New Spark-gap Technology with Efficient Line-follow Current Suppression for the Protection of Powerful LV Distribution Systems

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Abstract—**The electrical properties of low-voltage power systems (LVPS) can have a strong effect on the operational behavior of surge protective devices (SPDs) to be used for protection purposes. Besides the right selection, the qualification-testing of SPDs connected these systems has to be carried out under test conditions which meet the real operating conditions of the power systems in which these SPDs should be installed. In this regard, the "class I and II operating duty tests" according to *IEC 61643-11, chapter 8.3.4.3* is an essential test for the qualification of SPDs connected to LVPS. In this test the SPD is stressed with defined surge-current impulses while it is connected to a power system simulating the characteristic of the real LVPS in which the SPD should be installed. The focus of the work presented is laid on class I SPD based on a newly developed "line-follow current free" spark-gap technology. Fundamental aspects, like basic functional principles, construction details, the performance and also the advantages of this new *class I* SPD technology are presented and discussed in detail. A special focus is set on the performance of this technology in case of use in powerful LVPS with short-circuit currents up to *100 kA rms*.**

Keywords-Surge protective device, IEC 61643-11, class I and II operating duty tests, lightning current arrester, spark-gap technology, line-follow current.

I. INTRODUCTION

An effective protection of electrical systems and electronic equipment against lightning currents and surge voltages requires the use of surge protective devices (SPDs) with specifically tailored properties for the respective field of application. Therefore, varieties of SPDs with specific properties have been or will be developed. Particularly with regard to low-voltage power systems (LVPS) providing highest power performance it has to be considered that the electrical properties of these systems can have a strong effect on the operational behavior of installed surge protective devices (SPDs). Therefore, a careful selection of SPDs for the use in these systems is mandatory to provide optimum performance and reliability. In this regard, special attention should be paid also to the qualification-testing. It has to be carried out under test conditions which meet the real operating conditions of the

low-voltage power systems in which these SPDs should be installed. An essential test procedure for the qualification-testing of SPDs connected to LVPS is described in *IEC 61643-11, chapter 8.3.4.3* and it is called "class I and II operating duty tests" [1], [2]. During this test, the SPD is stressed with defined surge-current impulses *(8/20) µs* while it is connected to a power system simulating the characteristic of the real system in which the SPD should be installed (comp. *figure. 1*).
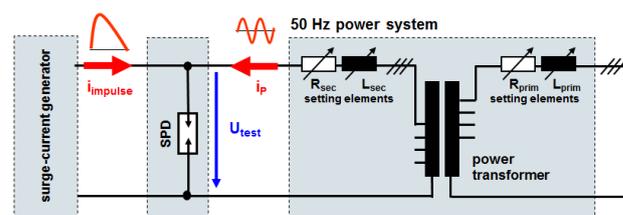

Figure 1. Principle of the test-setup for surge-load testing of SPDs under operating conditions according to IEC/EN 61643-11, *chapter 8.3.4.3* [1], [2].

This test demands additionally a defined synchronization of the surge-current impulses with the *50 Hz AC* voltage of the power supply. *Figure 2* shows the time-related conditions and the required synchronization of the *15* surge-current impulses to be applied to the specified phase angles of $\varphi = 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, 330°, 360°, 390°$ and $420°$.
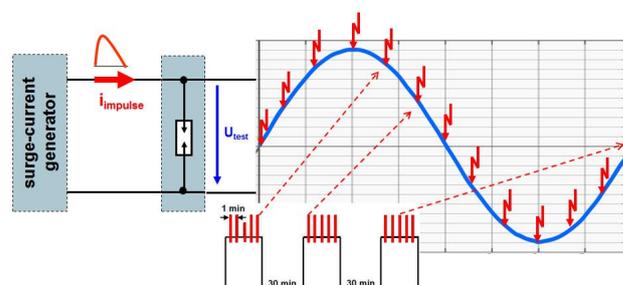

Figure 2. Required synchronization of the surge-current impulses to the phase angles of the *50 Hz* AC voltage [1], [2].

According to the standard, the interval between the impulses is *50 s – 60 s*, the interval between the groups is *30 min – 35 min*. The background for this is founded in the fact that every single discharge process leads to an energy intake of the SPD and therewith to an increase of its temperature. This can lead to an overheating of the SPD if the impulses are applied immediately one after the other. To avoid this effect a cooling time after a series of impulses *5 impulses* is defined. Therewith, the developed test sequence covers all possible combination regarding the synchronization of the impulses to the phase angles which may occur under practical operating conditions and enables an efficient laboratory testing.

The key-parameters defining the technical requirements and therewith the "difficulties" to pass this test are:

·   Maximum continuous voltage U_C
·   Short-circuit current rating I_{SCCR}
·   Follow current interrupt rating I_{fi}
·   Power factor $cos(\varphi)$
·   Nominal discharge current I_n

The test is passed if the SPD is able

·   to withstand the applied surge current impulses
·   cut-off, quench or suppress line-following currents occurring after the surge-current events
·   Shows no damage and no degradation of other key-parameters after the whole test sequence (comp. [1],[2])

In practice LVPS have large differences in their characteristic values. Especially, with regard to LVPS with highest short-circuit current ratings in the range of $I_{SCCR} = 50 \, kA$ or more different aspects have to be considered. Firstly, a powerful SPD technology with is able to provide a high follow current interrupt rating I_{fi} which is equal to the I_{SCCR} value of the power system is required. A basic precondition for the development an qualification of such a powerful SPD technology is a test-setup wich allows the coupling of a surge-current generator with a powerful *50 Hz*-LVDS providing the demanded test parameters.

The focus of the work presented is laid on the following aspects:

·   A study on the operational behavior of a new triggered and encapsulated spark-gap technology based class I lightning current arrester.

·   Technical features of this class I arrester with a special regard to the newly developed "line-follow current free" spark-gap technology.

·   Investigations on the performance of the "line-follow current free" spark-gap technology in case of use in LVPS with short-circuit currents up to $I_{SCCR} = 100 \, kA \, rms$.

·   Investigations on its performance in case of vary the maximum operating voltage U_C.

II.   Test-Setup and Condtions

A.   Test-setup

The test-setup which is part of an accredited laboratory [6] used for the investigations is presented and described in detail in [10].

B.   Proof of performance

Figure 3 shows the short-circuit characteristic of the power system used with the parameter set „$U = 264 \, V_{rms}$, $I_{SCCR} = 50 \, kA \, rms, \, cos(\varphi) = 0.25$" which is particularly relevant for the qualification-testing of powerful class I SPDs according to IEC 61643-11. The graph shows clearly, that this set of parameters is reached safely. The related power factor can be calculated according to [4], for example.

Figure 3.   Current and voltage in short-circuit case (*50000 A_{rms} @ 264 V_{rms}*).

III.   Fundamental Requirements for a Lightning Current Arrester Based on Spark-gap Technology

The essential requirements and linked to this, the basic quality-features of a lightning current arrester based on encapsulated spark-gap technology are the following [12]:

1. The ignition of the spark-gap in case of the occurrence of an overvoltage. Thereby, the ignition mechanism and its quality affect the voltage protection level U_p.

2. Discharge of the surge or lightning current impulse. The discharge capability of an arrester is characterized by the nominal discharge current I_n (impulse *(8/20) µs*) and the impulse discharge current I_{imp} (impulse *(10/350) µs*).

3. Cooling and quenching the electric arc to interrupt line-follow currents which may occur after the discharge of the surge or lightning current. These physical principles affect the follow current interrupt rating I_{fi} (line-follow current quenching capability/suppression).

4. After all these physical processes, the arrester must provide galvanic isolation to ensure a further undisturbed operation of the power system.

IV. Qualification-Testing of a Newly Developed Lighting Current Arresters Based on Encapsulated Spark-Gap Technology

A. SPD under test

The class I lightning current arrester under investigation is the FLT-SEC-P-T1-1S-350/25-FM which is based on triggered and encapsulated spark-gap technology [7]. *Figure 4* shows a complete module (FLT-SEC-P-T1-3C-350/25-FM) which is designed for the protection of a three phase TN-C-system. It consists of a base element and three pluggable spark-gap technology based lightning current arresters. *Table I* shows the essential technical data of the single arrester.

Figure 4. *Class I* lightning current arrester based on triggered and encapsulated spark-gap technology for the protection of a three phase TN-C-system (FLT-SEC-P-T1-3C-350/25-FM) [7].

TABLE I. TECHNICAL DATA FLT-SEC-P-T1-3C-350/25 [7]

Maximum continuous voltage	$U_c = 350\ V$
Nominal discharge current (8/20) µs	$I_n = 25\ kA$
Impulse discharge current (10/350) µs	$I_{imp} = 25\ kA$
Follow current interrupt rating I_{fi}	$I_{fi} = 50\ kA$
Short-circuit current rating I_{SCCR}	$I_{SCCR} = 50\ kA$
Voltage protection level	$U_p \leq 1.5\ kV$
Max. backup fuse with branch wiring	$315\ A\ AC\ (gG)$

B. Test parameters

According to the technical data of the SPD under investigation, the test-voltage is set to $U = 264\ V_{rms}$, the prospective short-circuit current I_P to $50\ kA$ and linked with this, the power factor $cos(\varphi)$ is 0.25 as required (comp. *EN 61643-11*, *table 8* [2]). The surge-current impulses $(8/20)µs$ with an amplitude of $I_n = 25\ kA$ are applied according to the time-related conditions and synchronized to the specified phase angles as described in *chapter I*, *figure 2*.

C. Test results

During the test, the arrester limits the voltage at its terminals in all cases to a value below *1.5 kV* (protection level $U_P \leq 1.5\ kV$ [7]). *Figure 5* shows the specific energy values of the measured line-follow current occurring during the test. In this graph the specific energy is plotted versus the specified phase angles. The result shows clearly that the specific energy has its highest value when applying the surge-current impulse at the phase angle of *270°*.
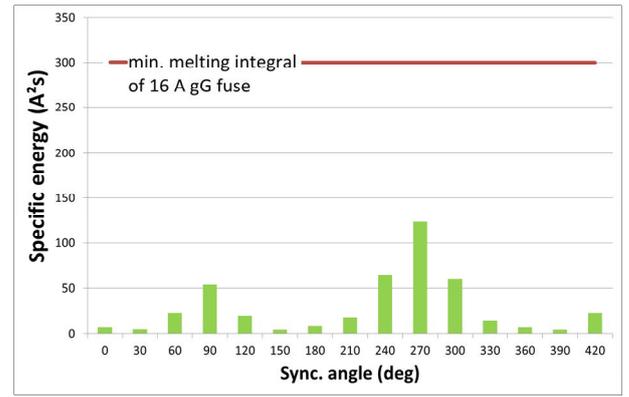
Figure 5. Specific energy of the line-follow current occurring during the „operation duty test" of the class I arrester FLT-SEC-P-T1 (green bars) in comparison to the melting integral of a 16 A gG fuse (red curve).

Figure 6a shows a detailed study of the line-follow current characteristic of the arrester in case of applying the surge-current impulse synchronized to a phase angle of $\varphi = 90°$ (green curve) and $\varphi = 270°$ (red curve) of the *AC* voltage.
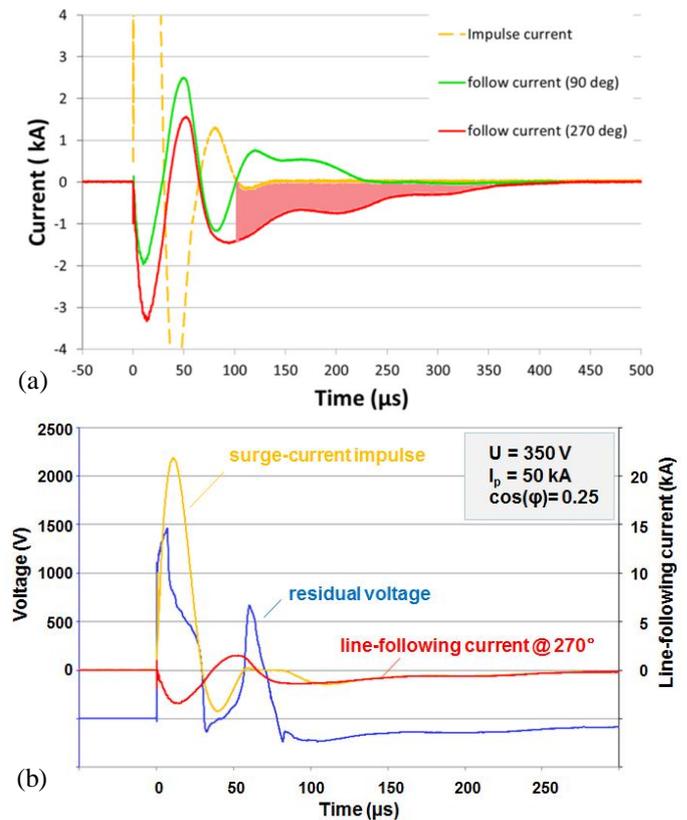
Figure 6. (a) Case study on the line-follow current of the class I lightning current arrester FLT-SEC-P-T1. Surge-current impulses applied at $\varphi = 90°$ (green curve) and at $\varphi = 270°$ (red curve). The red-filled area represents the charge Q of the line-follow current; (b) displays additionally the residual voltage in case of a surge-current appied at $\varphi = 270°$.

During the surge-current event the line-follow current cannot be measured. As a definition made, the surge-current event cannot be considered as a part of the line-follow current.

Due to this fact, the calculation and analysis of the line-follow current starts at the time when the impulse-current mainly has decayed. Under these pre-conditions and in case of a synchronization angle of $\varphi = 270°$ a line-follow current of *300 µs* duration with a peak value of approx. *1500 A* is measured. The waveform of the current component generated by the power supply (*figure 6a* and *6b*, bred curve) during the discharge process of the surge-current (yellow curve) can be interpreted as the reaction of the power supply system on a small part of the impulse energy charging its inductance in combination with the switching operation of the spark-gap itself. Therefore, the characteristic of the current component generated by the power supply system is mainly defined by its impedance.

The specific energy resulting from this line-follow current is calculated to *125 A²s* (its charge Q is represented by the red area, comp. *fig. 6*). In order to draw a comparison between this value and the melting integral of a fuse: The observed maximum of the specific energy of line-follow currents (*125 A²s*) is far below the melting integral of a *16 A* gG fuse, which is equal or greater *300 A²s* [8], [9]. Due to this very small value of the line-follow current and specific energy, their impact can be neglected under practical operation condition of this arrester. This result shows clearly, that the tested triggered and encapsulated spark-gap based class I/type 1 arrester is able to suppress the line-follow current very effectively even when it is triggered at the most demanding synchronization angle of *270°* (comp. *fig 5*). Based on these facts, this arrester technology can be considered practically as a "line-follow current free technology" [12].

The feature of a "line-follow current free technology" leads to outstanding advantages in practical operation of triggered and encapsulated spark-gap based *class I* lightning current arresters [12]:

· Due to the practically negligible line-follow currents, even the smallest fuses connected in series to the SPD don't blow. This supports a high availability of power systems to be protected.

· The abrasion of inner parts of the arrester is minimized because of the low energy consumption resulting from the very small specific energy linked with the very small line-follow currents. This property results in a significantly increased lifetime of the arrester.

V.   FURTHER ASSESSMENT OF THE CAPABILITY OF THE NEWLY DEVELOPED SPARK-GAP TECHNOLOGY

A.   Motivation

The results obtained from the qualification-testing using the series product FLT-SEC-P-T1-3C-350/25 (comp. *chapter IV*) leads to further essential questions:

· Does an increase of the short-circuit current rating I_{SCCR} has an influence on the line-following characteristic?

· Is an increase of the maximum continuous voltage U_C possible without having a significant influence on the line-follow characteristic of this spark-gap technology?

· If so, are there possibilities to adopt this spark-gap technology to increased performance parameters?

The answers to these questions have high practical relevance. The assessment of the performance reserve and therewith, the knowledge of the boundaries of this newly developed spark-gap technology may open up possibilities for the use to protect low-voltage power distribution systems with a short-circuit current rating I_{SCCR} which is higher than *50 kA* or for systems with a maximum continuous voltage U_C which is higher than *350 V*.

B.   Advanced tests with an increased I_{SCCR} values

The first test series has its focus on the line-follow current characteristic of the spark-gap when increasing the I_{SCCR} value form *50 kA rms* to *100 kA rms*. The test method used is also the "*class I and II operating duty tests*" according to *IEC 61643-11, chapter 8.3.4.3*. The reference for these tests should be the results obtained from testing the series product FLT-SEC-P-T1-3C-350/25 with the relevant test parameters I_{SCCR} = *50 kA rms*, cos (φ) = *0.25* and U_C = *350 V AC rms* (comp. *chapter IV*). But, with regard to the properties of the power system used, the testing with an I_{SCCR} = *100 kA* is done at U_C = *264 V*. Therefore, also a test with U_C = *264 V* is performed using I_{SCCR} = *50 kA rms* to achieve a better comparability of the results.

TABLE II. DEVICES UNDER TEST – VARIATION OF I_{SCCR}

DUT 1	I_{SCCR} = 50 kA	cos (φ) = 0.25 acc. IEC/EN 61643-11	U_C = 264 V
DUT 2	I_{SCCR} = 100 kA	cos (φ) = 0.20 acc. IEC/EN 61643-11	U_C = 264 V
DUT$_{REF}$	I_{SCCR} = 50 kA	cos (φ) = 0.25 acc. IEC/EN 61643-11	U_C = 350 V

C.   Advanced tests series with varied U_C values

The second test has its focus on the line-follow current characteristic of the spark-gap when vary the maximum continuous voltage U_C. The test method used is also the "class I and II operating duty tests" according to *IEC 61643-11*. Reference is the results obtained from testing the series product FLT-SEC-P-T1-3C-350/25 with the parameter set "I_{SCCR} = *50 kA*, cos (φ) = *0.25* and U_C = *350 V*" (comp. *chapter IV*).

TABLE III. DEVICES UNDER TEST – VARIATION OF U_C

DUT 3	I_{SCCR} = 50 kA	cos (φ) = 0.25 acc. IEC/EN 61643-11	U_C = **264 V**
DUT$_{REF}$	I_{SCCR} = 50 kA	cos (φ) = 0.25 acc. IEC/EN 61643-11	U_C = **350 V**
DUT 4	I_{SCCR} = 50 kA	cos (φ) = 0.20 acc. IEC/EN 61643-11	U_C = **440 V**

D. Results and discussion

The first result of the phenomenological studies on the line-follow current characteristic of the newly developed spark-gap is that basically, in all cases (*table II and III*) the "*class I and II operating duty tests*" according to *IEC 61643-11* is passed. For the further in-depth analysis the maximum specific energy value of the measured line-follow current occurred during the operation duty tests is used.

In all tested cases the maximum line-follow current is reached when the ignition of the spark-gap occurs at an angle $\varphi = 270°$ of the sine wave (comp. *section IV, C and VI, A*). The results are shown in *figure 7*. Thereby, each bar is the arithmetic average out of *6* samples. Above this, the spread of the measured line-follow currents is also given in this chart.
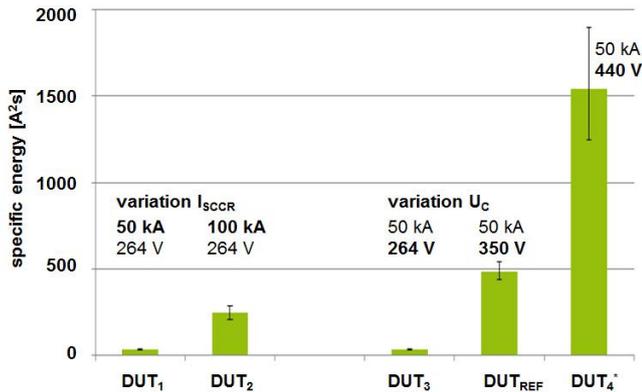
Figure 7. Specific energy of the line-follow currents occurring during the „operation duty test" determined for different test scenarios according *table II* and *table III*.

The results shows that the variation of the concerned parameters I_{SCCR} and U_C shows a clear influence on the line-follow current characteristic of the spark-gap. It can be seen that the increase of I_{SCCR} and also the increase of U_C leads to an increase of the line-follow currents. Also, the scattering of the measured line-follow current values increases with increased parameters I_{SCCR} and U_C.

From the physical point of view, the detected relationships obtained in these phenomenoligical investigation were expected. This is because of the well-known fact, that an increase of the test parameters I_{SCCR} and U_C represents a bigger challenge regarding the supression and quenching of the electric arc inside the spark-gap.

In practical terms, the results show clearly, that the tested spark-gap technology has a large reserve capacity. Only the increase of the spreading of the line-follow current values in case of an increase of I_{SCCR} and U_C indicates that a slow movement to the physical boundaries of this spark-gap technology took place. With regard to real applications to be protected the performance of this spark-gap technology offers the possibility also for the use in low-voltage power systems with I_{SCCR} values up of *100 kA* or with an U_C of *440 V*. This is

because, that the detected increase of the line-follow currents in these cases can be neglected under practical conditions.

From the energetic point of view, the specific energy of a line-follow occuring using $I_{SCCR} = 100\ kA$ (DUT_2) is *0.24 kA²s* which is equal the stress due to an impulse *(10/350) µs* with an amplitude of *1 kA*. This *1 kA* impulse represents the additional electric stress to – respectivly power conversion in – the spark-gap during the qualification-testing with an $I_{SCCR} = 100\ kA\ rms$ compared to the testing using $I_{SCCR} = 50\ kA\ rms$ (DUT_{REF}). Against the background of the test-sequence according to *IEC 61643-11* using lightning current impulses with amplitudes up to *25 kA*, this additional impaced of the can be neglected. In case of using $U_C = 440\ V\ AC\ rms$ the amplitude of the equivalent impulse *(10/350) µs* is *2,5 kA*.

Summerising, the increase of I_{SCCR} to *100 kA rms* and also the increase of U_C to *440 V* compared to the reference parameters (DUT_{REF}) have not a real practical relevance. The stress to the inner parts of the spark-gap can be neglected. Also the increase of the nominal value of a fuse which is tripped by the energy of the increased line-follow reaches not in a range of practical relevance. Based on these highly promising facts, further examinations and test according to *IEC 61643-11* have to be carried out to proof the possibility of an adaption and use of this spark-gap technology in low-voltage power systems with higher parameters like $I_{SCCR} = 100\ kA\ rms$ and $U_C = 440\ V$.

VI.   INTERPRETATION OF THE RESULTS

A. Critical phase angle of $\varphi = 270°$

The results of hundreds of „operating duty tests" performed, almost show that the ignition of the spark-gap at the phase angle $\varphi = 270°$ of the sine wave is the most critical case concerning the appearance of line-follow currents. The phenomenological orientated observations done during the performance of the "operating duty test" of the spark-gap based lightning current arrester under investigation underlines this and leads also to the following basic relationships:

·   When increasing the test parameters of the "operating duty test", e. g. the value of the *50 Hz* AC test-voltage, the line-follow currents occur first when applying the surge-current impulse at the phase angle of *90°* and *270°*.

·   In case of test parameters which lead to line-follow currents, the specific energy of these currents has its highest value when applying the surge-current impulse at the phase angle of *270°* (comp. *fig. 5*).

The reason for this is founded in the interaction between the surge-current generator and the inductance of the *50 Hz* AC power supply system. This interaction applies to every mains power supply and it is of course not only related to the setup used in the presented test facility. A detailed explanation for this behaviour is given in [11].

B. High-Performance and Line-follow Current free Spark-gap Technology

The residual voltage of modern spark-gap-based arresters has to be higher than the peak value of their maximum continuous operating voltage U_c. This is required to prevent the occurrence of line-follow currents in case of the ignition of the spark gap, e. g. caused by surge- or lightning currents. With regard to the tested class I lightning current arrester FLT-SEC-P-T1, which is based on triggered and encapsulated spark-gap technology, the high line-follow current quenching capability and the high interrupt rating is mainly founded in the efficient mechanism of plasma cooling. *Figure 8* shows construction drawings of the spark-gap.

(a)

(b)
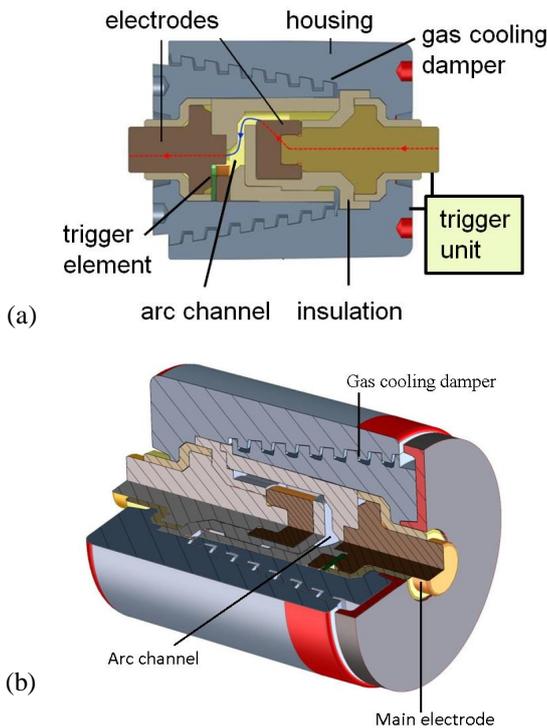
Figure 8. Construction drawings of the "line-following current free" spark-gap (diameter *30 mm*, length *32,5 mm*, volume *23 cm³*).

A trigger unit which is designed to provide defined ignition conditions of the main spark-gap is connected between one electrode and the pressure-proof housing of the spark-gap (*fig. 8a*). Via the conductive housing material the connection of this trigger unit with the ignition element (*fig. 8a*, green part) takes place. This element is directly contacted to the arc burning chamber nearby the second electrode. From the technical point of view the ignition element can be characterized as a resistor with a low current carrying capacity. In case of a surge current or overvoltage event, the trigger unit generates a well-defined short-term current impulse. This impulse causes a discharge on the surface of the ignition element which is used to ignite the main spark-gap. This principle ensures a low protection level of the spark-gap.

The arc channel (*fig. 8a*, blue path) between the two electrodes is optimized with regard to the dimensions and the function-determining materials. The channel profile supports a fast ignition of the spark-gap on one hand (comp. *chapter III, (1)*) and an effective quenching of the arc by the use of a specific plastic material generating extinguishing gas under the influence of an electric arc (comp. *chapter III, (3)*) on the other. The geometry of the isolated gas pressure chamber and the gas cooling damper, which is built by the two-part metal housing, are essential elements of the cooling management and therefore, for the line-follow current suppression. As mentioned before, the low energy consumption of the spark-gap under operation conditions leads to a minimization of the abrasion of inner parts which finally results in a long lifetime of the arrester. Defined modifications on specific parts of the channel geometry allow the control of the gas flow through the channel (gas dynamics). Therewith, a variation of the key-parameters of the spark-gap, like the continuous operating voltage, the discharge current and the line-follow current interrupt rating can be achieved. Based on this, the use of parameter optimization methods allows the adjustment of the whole set of parameters of the spark-gap precisely to the requirements of the respective application.

VII. CONCLUSION

The results of a study on the performance of a newly developed class I lightning current arrester which is based on triggered and encapsulated spark-gap technology is presented. Special attention is paid on its line-follow current behavior. Therefore the "class I and II operating duty tests" according to *IEC 61643-11, chapter 8.3.4.3* is performed which has one focus on this aspect. The results obtained show clearly, that the specific energy of detected line-follow currents has its highest value when applying the surge-current impulse at the phase angle of *270°* of the connected *50 Hz* AC voltage. But even in this case the specific energy resulting from this line-follow current has only a value of *125 A²s* which is far below the melting integral of a *16 A* gG fuse. This is a value which can be neglected under practical operation conditions. The outstanding feature of a "line-follow current free technology" provides two essential advantages in practical operation conditions of this lightning current arrester technology: Even the smallest fuses don't blow due to such a low line-follow current value. This leads to an increase of the availability of the *50 Hz*-power system. Above this, the abrasion of inner parts of the arrester is minimized because of the very low line-follow current (energy consumption). This results in a significantly increased lifetime performance of the arrester.

Additional tests using an increased short-circuit current rating I_{SCCR} and an increased maximum continuous voltage U_C as test parameter show a large reserve capacity of the tested spark-gap technology. Based on this highly promising fact, further examinations have to be carried out to proof the possibility of an adaption and use of this spark-gap technology in low-voltage power systems with higher parameters like $I_{SCCR} = 100$ *kA rms* and $U_C = 440$ *V AC rms*.

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