device to be protected.

4.4 Switching voltage diagram

Usually, the switching voltage is given at the fuse-link rated voltage. Operation of ultra-rapid fuse-links with a load voltage smaller than the rated voltage, reduction of the switching voltage has to be calculated. The diagram allows the determination of the arc voltage U_L in relation to the loading voltage U_B.

4.5 I^2t values

At high failure currents with melting times smaller than 5ms, an indication of the actual melting or switching times is no longer possible due to the adiabatic process inside the fuse-link. In this case, the melting integral has to be used for the melting process and the operating integral value stands for the sum of extinguishing and melting process.

Here the impulse of the electrical energy is defined which the current has to provide in order to melt the element notches. During arc extinguishing as well as certain energy amount is carried through the semiconductor component to be protected loading this component so that this has to be included in the calculations.

As the energy impulse for melting is always constant for a certain rated current this value is shown in the respective diagram as a statistic value. The correcting curve diagram allows calculating the operating integral at different operating voltages by giving a coefficient, which must multiplied with the operating integral given in the datasheet.

4.6 Operating classes
The respective range of currents, over which the fuse-link can operate, determines operating classes

aR: Back-up semiconductor protection
Partial range breaking capacity fuse-links, which are able to carry continuous currents from the lowest up to their rated current. The fuses are able to interrupt currents above a certain multiple of their rated current up to the breaking current.

gR: Full range semiconductor protection
Full range breaking capacity fuse-links, which are able to carry continuous currents from the lowest up to their rated currents and are able to interrupt currents from the minimum melting current up to the rated breaking current.

gRL: Fuses for the simultaneous protection of the semiconductor and the cables
Full range SIBA fuse-link with the same behaviour as the above mentioned fuses of class gR. Additionally this fuse is suitable for the overload protection of the cables. Instead of the older solution to take a semiconductor protection fuse and additionally a cable protection fuse, it may possible to take only one fuse of class gRL. Saving of space and cost is the main task for that kind of fuse. (See a special report at our web-side)

5. Applications

5.1 SIBA ultra-rapid fuse-links in rectifier circuits

The most common rectifier circuits are shown in table 5.1. The operating currents and operating voltages are coordinated to the individual circuits.

Given are the coefficients for:

- Operating current of a phase fuse-link as a multiple of the D.C. load current
- Operating current of a fuse-link placed at the inverter branch as a multiple of the D.C. load current
- Maximum value of the rectifier voltage as a multiple of the transformer voltage
- Operating voltage of the fuse-link as a multiple of the floating voltage

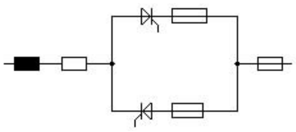
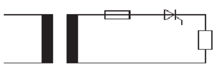
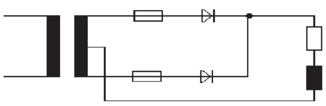
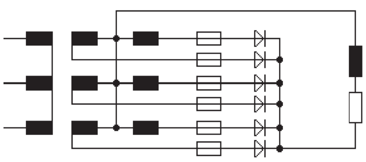
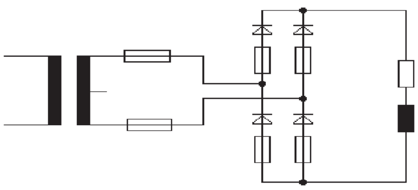
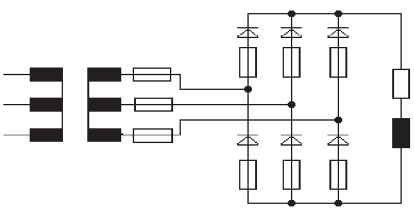
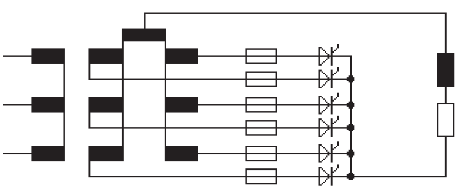
			Fuse @ Phase	Fuse @ Branch		
Circuit	Code	Type	I_{RMS} / I_{DC}	I_{RMS} / I_{DC}	U_{AC} / U_2	U_{Fuse} / U_D
		Single phase	1.00	0.50	1.41	-
	M1	Single phase half wave	1.57	1.57	1.41	2.22
	M2	Single phase full wave	0.71	0.71	2.83	2.22
	M6	Six phase	0.41	0.41	2.5	1.48
	B2	Single phase	1.00	0.71	1.83	1.11
	B6	Six phase	0.82	0.58	2.5	0.74
	SD6 SD12	Six phase Twelve phase	0.29 0.14	0.29 0.14	2.50 2.50	1.48 1.48

Fig. 5.1 Circuits for power semiconductors and the appropriate calculation coefficients

5.2 Series or parallel connection of SIBA ultra-rapid fuse-links

5.2.1 Series connection of fuse-links

Protecting rectifier circuits of operating voltages higher than the rated voltage of the available fuse-links or in case of standardized fuse-links shall be used there is the possibility of a fuse series connection. (See also Figure 5.2.a)

This kind of protection requires identical resistances of the series fuse-links of identical rated current. The same production batch and the same type made by the same manufacturer are also necessary. In addition, it has to be ensured that the size of the short-circuit current to be expected is at least 10 times the fuse rated current.

5.2.2 Parallel connection of fuse-links

To protect circuits with loading currents higher the current range of the available fuse ratings, two or more fuse-links can be used at parallel connection (see Fig. 5.2.b).

This application requires an optimal equal current load of the individual fuse-link group of identical rated current. In addition, the inner resistances of these fuse-links have to be in close tolerances. Also important is the use of fuses of the same production batch.

a) **b)** **c)**

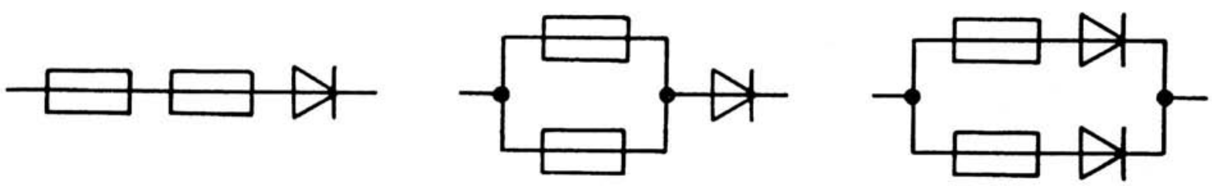


Fig. 5.2 Series and parallel connection of fuse-links

5.2.3 Semiconductors in parallel operation

Parallel connection of semiconductors also requires equal path currents. In general, it is sufficient to make sure that none of the semiconductors has to take a too high let-through current. Some applications, however, especially when several semiconductors are connected in parallel, require measures against too high closing losses of the fastest switching thyristor. Such a measure would be the series connection of resistances in the individual branches.

Fuse-links connected in series to thyristors can take over the function of resistances. Here it is certainly necessary that all fuse-links have equal resistances.
Circuits according to Fig. 5.2.c the same current flows through the fuse-link and the semiconductor cell to be protected. The load current splits each half on both sides at synchronous operation. The integral values of the fuse-link and the semiconductor cell are to be assigned directly to each other.

6. Consideration of practical behaviour in inverter circuits

SIBA ultra-rapid fuse-links are developed and rated according standardized conditions. In practice, however, use of fuse-links for semiconductor protection is seldom done that way. In case of operation, differing from these stipulations it may happen that the full rated current cannot be carried or that a higher load of the fuse-link is possible. The conversion coefficients in the data sheets consider such deviating conditions. Therefore, it is necessary to consider the special behaviour of the fuse-surrounded area like cooling, heat sources etc. In addition, it is of high importance to recognize cyclic load or peak currents.

6.1 Thermal influences

A warmer ambient temperature may reduce the current rating of the fuse-link. As the different types of fuse-links react different to higher temperatures, each type is given a constant "a". To consider a surrounding temperature above 30 °C it is necessary to calculate on the basis of "a" the coefficient "A1":

$$A1 = \sqrt{\frac{a - \vartheta U}{a - 30}}$$

Coefficient "B1" considers an additional cooling by external ventilation. If the air speed v_L (measured at the side of the fuse-body in a distance of 1 to 2 cm) is about 5 m/s then B1 has a value of 1.25, if the air speed is different to 5 m/s one has to calculate:

$$B1 = 1 + 0.05 * v_L$$

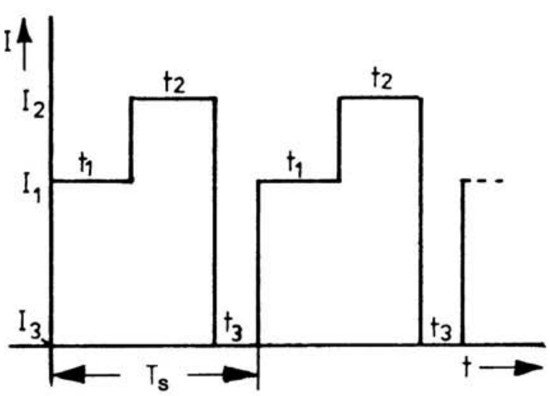
With A1 and B1 it is possible to up rate the load current I_L to the smallest fuse rated current I_{min}:

$$I_{min} = I_L / (A1 * B1)$$

In case of thermal influences, the chosen fuse rated current must be equal or higher than the calculated smallest fuse rated current $I_{min.}$

6.2 Cyclic load operation

Cyclic load operation with regular or irregular variation of load currents has considerable influence on the fuse-links lifetime. (See the technical essay at our web-side) This operation with load periods of 0.1 second up to one hour requires a complex calculation. For defined part times, coefficient A2 for regular and irregular load periods and B2 for each current step at the load periods has to be differentiated.



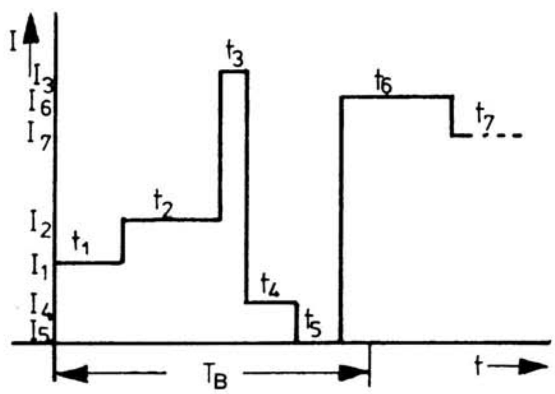


Fig. 6.2 Regular and irregular load

In case of cycling load, the RMS-value of the load current obtained over the period Ts has to be divided by coefficient A2 to get the smallest fuse rated current.

$$I_{min} = I_{RMS} / A2$$

While the coefficient A2 is influencing the rated current, the coefficient B2 has to be considered in coherence to the fuse curve. Here B2 indicates the distance between the value of the current step and the smallest value of the time/current-curve obtained over the part periods tn.

$$I_{TCC} >= I_n / B2$$

6.3 Extraordinary overloads

Should seldom appearing short time overloads be considered, however, not be interrupted by the fuse-link; or at load currents of a certain value a short-circuit breaker and not a fuse-link positioned behind the circuit breaker shall cause the interruption of the circuit, coefficient Cf3 has to be used. Similar to the application of coefficient B2, also Cf3 indicates the distance between the value of the current step and the smallest value of the time/current-curve obtained over the part periods tn.

$$I_{TCC} >= I_n / Cf3$$

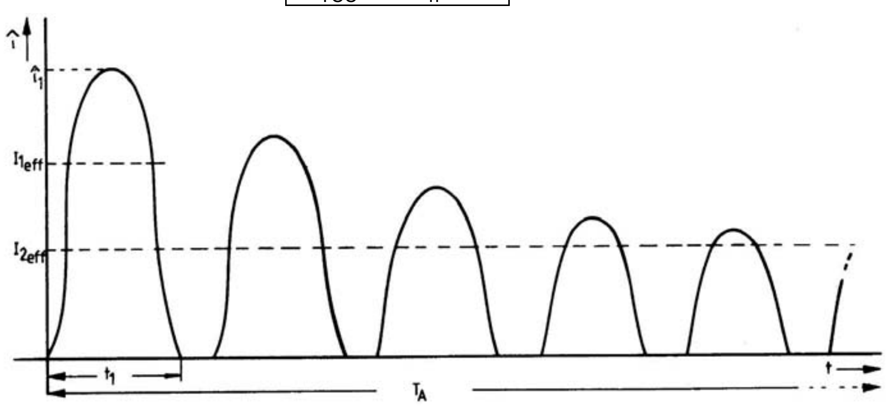


Fig. 6.3 Extraordinary overload

6.4 Application

In sum to have the appropriate rated current of the fuse-link one has to calculate at first the smallest possible rated current by

$$I_{rat} >= I_{Load} / (A1 * B1 * A2)$$

Afterwards there is a need for a comparison of the single load current and the fuse-curve

I_{TCC} of $I_{rat} >= I\ n / (B2)$ or/and I_{TCC} of $I_{rat} >= I_n / (Cf3)$

7. Optimal protection for your rectifier equipment

The criteria for selection of the fuse-link providing optimal protection of your rectifier are itemized below. To guarantee trouble free operation all mentioned points have to be considered.

7.1 Selection criteria

$I_B \le I_{rat}$

The fuse-link load current I_B has to be smaller or equal to the fuse-link rated current I_{rat}. All influencing components (alternating load, impulse load, thermal influences) have to be considered.

$U_B \le U_{rat}$

The operating voltage U_B calculated or determined from Figure 5.1 has to be smaller or equal to the fuse-link rated voltage U_{rat}. In case of doubts, the rated voltage of the component to be protected can be used as basis.
It has to be considered that during faults and generative load the voltage to be interrupted at the fuse-link may reach 1.8 times the supply voltage.

$I^2t_A < I^2t_{sem}$

The breaking integral value of the fuse-link I^2t_A has to be smaller than the limited load integral of the semiconductor cell. If necessary, the limited load integral has to be calculated by indication of the peak current limit value I_{TSM} of the semiconductor.

$U_L < U_{RRM / DRM}$

The arc or switching voltage U_L shall not exceed the value of the positive or negative blocking voltage of the semiconductor cell.

$I_{K''} < I_{K max}$

It has to be checked whether the possibly arising short-circuit current $I_{k''}$ resulting from reactance of the installation is smaller than the tested maximum breaking capacity of the fuse-link.

7.2 Selection procedure

A flow chart gives a guideline of how to select fuse-links considering all conditions and influences.

7.3 Protection lay out in our works

An easy possibility to design the protection of your equipment is the engineering of the proper protection in our company. Based on many years of research of semiconductor components, electrical tests and experience in dimensioning fuse-links in rectifier circuits SIBA is in the position to elaborate maximum possible safety. Supported by a fuse-calculating program our engineers will consider your given maximum conditions and can therefore recommend the proper ratings and types for a suitable protection.

7.4 Special designs

There might be applications that do not allow using standardized fuse-links or fuse-links of sizes as offered in the catalogues. Special design of contacts, decrease or increase of rated current offered in the data sheets or special characteristic of time-current behaviour of a fuse-link different from our data sheets are only some examples of our possibilities to meet your specifications. Of course, these variations are only practicable within the physical limits.
In any case, however, our engineers are of course prepared to discuss your technical problems.

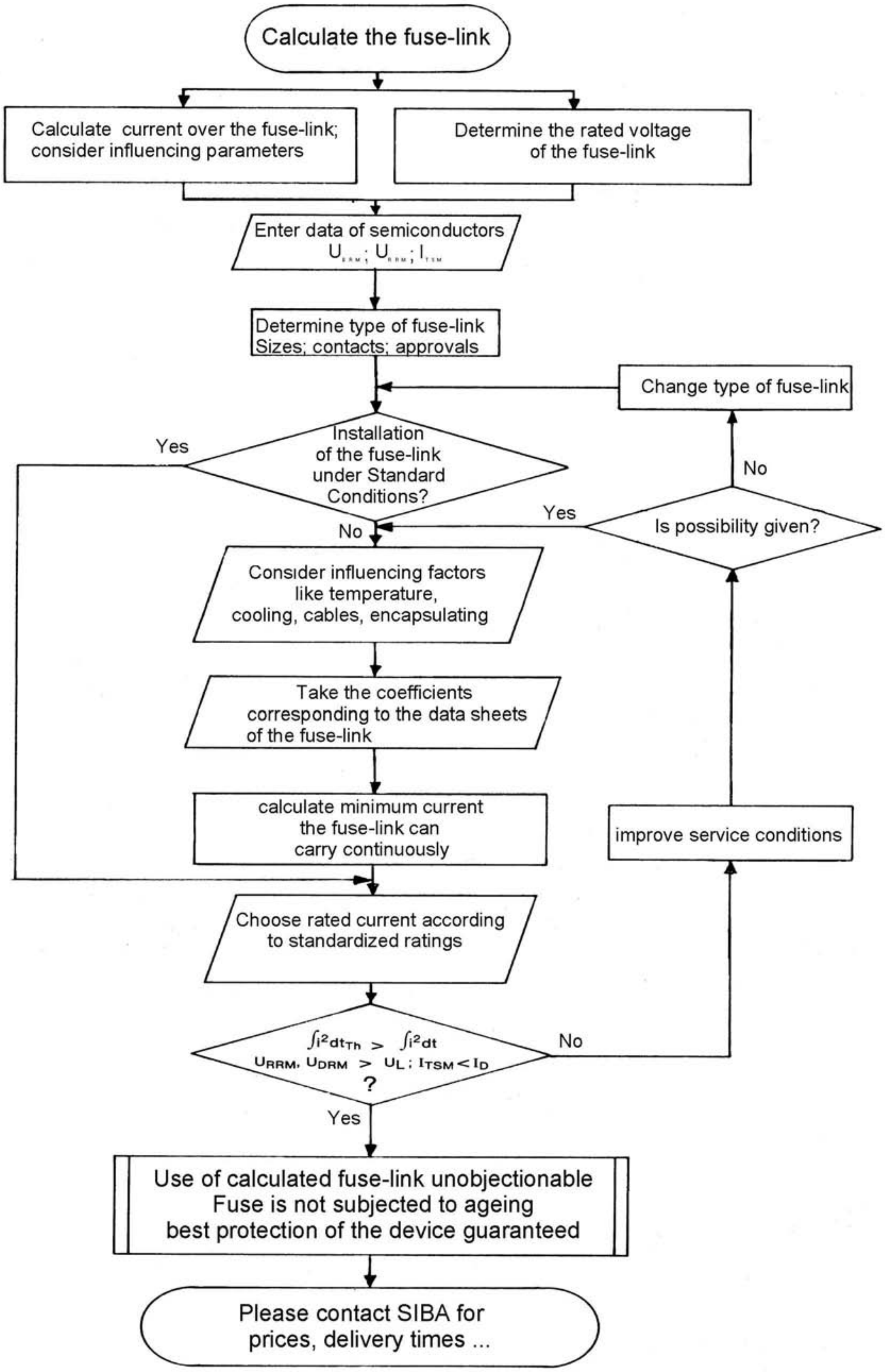


Fig 7.2 Flow chart for the selection of the semiconductor fuse-link

Ultra-Rapid Fuse-links for the protection of semiconductor-rectifiers

Annex A: Exemplary calculations

Thermal influences

A semiconductor cell has to be protected by a low-voltage fuse-link. The fuses are installed inside a temperature-controlled cabinet with an air speed of about v_L = 4 m/s while the temperature in the cabinet shows 80 °C.

The fuses should carry a load current of I_L = 200 A. Therefore L.V. fuses of size 000 with bolted connections are preferred. According our data sheets of that fuses the thermal constant "a" is given with 130.

$$A1 = \sqrt{\frac{a - \vartheta U}{a - 30}} = \sqrt{\frac{130 - 80}{130 - 30}} = 0.71$$

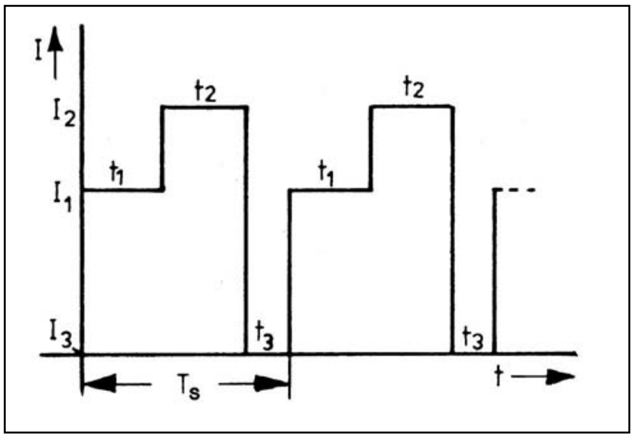
$$B1 = 1 + 0.05 * v_L = 1 + 0.05 * 4 = 1.2$$

$$I_{min} = I_L / (A1 * B1) = 200 / (0.71 * 1.2) = 235 \text{ A}$$

The rated current of the fuse-link should be 235 A or higher. Typically one would take a rating of 250 A.

Cyclic load operation

The designer calculated a regular load period through the thyristor in a given circuit. Load-times and currents are shown in the load diagram. The observed fuse-links will be connected in series to the semiconductor. As he preferred fuses of type "SQB" the coefficients for cyclic load operation "A2" and "B2" have to be taken from the fuse data sheet.



I1 = 260 A   t1 = 1020 s
I2 = 340 A   t2 = 300 s
I3 = 0   t3 = 420 s

From SQB-data sheet:
A2 = 0.75
B2 = 0.6

Calculation of the load current R.M.S. value:

$$I_{RMS} = \sqrt{\frac{I1^2 * t1 + I2^2 * t2 + I3 * t3}{t1 + t2 + t3}} = \sqrt{\frac{260^2 * 1020 + 340^2 * 300 + 0 * 420}{1020 + 300 + 420}} = 244\ A$$

Calculation of the smallest fuse rated current:

$I_{min} = I_{RMS} / A2 = 244\ A / 0.75 = 325\ A$

The rated current of the fuse-link should be 325 A or higher. Typically one would take a rating of 355 A.

Review of the load steps and comparison with the time current-curve of the rating 355 A:

$I_{TCC} >= I\ n / B2$

Checking the time current-curve of the rating 355 A at 1020 s: 560 A

560 A >= 260 / 0.6 = 433 A

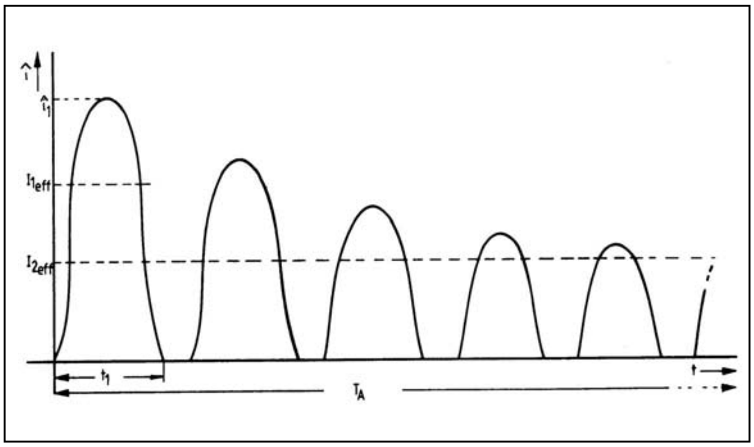
Checking the time current-curve of the rating 355 A at 300 s: 650 A

650 A >= 340 / 0.6 = 567 A

Based on the calculation above, a fuse rating of 355 A will carry the load according the diagram continuously. In a second step, one has to observe the I^2t-limits of the semiconductor and has to compare them with the fuse-integral. In this case, it may be necessary to reduce the fuse rated current.

Extraordinary overloads

An impulse load on the D.C. side of a converter causes a current through the fuse-link as shown in the load diagram. A load-break-switch interrupts such a load in a period of <200ms. It has to examine whether the fuse-link can carry the current for the duration of the overload without interruption.



$I1_{max}$ = 2000 A t1 = 14 ms

($I1_{RMS}$ about 1300 A)

$I2_{RMS}$ = 900 A t2 = 200 ms

SQB Fuse-link Size 1:

Rated current 355 A

Cf3 = 0.8

Review of the load first wave and the load-RMS value and comparison with the time current-curve of the rating 355 A:

$$I_{TCC} >= I\ n / Cf3$$

Checking the time current-curve of the rating 355 A at 14 ms: 1900 A

$$1900\ A >= 1300 / 0.8 = 1625\ A$$

Checking the time current-curve of the rating 355 A at 200 ms: 1600 A

$$1600\ A >= 900 / 0.8 = 1125\ A$$

Based on the calculation above, a fuse rating of 355 A will carry the load according the diagram continuously.

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