v simple
no allowance for burn back
we can always fit after the event

~~A SIMPLE METHOD TO CALCULATE THE MAXIMUM VOLTAGE THAT ARISES~~ WHEN A FUSE LINK BREAKS A DC SHORT CIRCUIT CURRENT.

Hans-Günter Rex , Berlinerstraße 5 , D-6902 Sandhausen

The breaking of a short circuit current needs a rising resistance of the breaking gap in the melting element of a fuse link. The voltage across the breaking gap increases simultaneously to a maximum value. In some cases this maximum value reaches ten times the value of the driving voltage. In the time interval before the maximum voltage experiments have demonstrated that the electric arc has a positive characteristic. The rise of the voltage has been found to depend allways in the same way on the arcing time.
On the following pages a simple method developped from experiments is described to calculate the maximum voltage with good accuracy for melting elements with one or more rows of restrictions and for dc short circuit currents of more than 20 times the rated current.

Das Unterbrechen eines Kurzschlußstromes erfordert einen zunehmenden Widerstand in der Schaltstrecke des Schmelzleiters. Die Spannung über der Schaltstrecke des Schmelzleiters wächst mit dem Widerstand zu bis zu einem maximalen Wert. In einigen Fällen kann der maximale Wert das Zehn-fache der Betriebsspannung erreichen. Experimente haben gezeigt, daß in dem Zeitraum vor der maximalen Spannung der Lichtbogen eine positive Charakteristik aufweist. Es hat sich auch gezeigt, daß das Ansteigen der Spannung immer auf dieselbe Weise von der Lichtbogenzeit abhängt.
Auf den folgenden Seiten wird ein einfaches aus Versuchen abgeleitetes Programm beschrieben mit ausreichender Genauigkeit für Schmelzleiter mit einer oder mehreren Engstellenreihen und für Kurzschlußströme von mehr als dem 20-fachen Nennstrom.

---

1. The purpose of the model and the range of application

In the last 15 years succesful attempts have been accomplished to get information about the current breaking process inside a fuse link (L3. L4. L5. L6). Today pc-programs are available to calculate the melting and the arcing process (L2. L7).
This paper deals with the arcing process inside a fuse link. The model of the arcing process is a mixture of theory and experiment.
This model informs about the reaction of a h.r.c fuse link with the melting element embedded in quartz sand of optimum grain size 4mm and its reactions to dc short circuit currents and breaking times up to 50 milliseconds.
If you know the numerical values of the arcing process evaluated for one characteristic experiment you can calculate the values for other experiments.
Equ.(6) is the base assumption for the model of the arcing process. All experiments were done at a time constant of 15ms. The melting element differs in the shape of the restrictions, in the number of the row of the restrictions and in the material.
The model informs about the voltage along the fuse link during the arcing period.
We only develop a model which gives necessary information about the current breaking process. The information is sufficient accurate and available in a few minutes without much effort.
In this paper I refer to melting elements with one or more rows of restrictions. The technical data of a manufactured fuse allow to develop a safe-fuse model and compare the calculated results with the experiment. You get necessary data with a minimum of experiments.
In the Lodz paper 1989 I did some assumptions to the arcing process in an ac circuit (L8). I had the opportunity to get detailed information about experiments in ac circuits (L9). When I compared the calculated results with the experimental values I found the error to be less than +- 10 percent. The short circuit current in an ac circuit is limited to the breaking time of about 15 ms. This is nearly the time of the first half wave of a 50 cycle ac current. In a dc circuit the region of the short circuit current is widened up to about 50ms breaking time. The arcing time sometimes exceeds 10ms. This needs a more precise model for the arcing process. Therefore I modified some assumptions of the Lodz paper 1989.
The dc-circuit model calculates ac circuits too.
The model is for a safe-operating fuse link only and not when limiting values are reached.

2. mathematical model of the arcing process

When we discuss electrical processes we refer to diagram no. 1. This means a circuit build up with dc voltage source Uo with the internal resistance Ri, resistor Ro and inductance L to control the short circuit current without fuse link. the resistor Rs of the fuse link solid melting element, a rising arc resistance Ra, a constant dc voltage Ue for each arcing gap in the element and switch s for breaking the melting current and for starting the arcing process.
Switch s in the closed position means the melting process is going on.
When switch s opens arcing begins. The current does not change very abruptly.
When a restriction is cut its Joulian resistance is replaced by an arc resistance Ra and a minimum arcing voltage Ue, the ignition voltage of the arc.
A changing current i(t) creates in the inductance L a counter voltage Ul(t) which delayes the changing of the current.

This effect can be expressed by

$$Ul(t) = - L *(di/dt) \tag{1}$$

The values of voltage and current in the circuit can be calculated by means of the differential equation

$$Uo = i(t)*(Ro+Ri+Rs) + i(t)*n*Ra + n*Ue + Ul(t) \tag{2}$$

The values Rs, Ro, Ri, L and Uo are known from the fuse link and the circuit. The values Ra and Ue belong to each cut restriction of the melting element. That means they do not belong to the solid restrictions during the melting period.
Inside the fuse link body shall be a melting element which contains n rows of equally shaped restrictions with the cross section Qe. Each restriction and the part next to it forms a single breaking device. This does not limit the applicability of the model.
In the prearcing period the fuse link in the circuit behaves like a resistor Rs. The value Rs and the whole melting process can be calculated by known methods.
In the prearcing period there is no arcing voltage Ue and no arc resistance Ra. When the melting element disrupts the resistance of each row of restrictions turns into a rising arc resistance value Ra and a voltage value Ue. We simplify and state the resistance Rs of the solid melting element material remains at nearly the same value Rs.
The process of creating the arc resistance Ra needs a minimum of time and energy. Therefore I propose the variable resistance Ra for the arcing process to be a function f(E) of the arcing energy E already done in a single arc. Other authors do assume other functions.
The breaking moment is set to zero and the arcing time begins at t=0. Thus after disruption of n rows of restrictions of the melting element the current i that flows through the melting element creates an arcing voltage value Ua measured along the fuse link.

$$Ua = n*Ue + i(t)*(Rs+n*Ra*f(E)) \tag{3}$$

Therefore equ.(2) changes into

$$Uo = i(t)*(Ro+Ri+Rs+n*Ra*f(E)) + n*Ue + L*di/dt \tag{4}$$

We look in equ.(4) for the derivation di of the current in the time interval dt

$$di/dt = (1/L) * (Uo - n*Ue - i(t) *(Ro+Ri+Rs+n*Ra*f(E))) \tag{5}$$

Nearly all numerical values belong to the prearcing process. The value Ue belongs to the arcing process and does not depend on any cross section of the melting element. The numerical value of Ue has little influence on the result.
The product Ra*f(E) must create a sufficient steep rise of the arcing voltage Ua and begin at a minimum value for t=0. The method try and error delivered for the function

$$Ra*f(E) = Ao/q * i*i*dt \tag{6}$$

The arcing factor Ao is of the dimension $mOhm*mm^2/(W*s)$.
The numerical value of Ao depends on the fuse link body and on the melting element. The value q is the cross section of the restrictions of the melting element in a defined fuse link body.
For the arcing process no significant difference between Ag- and Cu-material has been measured. The model therefore does not know any difference between the arcing of copper or silver material.
The current value i(0) in the moment t=0 at the beginning of the arcing process is the known melting current is. The voltage value i(t)*Rs is very small.
In the first time interval dt the energy dE(o) is

$$dE(o) = (Ra*is*is*dt)/n \tag{7}$$

In each following time interval the arcing energy increases with the value dE(t)

$$dE(t) = (Ra*i(t)*i(t)*dt)*n \tag{8}$$

Equ.(8) delivers the value of the variable arcing voltage at the end of the first time interval.
We calculate the value di/dt in the moment t=0 according to equ.(5) and determine the alteration di of the current within the time interval dt. In the moment (1) current has changed to

$$i(1) = i(0) + dt*(di(0)/dt) \tag{9}$$

$$i(t) = i(t-1) + dt*(di(t-1)/dt) \tag{10}$$

The formulas (3), (5) and (8) are simple equations to calculate the breaking process of a melting element inside a fuse link body for a wide variety of test conditions. The time interval dt = 25us delivers a good resolution in a program for accurate calculation and plotting. The program calculates simultaneously the arc voltage curve given by equ.(3).
We allways get the result within one minute and have allways sufficient accuracy. But we must not forget it must be a safe-operating fuse link.

The accuracy of the calculation is comparable with the accuracy of the experiment.

3. The melting element

A fuse can be designed with single strip or multiple strip melting element. When the melting process ends, the last row of restrictions in each strip is cut in the same moment. The arcing process starts when the melting current cuts the first row of restriction.
In order to get sufficient voltage withstand capability the disintegrated restrictions need a minimum gap and a minimum build-up energy. The necessary arc cross section carries the arc current, builds up an area with rising arc resistance Ra and develops the ability to withstand the rising voltage.
In real melting elements the cross section in each row of equally shaped restrictions is not equal. A difference in the cross section of +1% means an increase of the melting time of about 100 us. This means that the beginning of the arcing is

delayed about 100us, too. When we take into account this uncertainity of the beginning of the arcing process in each row of restrictions then the measured rise of the arcing voltage along the melting element is delayed and can show several steps.

There are melting elements with very much lead in the middle of one restriction. The heating up and the melting of such a restriction sometimes can be delayed so much that the restriction breaks only when current goes to zero. The arcing process then is controlled by one row less than intended. That means that less rows join the arcing process than the operator running the experiment expects.

It is easy to calculate a single or double strip melting element in a fuse link body. When there are three or more strips then often the arcing process does not need all strips. The arcing current reduces the necessary cross section and the arcing curve changes.

The value of the arcing resistance Ra increases.

You can calculate the arcing voltage when you reduce the value of the cross section for one strip less and when you reduce additionally the value of the inner cross section of the fuse link body proportional to the cross section of the melting element. The arcing process needs at least two strips of a multiple strip melting element.

Equ.(3) delivers the curve for the arcing voltage and equ.(10) the curve of the arcing current of a melting element.

The arcing process is controlled by the arcing factor Ae. Now the value Ae does not depend on the cross section of the restrictions.

4. The spacings of the dividing gaps

Stepwise calculation delivers both the voltage and the current.

Charge carriers leave the current path, carry away energy and go into the sand around the electric arc. Therefore I use a kind of non-adiabatic model.

When we have equally shaped rows of restrictions with equal spacings then all material between these restrictions is heated up by the arc current and especially by the arc heat and will change from liquid to gaseous within a few usec. This result in a remarkable decrease of the number n of the rows of restrictions and therefore in the values n*Ue and n*Ra. The current and the arcing voltage change.

It is significant for a well designed fuse element that this occurs only when the arcing voltage has passed its maximum value.

Melting elements with unequal spacings can be calculated or estimated separately for each spacing.

It is not difficult to calculate the arcing energy and adds it up until the necessary vaporizing energy of the gap connecting material is reached.

When we calculate the arcing process with a model that takes into account this breaking of the gap connecting material, then the displayed arcing voltage of the calculation shows the breaking of arcing voltage often at exact the same moment as the experiment.

5. The arcing voltage

In the first 25 usec a cutting voltage Ue is created along each gap and must be added to the voltage drop Rs*i(t) along the fuse element.

The arc resistance Ra increases and controls the arcing process. Gradually the current changes.

The rising arc resistance Ra and the falling current result in a maximum voltage within a few milliseconds after the beginning of the arcing process. Then the voltage decreases to supply voltage even when no disturbing process is going parallel.

When the current has fallen to zero the measured voltage becomes the emf-value of the voltage source.

We assume that n dividing gaps exist all over the arcing time. The gaps are separated by the gap connecting material (gcm). Then equ.(2) describes the arcing voltage curve.

When arcing begins the surrounding sand is an excellent insulating material and withstands high voltage values. When arcing goes on heat energy, electrons and positive ions leave the electric arc, disappear into the surrounding sand and heat it up. When the inner surface of the arc channel has reached a minimum temperature value then the inner surface of the arc channel begins to carry a resistive current parallel to the falling arc current. In this moment measurements show that the arcing voltage breaks to the supply voltage. The insulating capability of the sand decreases.

The arc resistance Ra increases.

6. Inside the volume of the fuse link body

The inner volume of the fuse link body influences the arcing process due to the pressure of the arcing material. The inner cross section of the fuse link body controls the arcing resistivity value Ae and changes the voltage value Ue.

The rising arc resistance can be realized by the increase of the gas pressure in the arc and by the decrease of the temperature in the arc.

When sand is not packed with normal density the compressibility of the sand increases and the arc quenching effect is lowered. Then the voltage rises less fast and arcing is delayed.

When the gap connecting material of the melting element vaporizes then gaseous material is added to encrease the pressure in the arc channel. This results in a better arc quenching but it lowers the arc voltage because it decreases the number of rows of restrictions.

When the arc is burning inside the quartz sand in a fuse link body then the surrounding sand is heated up and slowly begins to carry a fault current. When arcing does not decrease fast enough the fault current reaches a value equal to the arcing current. Then the arcing voltage falls to zero. The fault current is maintained.

7. How to use the program in practice

It is necessary to have the evaluated measurements of at least one experiment with the specified fuse link. Set the arcing factor Ae to 1 and calculate according to the above mentioned formulas. When the result is not as desired then change the arcing factor Ae and repeat the calculation until you get good approximation. Then calculate the fuse link with this same arcing factor Ae at modified test conditions.
Enter the complete mechanical information of the fuse link and the short circuit test conditions. Define the initial conditions for the beginning of the arcing process. Then the calculation is continued to the end of the breaking process.
It also helps to know the critical conditions of a given melting element. It helps to know the behaviour of a "not yet built" fuse link under various short circuit test conditions.
In practice it is important to get information fast and sufficient accurate. Extreme accuracy is not needed.
The program asks a minimum of questions and gives the needed information.
When the calculation is done it delivers numerical values about the arcing process, the arc current, arcing integral and arcing voltage.
At the beginning we did the limitation of equally shaped restrictions. We can neglect this limitation when we do extra calculation for each type of restriction as described above.
With modern small personal computers the calculation of the arcing process of a simple melting element needs about five minutes dialog time between computer and operator and less than one minute run-time.
The before mentioned method is part of a comfortable computer program STROMex. The program does not only the calculation of the arcing process of a simple fuse link but additional the melting process and heating up processes. It displays the curve on the monitor or external plotter and allows curve discussion.
Handling of the program is most simple. The answer is brought very fast. You can test various short circuit conditions without danger to material and with nearly no extra costs.

8. Literature

1. VDE-test-reports and technical data of h.r.c. fuse links
2. Rex: STROMex, das Rechnen mit Strömen. A program for model calculation developed for the MS-DOS-PC
3. Daalder, Schreurs: arcing phenomena in high voltage fuses, EUT-report, 1983

Liverpool papers 1976

4. Dolegowski : calculation of the course of the current and voltage of a current limiting fuse

Trondheim papers 1984

5. Paukert:electr. conductivity for arc extinguishing media for low voltage fuses
6. Leistad,Kongsjorden,Kulsetas: simulation of short circuit testing of high voltage fuses
7. Wilkins, Wade, Floyd: A suite of interactive programs for fuee design and development

Lodz papers 1989

8. Rex: The process of the breaking of an ac current in lv-hrc-fuse links calculated by means of a model in a personal computer
9. Ossowicki, Pisanko: influence of the distance of the contractions in the strip fuse element on breaking short circuit

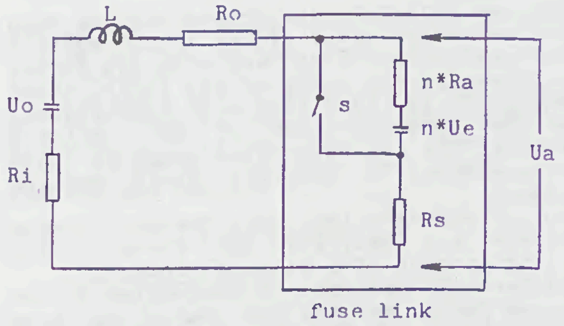

diagram no.1: circuit diagram

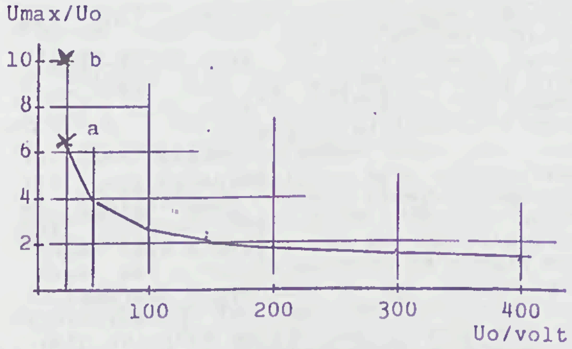

diagram no.2:
max. arcing voltage vs. supply voltage Uo

melting element: double strip
material : Ag
cross section : .1 mm^2
number of rows : 3
fuse link body
inner cross section: 380 mm^2
test current : 1200 A
measured values: a , b

The calculation of the arcing process delivers both values.
Umax, calculated as double strip: a
Umax, " " single strip: b