Simulation and verification of thermal modelling to prevent from damages caused by the use of HH fuses

Thomas Gräf
Hochschule für Technik und Wirtschaft Berlin
Berlin University of Applied Science for
Engineering and Economics
Wilhelminenhofstr. 75 A
12459 Berlin – Germany
thomas.graef@htw-berlin.de

Abstract— **Actually there were several cases reported, where HH fuses exploded and damaged the surrounding switchgear. The root causes for these destructions were broken fuse elements damaged by cyclic thermal-mechanical stress. The question arose how it will be possible to detect broken fuse elements while HH fuses are in operation at high voltage level. The access to the degrading HH fuse is especially not given in switchgear because of the presence of high voltage. An indicator for degrading fuses is the surface temperature. It is also of interest to know the actual temperature of the fuse elements itself to estimate the internal rate of rise of the temperature. This knowledge is important because at a certain temperature level the danger exists, that the ceramic fuse body will break unexpected by an explosion.**
Simulations and measurements were performed to get to know, how and if it would be possible to simulate the temperature distribution as a function of the number of broken fuse elements. With the knowledge of the thermal model of HH fuses it will be possible to predict the maximum temperature as well as the possibility to monitor the degradation level of HH fuses.

***Keywords*-- broken fuse elements, damage avoidance, temperature monitoring, thermal modelling**

I. Introduction

Fuses are a reliable product for the protection of electrical equipment against overload and short circuit currents. Under some circumstances fuses does not operate as they are expected. There are several root causes for the failure of fuses [1]-[5]. For the reduction of failures it would be helpful to know how it looks like inside the fuse e.g. to know the temperature at the fuse elements. With the knowledge of the temperature of the fuse elements it would be possible to estimate the thermal losses as well as the degree of utilization and the level of degradation. The contribution deals with investigations of the temperature distribution, modeling, simulation and comparison of temperature measurements at fuses, to reduce the risk of failure or the risk of additional damages to the usually protected electrical equipment.

II. Initial Situation

In Dresden at ICEFA 2015 a paper [2] was presented which applied to the avoidance of damages due to exploded fuses. The root cause for the explosion of fuses was science based on broken fuse elements because of the repetition of cyclic loads. For the reduction of explosions due to the degradation of fuses a sensor system was developed to measure the temperature at the surface of the fuse while this is in operation. Thermal energy harvesting needs to be used to convert thermal energy to electrical energy to power the temperature measurement sensor system Temperature Observation Contactless fuse (TOC fuse) because of the presence of high voltage. If there is a temperature difference between the surface of the fuse and the lower surface of the TOC the sensor will be in the situation to be powered, measure the temperature and transmit the measured temperature values outside the high voltage area via radio frequency. The TOC sensor is directly placed at the surface of the fuse where the highest temperature gradient can be expected. This is even possible inside e.g. a fuse tube. Fig. 1 shows a switchgear with inserted HH fuse whereas Fig. 2 shows a HH fuse with clamped TOC fuse sensor while it is pushed into the fuse tube.

Copyright © 2019 Published by Fuse Cliub and High Voltage and Power Systems Research Lab of the University of West Attica. All Peer-review process under responsibility of the scientific committee of the 11th International Conference on Electric Fuses and their Applications, ICEFA 2019

Fig. 1 Switchgear with HH fuse and TOC sensor adapted

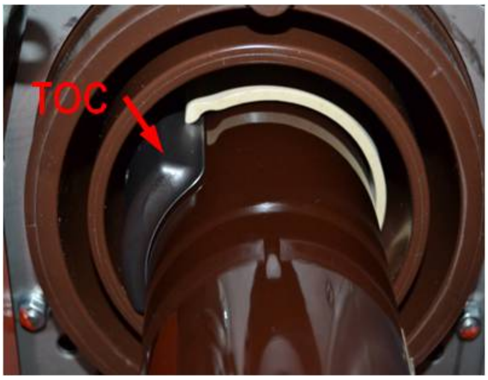

Fig. 2 Adapted TOC sensor with clamp ready for operation

III. MEASURMENTS AT DEGENERATED HH FUSE

Investigations were performed at prepared fuses because of the increasing number of broken fuses especially at the generation of renewable electrical energy. Fig. 3 shows a fuse tube in what the thermal investigations at fuses were performed. At different locations several thermocouples were installed to measure the temperature distribution around HH fuses. The TOC fuse sensor was placed later according to the results of these measurements due to the needed maximized temperature gradient. This arrangement of fuses corresponds to gas insulated switchgear shown in Fig. 2 and Fig. 5. Inside the HH fuse were 4 fuse elements integrated. The fuse had a rated current of 63 A. Soldering marks were placed at several points at four fuse elements while the HH fuse was produced. The soldering marks were used because silver melts at 968 °C which is too high for the insulation material surrounding the fuse. Soldering depots were placed to the fuse elements to reduce the melting temperature to lower values. The risk of uncontrolled behavior of the HH fuse was reduced with this manipulation. Fig. 4 shows the temperature distribution at different locations. The fuse was operated at a constant current of 45 A while it was inside the fuse tube. The heating of the fuse led to an increased resistance. The constant current source increased the voltage to keep the current constant. The sampling time of the data acquisition system was $t_{sample} = 5$ s ($\triangleq$ measuring point). The first fuse element melted after 120 minutes at a measured temperature of 110 °C at the surface of the fuse body. After additional 4,5 minutes later the second fuse elements melted while the measured temperature at the surface of the fuse reached 150 °C. After the melting of the second fuse element the temperature increased rapidly at the surface to 300 °C within 16 minutes. The rate of temperature rise increased to very high values. As a result of the high surface temperature of the fuse due to the melted fuse elements the temperature inside the fuse needs to be substantial higher. The investigations were stopped because of the unknown inner temperature and to limit the risk of explosion of the internal forces due to the thermal expansion of the quartz sand filling. For the detection of high rate of rise of the temperature due to broken fuse elements a temperature monitoring system based on an energy harvesting temperature measurement sensor was developed and patented [7]-[9].

Fig. 5 shows the location of the thermocouple to measure the temperature distribution inside a gas insulated switchgear while the HH fuse has a single broken fuse element at phase b. Due to the broken fuse element the temperature increases rapidly inside the fuse tube whereas in the other fuse tube only a slight increasing of the temperature due to the normal heating can be detected. The TOC fuse sensor is able to measure the temperature inside the fuse tube and transmits the data (Δ) outside the high voltage area to standardized control systems.

- In your paper title, if the words “that uses” can accurately replace the word “using”, capitalize the “u”; if not, keep using lower-cased.

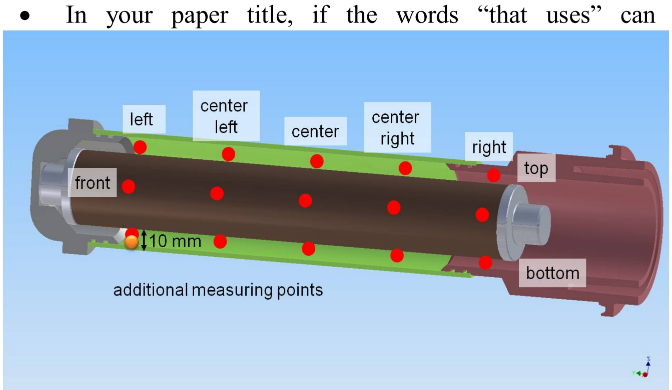

Fig. 3 Location of thermocouple inside switchgear and fuse tube

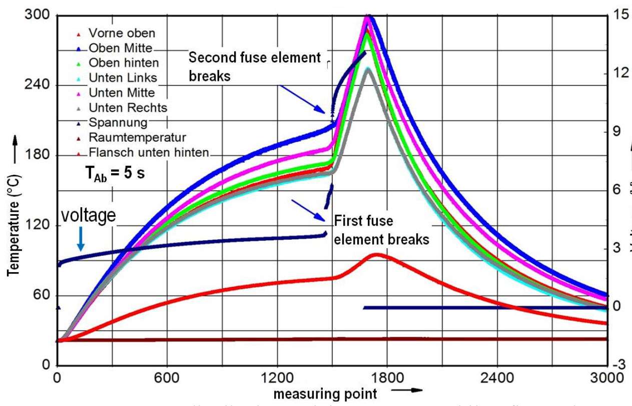

Fig. 4 Temperature distribution and time response while a first and second fuse element breaks

Copyright © 2019 Published by Fuse Cliub and High Voltage and Power Systems Research Lab of the University of West Attica. All Peer-review process under responsibility of the scientific committee of the 11th International Conference on Electric Fuses and their Applications, ICEFA 2019

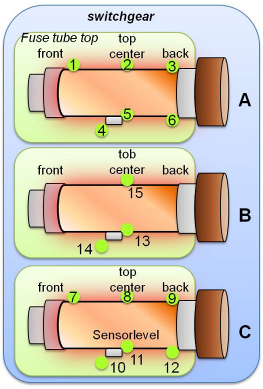

Fig. 5 Temperature measuring points inside fuse tube of gas insulated switchgear

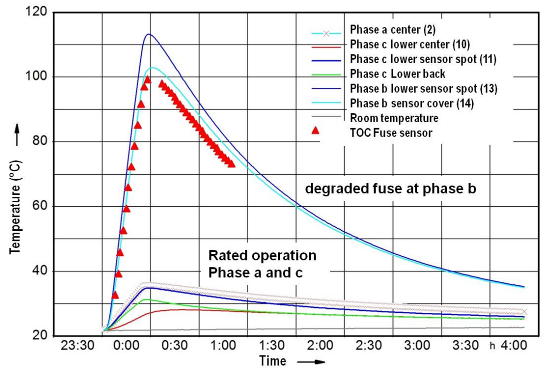

Fig. 6 Use of TOC fuse sensor and measured temperature distribution inside fuse tube while fuse with single broken fuse element is in operation

IV. Thermal Modelling of Fuses

Due to the fact that the temperature inside the fuse is much more higher than it can be measured at the surface it is worth to think about the modelling of the thermal behavior of the fuse. One of the goals of the simulation is to calculate the temperature of the fuse elements. If the temperature inside the fuse is known, the danger of uncontrolled explosion of the fuse can be reduced. The critical temperature inside the fuse is influenced by the quartz sand filling, the thermal capacity of the electrotechnical porcelain as well as the density of the quartz sand filling. Additional physical effects like thermal convection as well as thermal radiation need to be considered. The physical characteristics of the quartz sand are remarkable. The quartz sand changes at a temperature of 573 °C its thermal conductivity and density. At that temperature it is possible that the filled quartz sand starts to extend but the surrounding electrotechnical porcelain body does not expand in the same way. If the pressure inside the electrotechnical porcelain body reaches the limit of the mechanical strength of the electrotechnical porcelain body, the electrotechnical porcelain will explode suddenly. Sequentially the switchgear will be destroyed too. At least with the previously presented sensor it is possible to measure the temperature at the surface while the HH fuse is in operation and to detect abnormal conditions. Today it is possible to use software tools and less expensive computer to calculate and estimate the condition inside the fuses. But to come to sufficient accuracy and reliable calculation models need to be available that allow the exact prediction of the thermal situation inside the fuse. For the verification of the thermal modeling and results of thermal simulation the comparison between simulation and measurement is mandatory.

A. Determination of the thermal characteristics

For modeling the thermal behavior of a HH fuse different kind of physical aspects need to be considered. The temperature of the fuse depends

- on the losses, generated by the fuse elements,
- the heat conduction of the quartz sand and the electrotechnical porcelain,
- the heat capacity of the quartz sand and the electrotechnical porcelain,
- the convection flow of the heat and
- thermal radiation.

First of all it is necessary to determine the thermal heat, which is generated by the fuse elements. The thermal losses are generated by the fuse elements, which consists of silver. The thermal losses depend on the actual resistance and are temperature-dependent. If the current of the fuse is kept constant, the power loss increases with the increase of the resistance with the temperature.

For the simulation of the thermal behavior of the HH fuse the values for the heat conduction and heat capacity of the quartz sand and the electrotechnical porcelain were measured at the own laboratory. Actual available literature contains only a few references. Especially for the quartz sand it is difficult to specify the exact values for heat conduction and heat capacity due to the ration of silica and air. For the exact experimental determination the maximal compressed quartz sand the pore content needed to be estimated. The density for the quartz sand was measured to $\rho = 1680$ kg/m^3. Tab. 1 shows material specific values that were determined at the test laboratory and were needed to calculate and simulate the thermal behavior of HH fuses.

Copyright © 2019 Published by Fuse Cliub and High Voltage and Power Systems Research Lab of the University of West Attica. All Peer-review process under responsibility of the scientific committee of the 11th International Conference on Electric Fuses and their Applications, ICEFA 2019

TABLE I. THERMAL MATERIAL SPECIFIC VALUES

Physical characteristic of	Characteristic value	
	Heat capacity [a]	***Heat conduction*** [a]
Quartz sand	$c_{quartz\ sand} = 0{,}885 \frac{kJ}{kg\,K}$	$\lambda_{quartz\ sand} = 0{,}252 \ldots 0{,}332 \frac{W}{m\,K}$
Electrotechnical porcelain	$c_{porcelain} = 0{,}785 \frac{kJ}{kg\,K}$	$\lambda_{porcelain} = 1{,}2 \ldots 2{,}6 \frac{W}{m\,K}$

a. measured values

Upright and horizontal operating positions of the fuse were considered for the thermal convection model. This is necessary because the position of the HH fuse affects the thermal convection to a considerable extent. Due to this the Nusselt number, the Reynolds number and the Prandl number for free thermal convection were calculated for a cylindrical body.

Finally the thermal radiation according the Stefan-Boltzmann equation was considered. Fig. 7 shows the complete model used for the simulation of the thermal behavior of HH fuses. The thermal model of the HH fuse of the type SIBA HHD 40 A BU considers the number of fuse elements, the thermal conductivity to the external connection, the different kind of material, the electrotechnical porcelain body as well as the quartz sand filling. Fig. 8 shows within the sectional view the result of a simulation of the HH fuse while a current of 35 A heated up the fuse. Each fuse element can be detected and generated a local temperature gradient. At both ends of the HH fuse the temperature sink to lower values due to thermal conductivity of the external conductors. This is important to know because inside the fuse is a thermal release implemented – striker pin – which should release if the HH fuse will overheat [5], [6]. Due to the convex temperature distribution [2], [4] and lower temperature at the end of the HH fuse, where the striker pin is implemented, the temperature in the center of the fuse will be much more higher than at the ends. This effect increases the probability that the fuse will explode before or delayed the striker pin will be released and cut off the current flow with the help of a fused load-breaker switch.

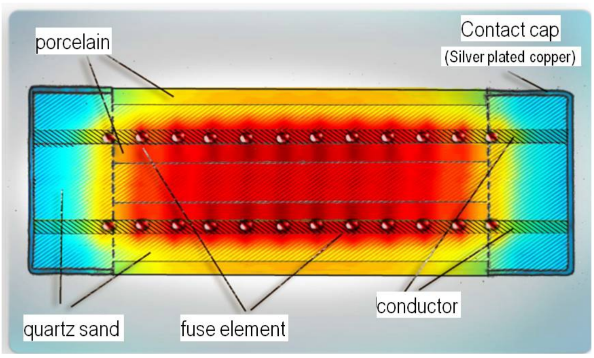

Fig. 7 Thermal model of the HH fuse in operation

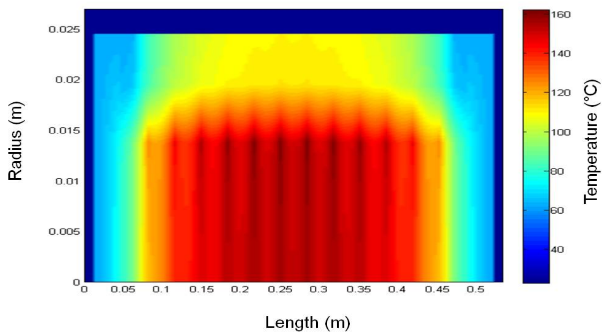

Fig. 8 Thermal simulation result at 35 A of the HH fuse type SIBA HHD 40 A BU

B. *Comparison of measurement and simulation*

The quality and accuracy of a thermal model can be determined by comparison with real measurements. For this purpose a HH fuse was equipped with thermocouple at different locations. Fig. 9 shows the prepared HH fuse equipped with thermocouple inside and outside the electrotechnical porcelain. Some of the thermocouples were fixed directly at the fuse elements. This fixation of thermocouples with an additional mass was difficult to build because the heating effect should not be significantly affected.

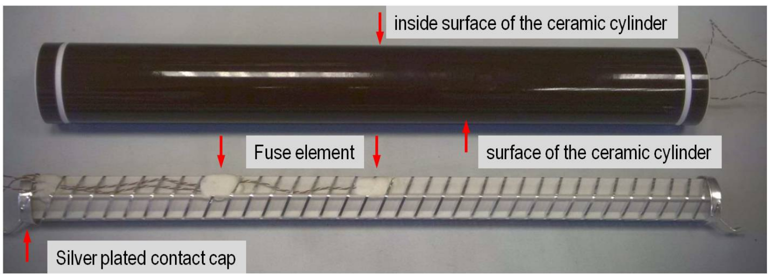

Fig. 9 HH fuse equipped with thermocouples inside and outside the electrotechnical porcelain, type SIBA HHD 40 A BU

Copyright © 2019 Published by Fuse Cliub and High Voltage and Power Systems Research Lab of the University of West Attica. All Peer-review process under responsibility of the scientific committee of the 11th International Conference on Electric Fuses and their Applications, ICEFA 2019

C. Comparison of Simulation versus Measurement of the temperature distribution

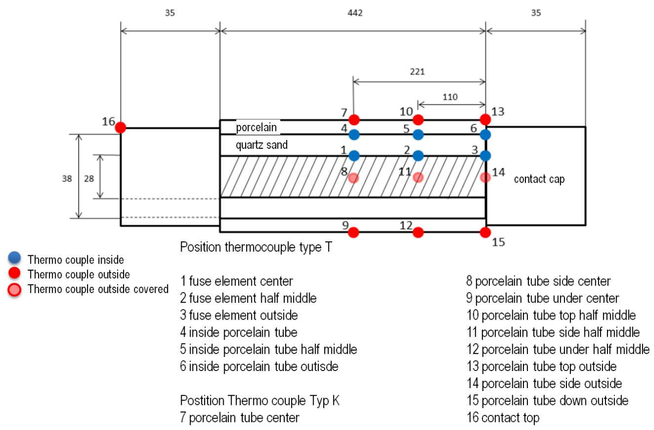

Fig. 10 Temperature metering points

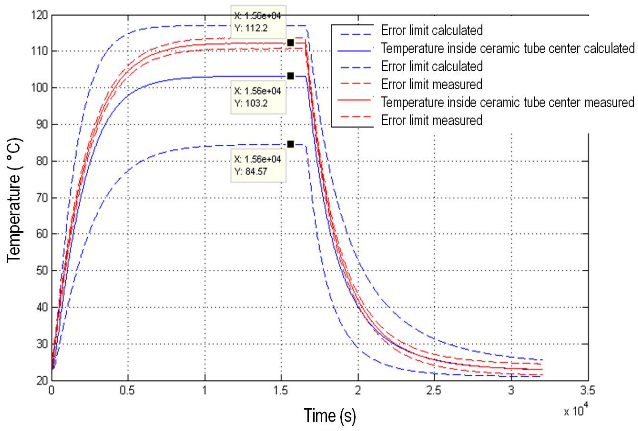

Fig. 11 Comparison of simulation and measurement of the temperature at metering point 4

Fig. 10 shows the temperature metering points at the HH fuse prepared with thermocouples. Fig. 11 shows as an example the calculated temperature using the thermal model of the HH fuse and the measured temperatures at metering point 4. For the calculated and the measured temperature the error limit was estimated too. The temperature difference $\Delta T = 10$ K for the metering point 4 is quite less. The temperature difference increases at the ends of the HH fuse caused by the thermal conductivity of the external conductor. But this is not the important metering point, where the temperature needs to be known.

V. Conclusion

With the knowledge of the different physical thermal data and a approved thermal model it is possible to calculate the temperature distribution inside a HH fuse especially at the fuse elements. This is an advantage to detect thermal degradation of HH fuses caused by broken fuse elements. Together with high-performance low cost computer it will be possible to calculate the load level, detect broken fuse elements and additionally it is possible to calculate the temperature distribution around the HH fuse. All calculations were performed with Matlab®.

Acknowledgment

The author gratefully acknowledge the contributions of NH HH recycling e.V. and SIBA, Mr. Haas and Mr. Wilhelm, for supporting the project.

References

Unpublished Papers:

A. Kunze. Zustandsmonitoring an einer HH-Sicherung. Unpublished Master Thesis HTW Berlin, department Elektrische Anlagentechnik, 2015, Berlin

Papers from Conference Proceedings (Published):

T. Gräf. Damage avoidance due to the use of high voltage fuses and temperature monitoring, IECFA 2015, Dresden, Tagungsband NH-HH Recycling Verein e.V.

T. Gräf. Contactless thermal online-monitoring of electrical equipment under load to determine the load level and damage avoidance. A3-204, 46. Cigré Session Paris 2016, France.

T. Gräf. Schäden an regenerativen elektrischen Erzeugungsanlagen durch degradierende Hochspannungs-Hochleistungssicherungen und Vermeidung durch berührungsloses Online-Monitoring. EW Medien und Kongresse GmbH, Netzpraxis, 7/8 2017, S. 60 – 66, ISSN 1611-0412-D 7656 E

U. Haas. Thermischer Schaltanlagenschutz durch Hochspannungssicherungen mit integriertem Temperatur-Begrenzer unter Berücksichtigung der IEC 420:1990. Sonderdruck SIBA Lünen

H. Bessei. Fuse manual. Publisher: NH- und HH-Recycling e.V., 5. Aktual. Aufl. 2015, Kerschensteiner Verlag, Lappersdorf

Patents:

T. Gräf: Autarke Temperaturmessung DE 102014101156.2, 2014

T. Gräf: Anordnung mit einer elektrischen Sicherungseinrichtung und einer an der Sicherungseinrichtung angeordneten Messeinrichtung sowie Messeinrichtung. DE 10 2015 100 399.6

T. Gräf: Kabelüberwachung PCT/EP 2016/ 055678, EP 16711801.7

Copyright © 2019 Published by Fuse Cliub and High Voltage and Power Systems Research Lab of the University of West Attica. All Peer-review process under responsibility of the scientific committee of the 11th International Conference on Electric Fuses and their Applications, ICEFA 2019