High Voltage Hybrid Fuse
- A new concept for the full range protection -

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Abstract

Conventional high voltage fuses, in which the fuse wire is surrounded by sand, have been successfully developed and are applied for many years, while the relevant arc quenching mechanisms studied intensively in the past is being fairly well understood now. However, there is a lack of switching capability in the low overcurrent range, which is depending on the basics of the arc quenching mechanism in sand filled fuses.

To fill this gap, investigations at the High Voltage Laboratory of the Technical University of Darmstadt have been performed since 1983, which aimed at eliminating this weakness. As a possible solution the design of a so called "High Voltage Hybrid Fuse (HVHF)" was proposed consisting of a modified conventional sand-filled fuse and a SF_6-filled fuse in series. While the conventional sand-filled fuse-part acts as a current limiter the new SF_6-filled fuse part acts as a current zero extinguisher.

Theoretical and experimental work will be dealt with in this contribution including considerations with respect to the coordination of the function of the two parts of the HVHF including relevant design criteria.

1. Introduction

Conventional high voltage fuses in general have a zone of an uncertain arc quenching capability and by this show an uncertain switching performance in the low overcurrent region. The relevant standard takes this weakness into account by defining several classes of fuses [1]. Back-Up-Fuses must be able to interrupt all currents between the minimum switching current $I_{a\ min}$ and the rated breaking capacity. General-Purpose-Fuses must be able to interrupt all currents from the level I_{1h} , at which operating time is one hour, up to the rated breaking capacity. Since 1992 a third class is defined by [2]. Full-Range-Fuses must be able to interrupt all currents which lead to fusing.

Thus the aim of future fuse development is defined by this standard. Now there are concepts required to be able to design a new type of High-Voltage-Fuse with these properties. Those must switch off all currents while the breaking and current limiting capacity of conventional fuses is maintained. In order to realize such a fuse the applicability of SF_6 for arc quenching in fuses is investigated.

2. Reasons for the uncertain switching performance in the low overcurrent range

When a conventional high-voltage fuse is stressed by a low overcurrent, a temperature profile across the fuse results as shown in Fig. 1. In the middle of the fuse the melting temperature T_m of the fuse wire will be reached. Thus a short arc is generated, which burns back to the caps of the fuse. The velocity of this burn-back process is proportional to the current. Low overcurrents lead to a low burn back velocity and thus to a low burn back length. The burn-back process continues until a gap distance is reached, which can withstand the recovery voltage after the arc has extinguished at current zero. The length of a gap needed in high voltage fuses is considerable. For a 10 kV-fuse a necessary gap distance of about 1 m was found in [3]. Furthermore the time required to melt the fuse wire is very high. Increasing temperature reduces the arc extinguishing properties of the filling media [4]. Thus a long arcing time results until the required gap distance is reached. The generated heat is transferred mainly in radial direction. The permissible temperature difference between the inner and the outer surface of the ceramic tube must not exceed 100 K [5]. This difference is reached after a few current cycles. Longer arcing times lead to bursting of the ceramic body. Then there is no chance for arc extinguishing.

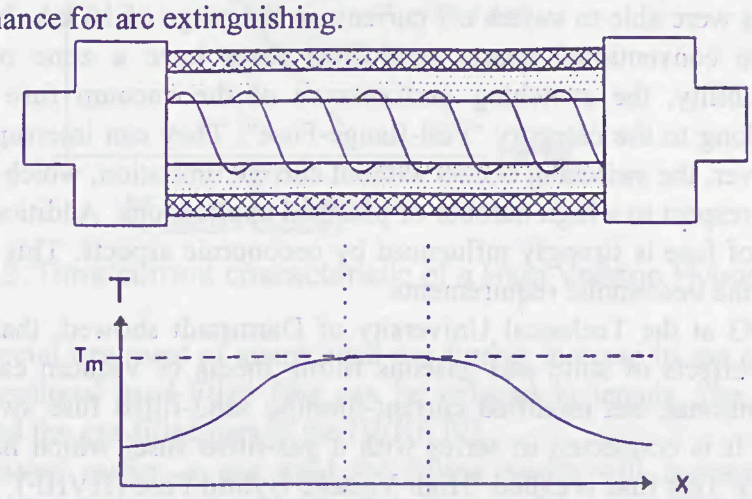


Fig. 1: Principle temperature distribution across a conventional high voltage fuse stressed by a low overload current

3. Ways towards the Full-Range-Fuse

The minimum current which can be cleared by fuselinks can be reduced firstly by varying the number of fuse elements. This method is well known and used in conventional fuses. But it is not possible to reach a Full-Range-Fuse only by the application of this method [6].
Secondly there the fuse wire material can be modified. In [7] a concept of a high-voltage fuse is proposed, which contains a fuse wire made of cadmium.The burn-back rate of a cadmium strip in sand is higher than that of a silver strip. Thus the required arc length is acchieved faster. One serious problem is the long-time stability of cadmium. Temperatures of more than 150 °C lead to sublimation of the fuse wire. The literature gives further examples for other fuse wire materials and material combinations. But mostly those are applied in low-voltage fuses, where the fusing of the wire is the major problem, while the required arc length after current zero is very short compared to high-voltage fuses. Thus these solutions are not simply transferable to high-voltage fuses, where the burn-back process is decisive.
There is thirdly the possibility of modifying the surroundings of the fuse wire. In [6] a star core made of an outgassing material is recommended. This measure should lead to a better cooling of the arc and a faster recovery of the dielectric strength after current zero. Similar considerations were presented in [8], where the fuse wire is arranged inside a tube made of an outgassing material. In [9] the properties of different filling media were investigated. High heat conductivity and high heat capacity were found to be necessary for clearing high short circuit currents and recognized to be responsible for the bad performance in the low overcurrent range. These properties lead to a low burn-back rate. However, filling media with low heat conductivity and low heat capacity lead to high burn-back rates. Gases and vacuum

are filling media having these required properties. Thus they enable a reliable switching of small overcurrents.
Other considerations for eliminating the weakness of conventional high voltage fuses were influenced by the excellent arc quenching capability of vacuum interrupters. The technologies of vacuum interrupters and power fuses were combined [10]. This resulted in a vacuum fuse, which is very similar to a vacuum interrupter. In an interrupter the arc is created by seperating the contacts. In a vacuum fuse the fuse wire is connected between two fixed electrodes. A fault current leads to fusing and creating of an arc. Due to the similarity to vacuum interrupters such vacuum fuses were able to switch off currents in the range of 10 kA. In the low overcurrent range, where conventional quartz sand-filled fuses have a zone of an uncertain arc quenching capability, the switching performance of the vacuum fuse was excellent, too. These fuses belong to the category "Full-Range-Fuse". They can interrupt all ranges of fault currents. However, the switching occurs without current limitation, which may be a severe disadvantage with respect to a high number of practical applications. Additionally the acceptance of a new type of fuse is strongly influenced by oeconomic aspects. This type of vacuum fuse does not meet the oeconomic requirements.
Investigations made since 1983 at the Technical University of Darmstadt showed, that the very different properties and effects of solid and gaseous filling media or vacuum can be skillfully combined. A conventional, but modified current-limiting sand-filled fuse switchs off the short circuit currents. It is connected in series with a gas-filled fuse, which has to interrupt the small overcurrents. This fuse is called "High Voltage Hybrid Fuse (HVHF).

4. Concept of the High Voltage Hybrid Fuse (HVHF)

Fig. 2 shows the principle of the High Voltage Hybrid fuse, in the following called HVHF. At the left, there is a sand-filled fuse part. At the right, there is a gas-filled one. These two

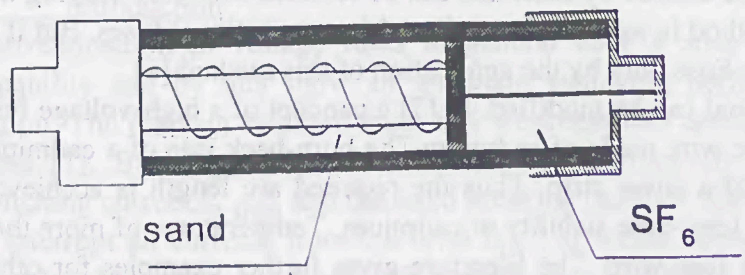


Fig. 2: Design of the High Voltage Hybrid Fuse (HVHF)

chambers are connected in series. By appropriate coordination of the sand-filled and the gas-filled fuse parts a time/current-characteristic can be acchieved as given in Fig. 3. All fault currents lower than the crossover-current I_C are switched off by the gas-filled fuse part, while higher currents are switched off with current limiting effects by the sand-filled fuse part. To meet the requirements of existing standards with respect to standardized dimensions the geometry of the new HVHF must be the same as for conventional sand-filled fuses. Thus investigations were necessary to optimize the sand-filled part for getting enough space for the gas filled part. Furthermore, investigations had to answer the question which filling media can be applied in the gas-filled part and which problems are connected with their application. Comparative investigations of different promising solid filling-media showed, that none of those filling media a enables a similar high breaking capacity as it was found for sand.

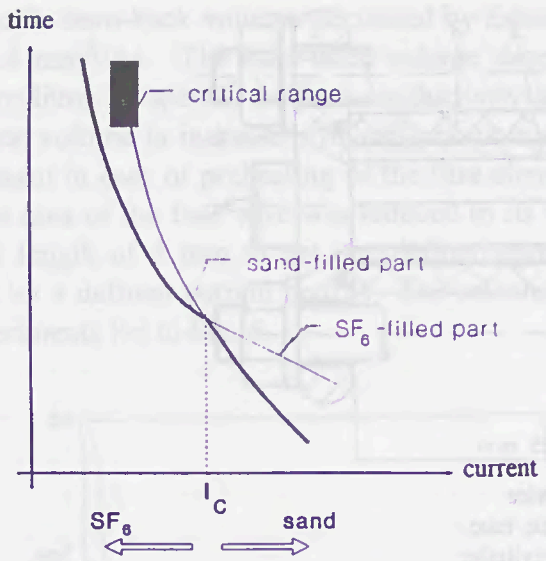
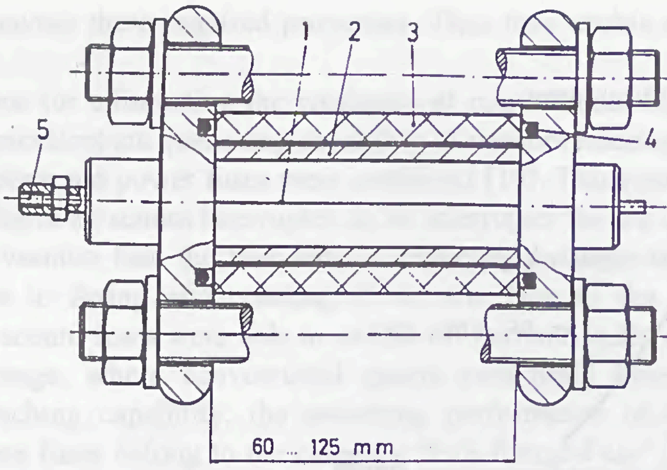


Fig. 3: Time/current characteristic of a High Voltage Hybrid Fuse (HVHF)

A special treatment of quartz sand can further increase its arc quenching capability. Thus the conventional sand-filled fuse can be reduced in length. The saved length can be used to extend the gas-filled part of the HVHF [9].
As stated earlier, a gas used for filling media will increase the burn-back length. The question, if a arc quenching will be successful or not will be strongly influenced by the recovery of the dielectric strength after current zero. Available experiences in the field of Gas Insulated Switchgear (GIS), where SF_6-gas is applied as an excellent insulating and arc quenching medium should be used. Therefore $SF_6$was mainly choosen for further investigations. The oeconomic aspects require a simple design of the fuse. Aim of the investigations at the Technical University of Darmstadt is to get knowledges about the possibilities and limits of simple designed SF_6 -fuses.

5. Test Arrangement

Fig. 4 shows the object of the investigations. The fine grained silver fuse wire (1) is placed concentrically in the ceramic tube (2). The PVC cylinder (3) and the sealing rings (4), ensure the gas-tightness of the test chamber. The test chamber can be filled with SF_6-gas by the valve (5). The fuse wire diameter varied from 0.15 mm to 0.67 mm. The investigated lengths of the wire and thus the ceramic tube were varied between 60 mm and 125 mm. The inner radius of the tube was 11 mm or 16 mm.
Investigations of the burn-back rate were performed singlepole in a 20 kV - network system. The current setting was made by inductances. The test current range is 2 - 150 A. A detailed description of this test circuit is given in [9,11].
Investigations about the influence of the fuse wire deposit on the dielectric strength after successful arc quenching were performed in a capacitor bank combined with an inductance. The 50 Hz test currents could be varied up to 800 A. After evaporation of the wire, the test chamber was stressed with variable voltages (AC) up to 100 kV. A detailed description of these tests is given in [12].



1 - fuse wire
2 - ceramic tube
3 - PVC-cylinder
4 - sealing rings
5 - valve

Fig. 4: Test arrangement

6. Burn-back performance of a fuse wire in SF_6

Under low overcurrent conditions the fuse-element reaches its melting temperature right in the middle of the fuse wire, where one arc is established. This arc is lengthened along the axis of the fuse wire. As long as the low overload current keeps running, the established arc burns back. The burn-back rate of the fuse wire is depending on the fuse-element material, its geometric dimensions, the filling medium and the current rating.
In [13] the burn-back rate v is described as proportional to the current density J. With the introduction of the specific burn-back volume c can be given:

$$v = c * J \qquad (1)$$

It is difficult to measure the burn-back rate v, which is proportional to the time dependent sinusoidal current. To assess the burn-back performance of different filling media, it is necessary to determine the specific burn-back volume c. The quantity c can be calculated, if Equation (1) is be developed by integration to:

$$c = A * L \frac{A * L_{bb}}{\int_{t_0}^{t_1} i\,dt}$$

where c - specific burn-back volume
A - cross area of the fuse wire
L_{bb} - burn-back length
t_0 - time of arc generation
t_1 - time of arc extinction
i - current

The arcing time as a difference between t_1 and t_0 and the current can be measured. The cross area of the fuse wire is known. After opening the test arrangement, the burn-back length l_{bb} can be measured.

The specific burn-back volume calculated by Equation (2) in sand is nearly constant value of about 1.4 mm^3/As. The burn-back volume depends on the heat transport features of the filling medium, in special the heat conductivity and the heat capacity [9]. Thus in SF_6 the burn-back volume is increased. Investigations in [13] determined that the burn-back rate is not constant in case of preheating of the fuse element. To check the influence of preheating, the cross area of the fuse wire was reduced in its middle reduced to the half of the diameter across a length of 1 mm to get one defined spot of interruption. Then the fuse wire was stressed by a defined current density. The calculation of the specific burn-back volume c of the experiments led to Fig. 5.

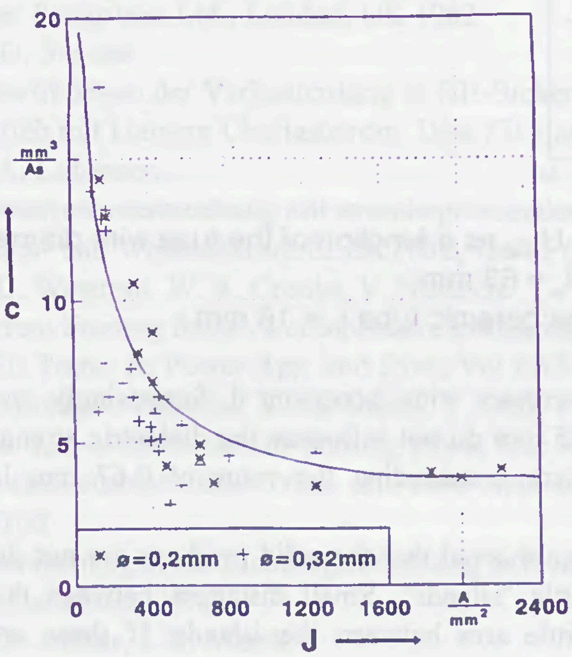


Fig. 5: Specific burn-back volume c in a SF_6-fillded fuse (p_{abs}=0.4 Mpa) as a function of the current density J for different fuse wire diameters

It shows the specific burn-back volume as a function of the current density for two different fuse wire diameters. The specific burn-back volume c for current densities of more than 800 A/mm^2 is about 4 mm^3/As and nearly constant. The arc lengthening in this current density range happens in SF_6 about three times faster than in sand. But with decreasing current densities this value increases up to 20 mm^3/As, which is a factor of about 15. This means, that very low overload currents increase the specific burn-back volume and thus these critical currents lead to over proportional high burn-back lengths.
This effect might be caused by the temperature distribution across the fuse wire. Inside a 10 mm large region near the caps, the wire temperature reaches 95% of its maximum value [14]. If an arc is generated, the rest of the fuse wire already has reached nearly its melting temperature.

7. Dielectric strength of the ceramic tube contaminated by silver wire deposit

Interactions between the evaporated fuse wire and the dissociated SF_6-gas produce gaseous and solid decomposition products. The solid products form a deposit layer on the inner surface of the ceramic tube, which increases with the volume of the evaporated wire. The aim

of the investigation is to find correlations between the geometrical characteristics of the ceramic tube, the fuse wire and the dielectric strength reduction due to the deposit.
The fuse wire was evaporated with a current density of more than 3000 A/mm^2. Then the test chamber was stressed with AC-test voltages up to 100 kV. Fig. 6 shows the one-minute withstand voltage U_{1min} as a function of the fuse wire diameter d.

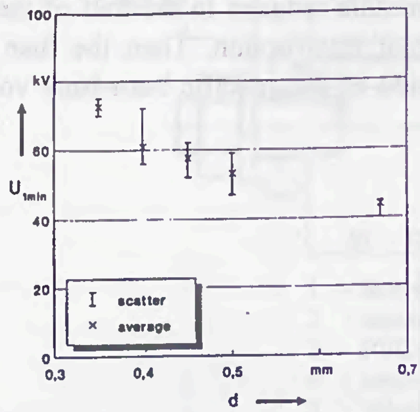


Fig. 6: One-minute withstand voltage U_{1min} as a function of the fuse wire diameter d
Parameters: fuse wire length l_{fw} = 63 mm
inner radius of the ceramic tube r_i = 16 mm

U_{1min} and thus the dielectric strength decreases with increasing d. Surprisingly, evaporated fuse wires with a diameter less than 0.35 mm do not influence the dielectric strength in the investigated range of voltages. Diameters d exceeding the value of 0.67 mm lead to a dielectric strength of less than 10 kV.
Optical investigations using a microscope showed that the solid products are not distributed homogeneously, but in the form of little "islands". Small distances between the islands require low voltages for ignition of little arcs between the islands. If these arcs unite, breakdown of the voltage across the specimen will follow. For very large fuse wire diameters (like the 0.67 mm in this example) many islands merge bridging parts of the insulating tube and reduce drastically the dielectric strength. Decreasing wire diameters lead to an increasing of the distance between the islands. Beyond a maximum distance, an influence of these islands on the dielectric strength does not exist up to a stress of 100 kV. It might be useful to get estimated values for the expected one-minute withstand voltage as a measure of the dielectric strength after arcing, in order to enable an optimization of a fuse filled with SF_6 with respect to variable chamber and wire geometries. Since neither this formation nor the behaviour of the internal arcs can be described precisily, a model was developed to solve this problem. A detailed description of this model is given in [12, 15].

Summary
Investigations performed during the past 10 years have showed that SF_6-filled fuses with a simple design are able to interrupt overload currents. However, SF_6-fuses can not switch current limiting, which is generally required for short circuit interruption. This task must be done by a sand-filled fuse part, which is connected in series with the SF_6-filled part. By optimizing the sand-filled part, these two fuses could be inserted in a conventional fuse housing, which has standardized dimensions. This new fuse, called High Voltage Hybrid Fuse (HVHF) fulfils the requirements of a Full-Range-Fuse. It can interrupt all currents, which lead to fusing, up to its breaking capacity and is able to act current limiting at high currents.

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