SIBA FUSES

Ultra-Rapid Fuse Links for the Protection of Semiconductor Rectifiers

1.General

The design of rectifier equipment requires specific provisions in the switchgear for the protection of power semi-conductor components have low thermal capacity so that the requirements for the planned protective device exceed those of standard devices. Both the rated current and voltage as the criteria for the fusing selection are no longer sufficient and the following has to be considered:

- High speed of response in the overload range
- Operating integrals adjusted to the limited load integrals of the semiconductor cell
- Low switching voltages 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 the equipment, as well as down time after a fault. SIBA ultra-rapid fuse links meet these requirements and efficient protection is provided. Features include:

- Extremely fast time/current behavior and low operating integral values
- Low temperature rise at the insulating body due to excellent thermal conductivity of the
- special ceramic.
- Low power loss under rated conditions.
- Free of ageing, due to the use of pure silver elements.
- Low switching arc voltage due to special element design.

The technical information presented here is intended to be used as a basis for design, and includes all the basics necessary for the selection of devices offering the maximum protection for rectifiers. Firstly, the fuse specific data is explained in detail, rendering a basis for the following chapters which examine the breaking process.

SIBA data sheets include characteristic curves, these are described in this documentation and examples given. The most commonly used rectifier circuits are shown in tabular form, properties of parallel and series connection of fuse links are given, and possible faults in circuits are treated.
Thermal influences, alternating load operation and current shock loads are considered and compensated by conversion coefficients described in the following chapter.
Finally, the last chapter shows, the criteria for calculating the optimum fuse link, and includes a flow diagram for an easy overview.

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 AC 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 AC current at a frequency range of 45Hz to 62 Hz. It is the current with which the fuse link can be loaded continuously under determined conditions without changing its characteristics.

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These conditions, provided by the standards, are:

- Ambient temperature (20 ± 5)°C
- No external cooling
- Connecting cross section specified

  Fuse links are mounted in open test rigs while testing

In practice, however, conditions are usually more diverse, and so 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 is calculated by multiplying the rated current by the value of the voltage drop measured over the fuse link after loading with rated current up to a final the steady temperature 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 or 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 or Arcing Voltage - U_L

Maximum value (peak value) of the voltage occurring at the term

Melting Integral - I^2t_s

Integral of the current square above the melting time. The value of the melting integral depends, amongst other things, on the construction of the fuse elements and the ambient temperature.

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

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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^2t_A

Total of the melting integral and the arc integral

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

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 is in the form of heat, is transferred to the environment via the terminals and the cables. At load currents above the rated fuse current, temperatures rise at the melting element notches inside the fuse link, so that in time these notches will melt. At these interrupting spots individual arcs occur, allowing 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 wave, an arcing time of less than 5 ms can be regarded as negligible. This melting time then 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 nearly one millisecond due to the steep current rise. At the melted notches, arcs occur which remain active as long as a 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 the specific SIBA design of the melting element. The arcing time in this case can no be longer regarded as negligible, because the arcing time is than the melting time.

Addition of melting time (t_S) and arcing time (t_i) results in the operating time (t_A). For protection of semiconductor components in this range the operating integral I^2t_A is decisive, that means the total of the melting integral and arc integral, **I^2t_A must always be smaller than the limited load integral of the semiconductor element to be protected.**

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 that time. The time t_0 is the beginning of the short circuit; a peak value as it is the maximum asymmetric short circuit current can be reached. After the time ts 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 influence of quartz sand. The breaking process is finished after the time t_A.

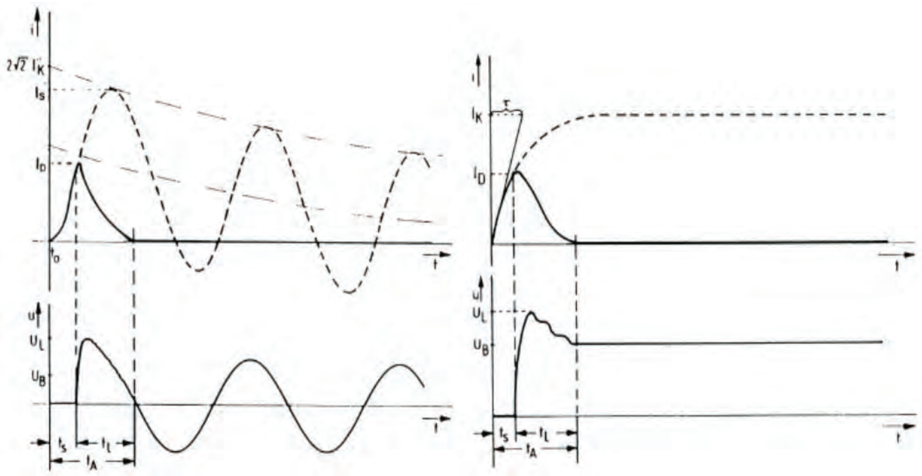

Fig. 3.3 Short circuit interruption at AC and DC currents

4. Graphic Presentation of the Fuse Link Operating Behavior

4.1 Time-Current Curves(TCC)

Time-current curves demonstrate the dependence of the melting time on the fault current 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 ± 7 % in direction of the current.

The limited operating ranges of ultra-rapid fuse links are indicated by the dotted part of the curve. This 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 overcurrents have to be limited with preconnected protection devices. A parallel curve with a value 80 % of the dashed ones indicates the maximum acceptable interrupting current and response 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, depending on the initial short circuit alternating current $I_{K"}$ to be expected.

The diagonal line in the diagram represents the possible peak value of the short circuit current to be expected according to the simple relation: $Is=I_{K"} * \sqrt{2}$, should a fuse link not be used.

Of more 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 cases of short circuit is an 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. For operation of ultra- rapid links with a load voltage smaller than the rated voltage, reduction of the switching voltage has to be fuse calculated. The diagram allows

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the determination of the arc voltage U_L in relation to the loading voltage U_B.

4.5 I²t Values

At high failure currents with melting times smaller than 5ms, an indication of the actual melting or switching times is 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 value of the operating integral stands for the sum of the extinguishing and melting process. Here the impulse is defined I^2t_A, which is a constant for each rating. I^2t_A is composed of two parts; I^2t_s, the current impulse needed to melt all of the element's notches, notches, and I^2t_L, the impulse current of the arc during the extinguishing process of the fuse. Note that this current impulse I^2t_A also passes through the semiconductor to be protected. In order to protect the semiconductor component from catastrophic failure, the rupture I^2t of the device must be obtained. $I2t_A$ than the I^2t rupture value of the semiconductor component.

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 correction curve diagram allows calculation of the operating integral at different operating voltages by giving a coefficient which is then multiplied by the operating integral given in the datasheet.

4.6 Operating Classes

The respective range of currents, over which the fuse link can operate, determines the 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 and 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(gS) - Fuses For the Simultaneous Protection of the Semiconductors and Cables

Full range SIBA fuse links with the same behavior as the above mentioned fuses of class gR. In addition, this fuse is suitable for the overload protection of cables. Instead of using a semiconductor protection fuse and a cable protection fuse, it may possible to use only one fuse of class gRL hence saving on space and cost.(See a special report at our website)

5. Applications

5.1 SIBA *U* ltra-*R* apid Fuse Links In Rectifier Circuits

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

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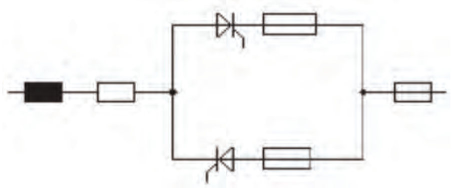
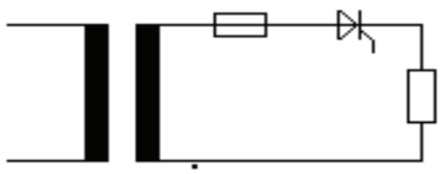
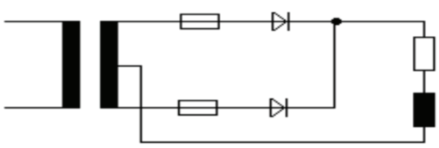
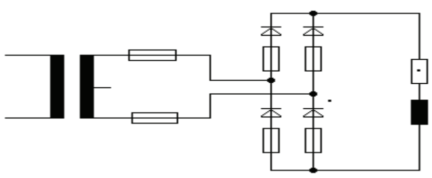
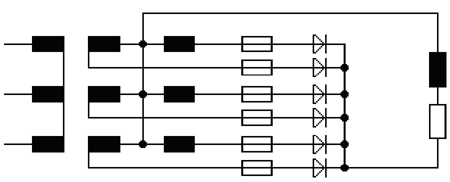
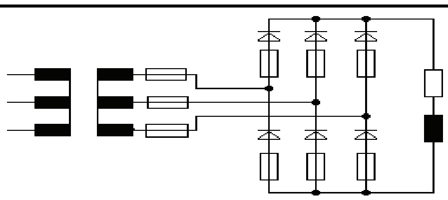
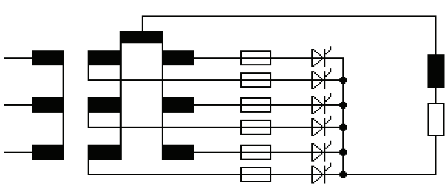
Circuit	Type	Code	Fusing Location			
			Phase	Branch		
			I_{RMS}/I_{DC}	I_{RMS}/I_{DC}	U_{AC}/U_2	U_{fuse}/U_{DC}
	Single Phase		1.00	0.50	0.41	–
	Single Phase Half Wave	M1	1.57	1.57	1.41	2.22
	Single Phase Full Wave	M2	0.71	0.71	2.83	2.22
	Single Phase	B2	1.00	0.71	1.83	1.11
	Six Phase	M6	0.41	0.41	2.50	1.48
	Six Phase	B6	0.82	0.58	2.50	0.74
	Six Phase	SD6	0.29	0.29	2.50	1.48
	Twelve Phase	SD12	0.14	0.14	2.50	1.48

Fig. 5.1 Cont. - Circuits for power semiconductors and appropriate calculation coefficients

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5.2 Series or Parallel Connection of SIBA *U*ltra-*R*apid Fuse Links

5.2.1 Series Connection of Fuse Links

Rectifier circuits that operate at voltage levels exceeding, the rating of a single fuse, may have the possibility of being protected by the use of two standard voltage rated fuses that are series connected (see Figure 5.2a).

This kind of protection requires that the series connected fuses are of the same voltage rating, and that the sum of the fuses, voltage ratings exceeds the rectifier's operating voltage. Fuses of the same current rating utilized in series requires that the resistance tolerance be very small. Usually this can be achieved by the use of fuses from the same production batch. In addition, **it has to be ensured that the size of the available short circuit current exceeds the fuse's rated current by a minimum of a factor of 10.**

5.2.2 Parallel Connection of Fuse Links

To protect circuits with loading currents higher than 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 for each fuse link group with identical rated current. In addition, the inner resistances of these fuse links have to be in close tolerance. It is also important to use fuses of the same production batch.

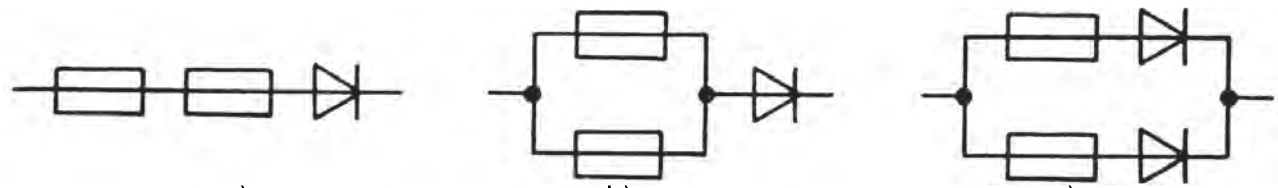

Fig. 5.2 Series and Parallel Connection of Fuse Links

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 have to take a too high let-through current. Some applications, especially when several semiconductors are connected in parallel, require measures against too high closing losses of the fastest switching thyristor. The series connection of resistances in the individual branches would be such a measure.

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. In such circuits (see Fig. 5.2.c) the same current flows through the fuse link and the semiconductor cell to be protected. The load current splits synchronously, half on each side. The integral values of the fuse link and the semiconductor cell are to be assigned directly to each other.

6. Consideration of Practical Behavior In Inverter Circuits

SIBA ultra-rapid fuse links are developed and rated according to standardized conditions. In practice fuse links are often used for semiconductor protection under conditions differing from those stipulated and 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 particular behavior of the fuse surrounding area, such as cooling, heat sources etc., and also to recognize cyclic load or peak currents.

6.1 Thermal Influences

A higher ambient temperature may reduce the current rating of the fuse link. As the different types of fuse links react differently to high 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":

$$A1 = SQRT \left[\frac{a - T_{(ambient-°C)}}{a - 30} \right]$$

Coefficient "B1" considers an additional cooling by external ventilation. If the air speed v_L measured at the side of the fuse-body at 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 to or higher than the calculated smallest fuse rated current Imin.

6.2 Cyclic Load Operation

Cyclic load operation, with regular or irregular variation of load currents, has considerable influence on the fuse link's lifetime. (See the technical essay at our web-side) This kind of 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 have to be differentiated.

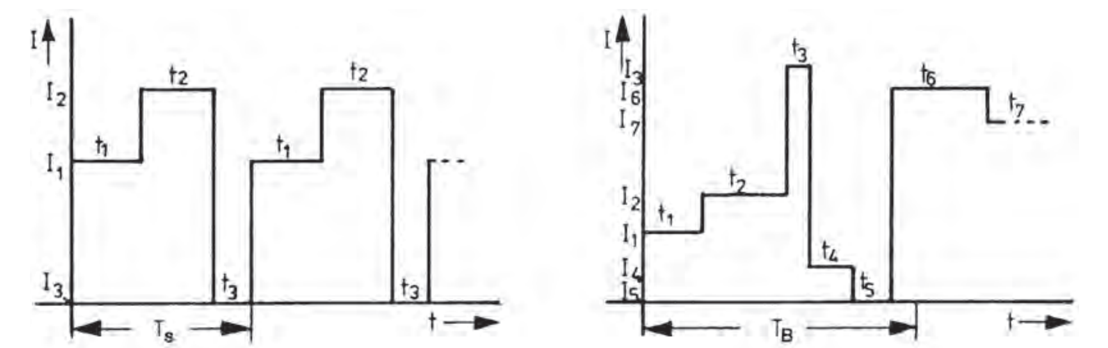

Fig. 6.2 Regular and Irregular Load

In the case of a cyclic 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.

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

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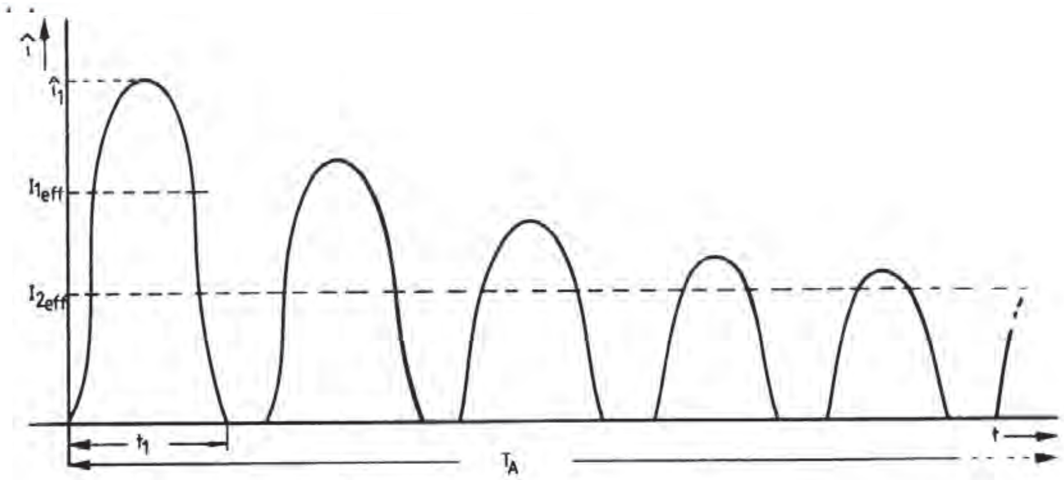
While coefficient A2 influences the rated current, coefficient B2 has to be considered in coherence with the fuse curve. Here B2 indicates the distance between the value of the current step and the smallest value of the time-current curve obtained over the part periods tn.

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

6.3 Extraordinary Overloads

Should occasional short time overloads without interruption by the fuse link be considered; or if at load currents of a certain value a short circuit breaker, and not a fuse link positioned behind the circuit breaker, should cause the interruption of the circuit, coefficient Cf3 has to be used. Similar to the application of coefficient B2, Cf3 also indicates the difference between the value of the current step and the smallest value of the time/current-curve obtained over the part periods tn.

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



6.4 Application

In sum, to find the appropriate rated current of the fuse link one first has to calculate the smallest possible rated current by

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

Then one needs to compare the single load current and the fuse curve

$$I_{TCC} \text{ of } I_{rated} >= I_n / (B2)$$
or/and
$$I_{TCC} \text{ of } I_{rated} >= I_n / (Cf3)$$

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7. Optimal Protection For 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 the given points have to be considered.

7.1 Selection Criteria

$I_B \leq I_{rated}$

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

$U_B \leq U_{rated}$

The operating voltage U_B calculated or determined from Figure 5.1 has to be smaller than or equal to the fuse link rated voltage U_{rated}. If in doubt, the rated voltage of the component to be protected can be used as a basis. It has to be considered that during faults and regenerative loads the voltage to be interrupted at the fuse link may reach 1.8 times the supply voltage.

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

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 can be calculated by indication of the peak current limit value ITSM 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 semi-conductor cell.

$I_{K''} < I_{kmax}$

It should be checked whether the prospective short circuit current $I_{K''}$ resulting from the reactance of the is installation smaller than the tested maximum breaking capacity of the fuse link.

7.2 Selection Procedure

The flow chart gives guidelines on how to select fuse links considering different conditions and influences.

7.3 Protection Analysis or Synthesis Available at SIBA

A straightforward solution to designing the appropriate protection for your equipment is offered by the engineering staff in our company. Based on many years of research into semiconductor components, electrical tests and experience in rating 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 accordingly recommend the proper ratings and types for suitable protection.

7.4 Special Designs

There may be applications that do not allow the use of standardized fuse links or fuse links of sizes the offered in the catalogues. Our possibilities to meet your specifications include, for example, the specific design of contacts; decrease or increase of rated current offered in the data sheets, or specific characteristic of time-current behavior of a fuse link different from our data sheets. Any variation is of course only practicable within physical limits. In any case, our engineers are of prepared to discuss and analyze your technical problems.

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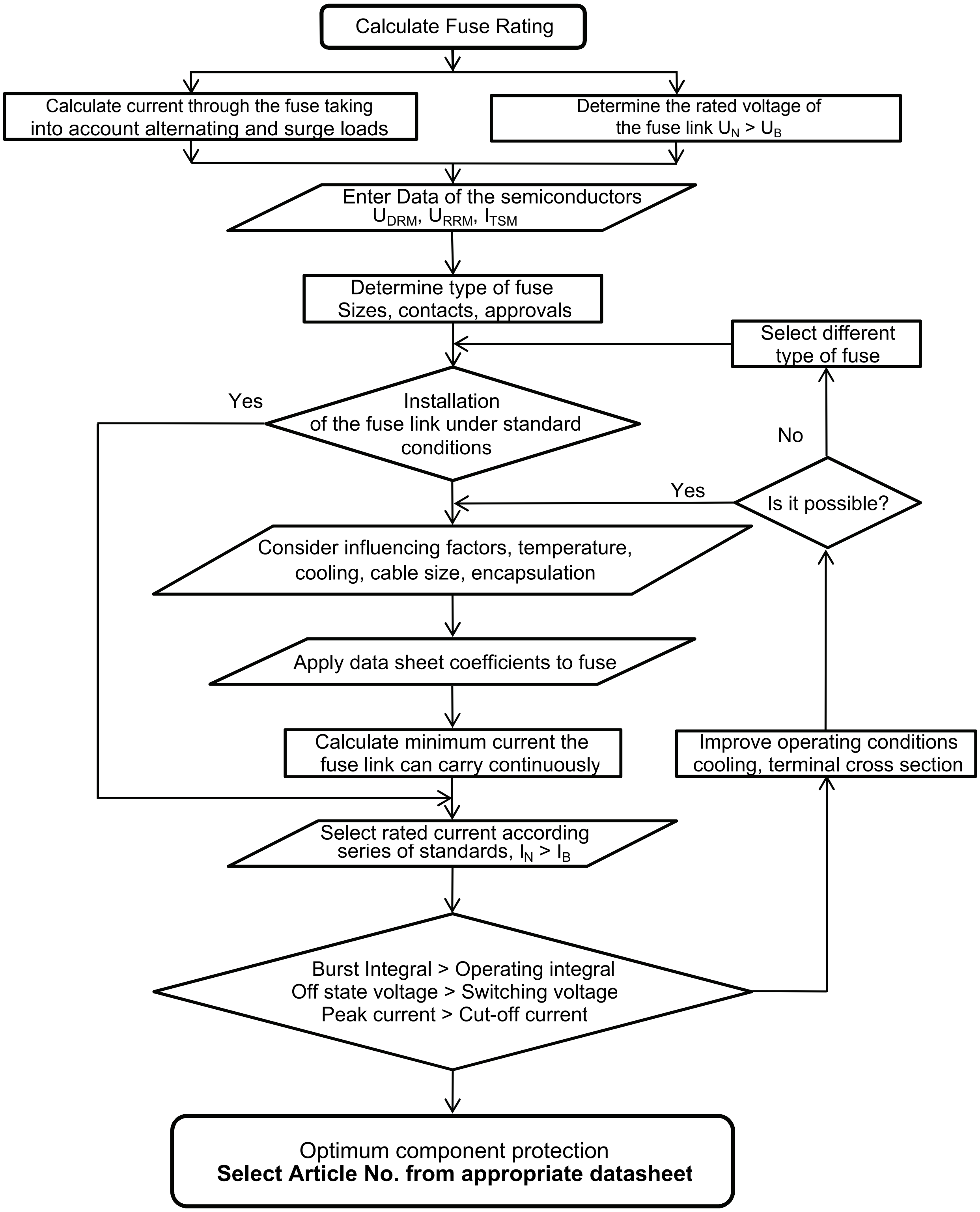

Fig 7.2 Flow chart for the selection of the semiconductor fuse link

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*U*ltra-*R*apid Fuse Links for the protection of semiconductor rectifiers

Annex A: Example 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 is 80 °C. The fuses carry a load current of I_L = 200A. Fuses of size 000 with bolted connections was preferred. According to the data sheets for these fuses the thermal constant "**a**" is given as 130.

$$A1 = SQRT\left[\frac{a - T_{(ambient\text{-}^oC)}}{a - 30}\right] = SQRT\left[\frac{130 - 80}{130 - 30}\right] = 0.71$$

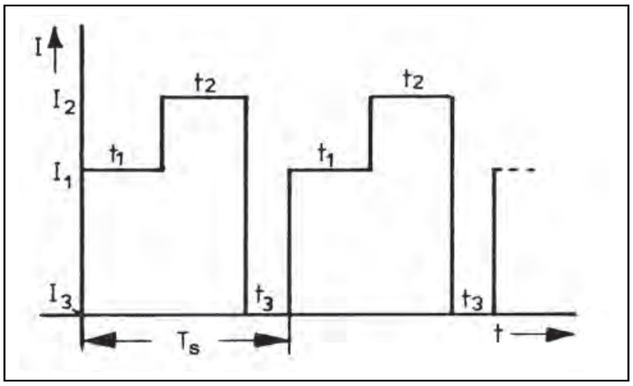
$$B1 = 1 + 0.05 * V_L = 1 + 0.05 * 4 = 1.2$$

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

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

Cyclic Load Operation

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



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

$$I_{RMS} = SQRT\left[\frac{I_1^2*t_1 + I_2^2*t_2 + I_3^2*t_3}{t_1 + t_2 + t_3}\right] = SQRT\left[\frac{260^2*1020 + 340^2*300 + 0*420}{1020 + 300 + 420}\right] = 244A$$

Calculation of the smallest fuse rated current

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

The rated current of the fuse link should be 325A or higher. Typically, one would take a rating of 355A. Review of the load steps and comparison with the time-current-curve of the rating 355A:

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

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

560 A >= 260A / 0.6 = 433A

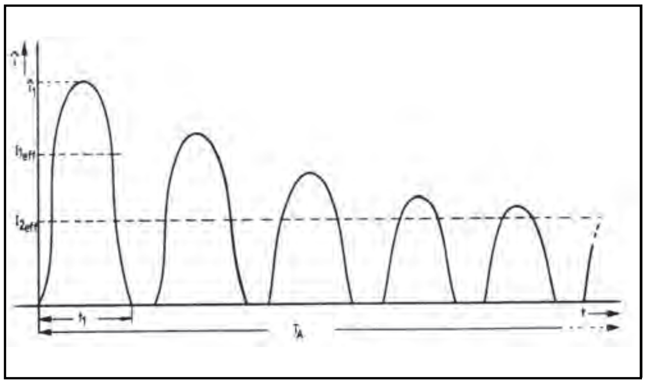
Checking the time-current-curve of the rating 355A at 300s: 650A

650A >= 340A / 0.6 = 567A

Based on the above calculation, a fuse rating of 355A will carry the load represented in the diagram continuously. As a next step, one should observe the I^2t-limits of the semiconductor and 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. One should determine whether the fuse link can carry the current for the duration of the overload without interruption.



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

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

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

1900A >= 1300A / 0.8 = 1625 A

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

1600A >= 900A / 0.8 = 1125 A

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

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