HYBRID CHAMBER WITH VACUUM AND GAS INTERRUPTERS FOR HIGH-VOLTAGE CIRCUIT-BREAKERS

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Summary

SF6 technology for high-voltage circuit-breakers was introduced during the 1960’s in the transmission voltages range. In the 1970’s SF6 soon became the dominant medium in this range due to its excellent arc quenching and dielectric withstand capabilities. In spite of continuous researches for alternative gases, some are conducted at the present time, no other gas has been found yet that could combine both the arc quenching capability required for high voltage applications and the dielectric withstand necessary to have a reduced number of chambers per pole. Among the alternative technologies for high-voltage circuit-breakers, the application of vacuum technology has already been investigated and several contributions were presented during the CIGRE session of 2002.

This report intends to present another interrupting principle were a vacuum interrupter is combined in series with a gas blast chamber to provide the required performances. During interruption of high breaking currents, the withstand of the initial part of TRV (thermal phase) is given by the vacuum interrupter and the withstand of the peak TRV (dielectric phase) is mainly provided by the gas blast interrupter. Both interrupters contribute to the dielectric withstand required for switching tests and for the insulation level.

After a brief history on the matter, the report explains the interrupting principle and shows some examples of geometry where this principle has been implemented for testing. It is preferable in practice that both interrupters are operated by the same operating mechanism. Special arrangements had to be designed in order to obtain ratios of 10 or more between the strokes and velocities of the two interrupters.

Tests results obtained on a full scale mock up are presented, showing the potential and limitations for the main type test duties.

Comparisons are made with present interrupting techniques for high-voltage circuit-breakers. The possible uses of the hybrid technique are given in the report. It is shown that this technology allows to reduce the size and the operating energy of high-voltage circuit-breakers, and can be an alternative to present technologies in some high-voltage applications.

Keywords

Hybrid – circuit-breaker – vacuum – gas blast – SF6

1 Introduction
The self-blast technique of interruption is now widely accepted as the dominant technique for high-voltage circuit-breakers [1] [2]. Self blast, or thermal blast circuit-breakers as they are sometimes called, are in service for high-voltage applications since the mid 1980’s. Starting with the rated voltage of 72.5 kV, this technique is now available up to 800 kV with rated breaking currents up to 50 kA or 63 kA. The self blast technique has allowed the use of low energy spring-operated mechanisms at all rated voltages, thus reducing stress and wear of the mechanical components and increasing the reliability of circuit-breakers.

Following this success story, one may wonder if a final optimum interrupting technique has been definitively found in the high-voltage range and that no more research was necessary in this field.

Research on interrupting techniques has continued with unabated interest, as experience has shown that even the well established puffer technique has been overtaken by the self blast technique. One driver for such studies is the concern over the environmental impact of SF6. This concern has been properly addressed, in particular, by the reduction of the leakage rate of circuit-breakers and improvements in the handling of SF6. The impact on the environment can also be reduced by decreasing the volume of SF6 used in high-voltage circuit-breakers, through a reduction of the filling pressure and the size of the interrupting chamber.

For this reason, and for others developed in this report, it has been found useful to search for an alternative interrupting technique applicable to circuit-breakers rated 72.5 kV and higher.

Among the alternative technologies for high-voltage circuit-breakers, the application of vacuum technology has already been investigated and several contributions were presented during the CIGRE session of 2002.

This report intends to present another interrupting principle were a vacuum interrupter is combined in series with a gas blast chamber to provide the required performances. During interruption of high breaking currents, the thermal interrupting capability is given by the vacuum interrupter and the withstand of the peak TRV is mainly provided by the gas blast interrupter.

After a brief history on the matter, the report explains the interrupting principle and shows some examples of geometry where this principle has been implemented for testing. It is preferable in practice that both interrupters must be operated by the same operating mechanism. Special arrangements had to be designed in order to obtain ratios of 10 or more between the strokes and velocities of the two interrupters.

Tests results obtained on a full scale mock up are presented, showing the potential and limitations for the main type test duties.

Comparisons are made with present interrupting techniques for high-voltage circuit-breakers. They are commented and perspective on their possible use is given in the report.

It is shown that this technology allows to reduce the size and the operating energy of high-voltage circuit-breakers, and can be an alternative to present technologies in some high-voltage applications.

2 History – Basic interrupting principle

In this report the term hybrid is used to describe breaking chambers with the series connection of a vacuum interrupter and a gas-blast interrupter.

As it was already the case for the self-blast techniques, the origin of hybrid solutions can be traced back a long time ago in some patents from the 1960’s [3] [4].

There was renewed interest in this matter from the mid 1970’s to the mid 1980’s with patent applications made by several manufacturers in USA and Japan.

However none of these ideas led, to our knowledge, to industrial products due mainly to the complexity of the interrupting chambers, and as no obvious advantage was obtained, compared to the puffer chambers that were developed and produced at that time.

Several reasons can explain a renewed interest in this type of technology:
great progress has been made during the last decade in vacuum technology with, in particular, a high short-circuit interrupting capability that has been obtained in bottles of reduced size,

environmental concerns gave a new incentive towards the search of solutions with a low SF6 content,

the possibility of combining the functioning at low ambient temperatures (−40°C, −50°C) and a high interrupting capability without additional capacitor.

the progresses made in the self blast/thermal blast techniques of interruption, that allow optimised design of the gas part of the interrupter.

From a technical point of view, the following considerations support the choice of a hybrid interrupting chamber:

the short-line fault interrupting capability of gas blast interrupters is difficult to obtain at low filling pressures of SF6 or when the size of the SF6 chamber is such that the necessary gas blast at current zero cannot be obtained by the combination of gas compression and thermal effect;

Vacuum interrupters are known to withstand a very high rate-of-rise-of-recovery voltage (RRRV) during high short-circuit current interruption;

the rated voltage per break of a vacuum interrupter cannot be increased in an economical way above 52 – 72.5 kV;

the withstand of peak values of TRV can be obtained with a relatively low blast in SF6 chambers, a blast in any case much lower than that required for the withstand of RRRV during short-line fault interruption.

An almost obvious possibility is then to combine the high RRRV withstand capability of a vacuum interrupter and the high TRV peak withstand capability of an SF6 interrupter. In principle, the series connection of these two interrupters allows to combine both capabilities and to obtain high short-circuit interrupting capabilities with a low SF6 content.

Figure 1 shows the envelope of a TRV during a short-line-fault interruption by a high-voltage circuit-breaker. The initial part of the TRV, segment with the highest RRRV, is withstood almost entirely by the vacuum interrupter whereas the second part of TRV, including the peak (Uc), is withstood mainly by the gas interrupter. Distribution of voltage on the two interrupters is obtained generally naturally by arc conductivity during the post arc current phase and by capacitive coupling at a later stage.
3 Description of hybrid chambers

A possible but not necessary requirement for industrial application is that both vacuum and gas interrupters can be operated by the same mechanism. The two interrupters can be located in the same envelope or in separate ones as shown respectively in Figures 2 and 4. Many implementations of the interrupting principle can be imagined. Several examples are given in this section.

Figures 2a to 2b illustrate a solution with a self-blast gas interrupter having a fixed insulating nozzle and a moving arcing pin.

Figure 3 shows a geometry with a thermal blast chamber having, as usual, a moving insulating nozzle and a stationary arcing pin.

Figure 4 shows an alternative arrangement with a vacuum interrupter located in a separate volume at the bottom of the gas interrupter and with a movement of its arcing contact perpendicular to the axis of the gas interrupter.

These figures show applications to open-type circuit-breakers, but similar solutions exists for dead tank and Gas Insulated Substations.

As the contact stroke and the opening speed of a vacuum interrupter are significantly smaller than in a typical gas interrupter, a chamber mechanism must be designed that will allow the almost simultaneous operation of the two interrupters at their respective speeds and strokes. Special arrangements had to be designed in order to obtain ratios of 10 or more between the strokes and velocities of the two interrupters. Arcing times are several milliseconds shorter in a vacuum interrupter, therefore it is preferable to open first the gas interrupter and to delay the opening of the vacuum interrupter by a few milliseconds.

A first example of chamber geometry with a fixed insulating nozzle is illustrated on figures 2a to 2d. The captions explain the different steps of a tripping operation.

Figure 2a : Both interrupters are in closed position.
V.I. = vacuum interrupter G.I. = gas interrupter
The moving part of the gas interrupter will be driven by the spring operating mechanism (on the right, not shown on the figure) and spring S1. The resultant force from springs S1 and S2 maintains the required pressure on the vacuum contacts.

*Figure 2b*: Arcing contacts of the gas interrupter separate while they are still closed in the vacuum interrupter

The resultant force from springs S1 and S2 maintains the required force on vacuum contacts. During this period, the movement of the mobile part generate a pressure rise by compression in the blast volume of the gas interrupter.

*Figure 2c*: The spring S1 is no longer active, the contacts in the vacuum interrupter are opened by spring S2. The contacts in gas interrupter are driven by the spring operating mechanism.

*Figure 2d*: Both interrupters are in open position.

Figure 3 shows that the same principle can be implemented with a gas interrupter having a mobile insulating nozzle and gas compression during the full stroke of the interrupter.

The functioning of the chamber mechanism is the same as shown on figures 2a to 2d.
4 Tests results and analysis

Type tests according to IEC 62271-100 have been performed on a full scale mock-up 145kV 40/50kA 60Hz in order to check the validity of the interrupting principle and to determine the performances that can be achieved.

The geometry of the hybrid circuit-breaker is as shown on figure 3. The gas interrupter is of a standard self-blast design, but with modified parameters so as to have a reduced pressure rise during no-load and breaking operations.

During these investigations the filling pressure was 3.0 bar (gauge).

A standard 17.5/24 kV 50/40 kA vacuum interrupter is used with its normal operating conditions.

Although the other standard test duties (terminal fault, capacitance current switching) have been also performed, the emphasis is made here on the short-line fault tests for which the hybrid solution is of particular interest.

Synthetic tests with current injection have been performed on the basis of L90 145 kV 50kA 60Hz without capacitor.

The inherent RRRV across the circuit-breaker terminals is 10.8 kV/μs and the first TRV peak (UT) is 19 kV, as specified by IEC standard. The line side TRV is with insignificant time delay (<0.1 μs).

The full interrupting window has been demonstrated with a minimum arcing time of less than 10 ms.
Figure 5 shows an example of test oscillogram.

Figure 5: SLF Test L90 145 kV 50kA 60 Hz

$\mathbf{I}_t = \text{total current}$ \quad $\mathbf{I} = \text{high current}$

$\mathbf{I}_{\text{inj}} = \text{injected current}$ \quad $\Delta \mathbf{P} = \text{pressure rise in thermal volume}$

$\mathbf{U} = \text{recovery voltage}$ \quad $\mathbf{X} = \text{contact displacement (Gas interrupter)}$

The pressure rise at current zero, in the thermal volume of the gas interrupter, was less than 8 bar for the minimum and maximum arcing times. It is 4 or 5 times smaller than in a self-blast chamber with the same rating.

This example shows obviously that the gas blast can be greatly reduced during interruption of a short-line fault, as the first part of TRV (up to $U_T$ as shown on figure 1) is mainly withstood by the vacuum interrupter in series.

However it must be carefully checked, by simulations and/or testing, that the vacuum interrupter is also suitable for the other short-line fault conditions (such as L75 and L60) as the first peak of TRV ($U_T$) tends to increase with the length of the line.

Figure 6 shows an example of post-arc current measurement made during interruption of a short-line fault L90 145kV 40kA 60Hz. A Rogoswki coil especially designed for this purpose was used for post-arc current measurements. The maximum amplitude of 3A is typical of what can be expected when current is interrupted by a vacuum interrupter (the time scale can be derived knowing that the slope of current is 19.2 A/µs).

Figure 6: Current during SLF L90 145 kV 40kA 60 Hz
If the gas interrupter is properly dimensioned, its TRV withstand capability will increase with lower short-circuit currents, therefore the gas interrupter will better contribute to the TRV withstand when the short-circuit current decreases and it will ease the interruption by the vacuum interrupter.

During the study it has been verified by power tests that a short-line fault test duty L60 was not critical for this hybrid chamber. On the same basis of 145kV 50kA 60Hz, the minimum arcing time was even shorter than for L90:

Another check of the short-line fault breaking capability was made by performing L60 based on 63kA 60Hz 145 kV i.e. with a current of 39 kA. The inherent RRRV across the circuit-breaker terminals was 9 kV/µs and the first TRV peak (UT) was 90 kV, as specified by IEC 62271-100. The filling pressure was 3.0 bar (gauge).

The full interrupting window was demonstrated, with a minimum arcing time of less than 9 ms. A test oscillogram is shown on figure 7, in this example arcing time is 14 ms.

![Figure 7: SLF Test L60 145 kV 63kA 60 Hz](image)

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\begin{align*}
    I_t &= \text{total current} \\
    I &= \text{high current} \\
    I_{inj} &= \text{injected current} \\
    \Delta P &= \text{pressure rise in thermal volume} \\
    U &= \text{recovery voltage} \\
    X &= \text{contact displacement (Gas interrupter)}
\end{align*}
\]

As with self-blast technologies, the interruption of terminal fault at 30% of rated breaking current has to be verified, the difference being that in an hybrid interrupter the vacuum can contribute to the TRV withstand.

Dimensioning of the gas interrupter is therefore done to obtain the gas blast necessary to interrupt terminal faults and breaking in out-of phase conditions. This is quite different to what is done usually for puffer and self-blast interrupters for which a compromise has to be found between competing requirements for short-line fault and terminal fault interruptions.

Dimensions of the gas interrupter have been optimised using the simulation software developed for the study of self-blast circuit-breakers.

Figure 8 shows, as an example, the calculation of the pressure rise in the thermal volume during a terminal fault interruption and for 5 different values of arcing time.
Figure 8: Pressure rise calculated for 5 different arcing times in the case of a terminal fault interruption.

In the end, an optimum dimensioning of a hybrid solution leads, especially in the case of high interrupting capabilities, to a lower operating energy and a chamber of a smaller diameter.

5 Comparison with existing technologies

It has already been widely reported that the self-blast technique allows to operate high-voltage circuit-breaker with low energy spring-operated mechanisms over the entire range 72.5 kV to 800 kV [2].

For rated breaking currents up to 40kA and the standard ambient temperatures of –25°C and –30°C, the hybrid technology would not bring a significant gain compared with the self-blast technique.

On the opposite, for high rated breaking currents of 50kA and higher and/or low minimum ambient temperatures (-40°C or –50°C) the situation is quite different as the energy required by an hybrid interrupter can be significantly smaller than for a self blast interrupter. As the size of the active parts is also reduced, it appears that the gain in energy and size can more than compensate the added cost due to the introduction of a vacuum interrupter (and its mechanism). For these specifications, the relatively short arcing times obtained with an hybrid circuit-breaker brings also an increase in electrical endurance that can be valuable in service.

For the higher current ratings, such as 63kA-60Hz, it has been shown in section 4 that there no need to reduce the slope of the TRV during SLF with an additional capacitor. It is another feature of the hybrid circuit-breaker that can justify future developments.

Concerning the content of SF6, the hybrid technology allows to reduce the volume of a 145V 40kA 60Hz by approximately 25%. For the same size and filling pressure, it is estimated that the rated breaking current can be increased by approximately one step in the R10 series used in IEC 62271-100 for high-voltage circuit-breakers.

6 Conclusion

The report has presented new research on hybrid (vacuum + gas) circuit-breakers for high-voltage applications. New chamber arrangements have been designed, some patented [5], that allow operation by a single low energy spring-operated mechanism.

These studies have benefited from the progresses made in recent years in the self blast/thermal blast techniques of interruption.

Type tests on a full scale 145kV circuit-breaker have shown the possibility to obtain high interrupting capabilities (50kA-63kA at 60 Hz) in a range of performances where such a solution can be competitive.
The integration of a vacuum interrupter allows to reduce the content of SF6 (in terms of volume and filling pressure) for a given performance.

Another potential benefit is an increased electrical endurance, as shorter arcing times are obtained with this technique.

The self blast technique of interruption will continue to be dominant for high-voltage circuit-breakers (≥ 72.5kV), due to the simplicity of its breaking chamber, the reliability of these circuit-breakers in service and the high level of performance that has been achieved. However, this study shows that the hybrid technology can be a suitable solution in applications where high rated breaking currents are required and/or low minimal ambient temperatures are specified (i.e. when low filling pressures of SF6 must be used).

7 References


