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A3 - 101

CIGRE 2012

3AV1FG – 72.5 kV Prototype Vacuum Circuit Breaker (Case Study with Pilot Customers)

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SUMMARY

Vacuum switching devices are used worldwide in all kinds of medium-voltage distribution systems. With their outstanding technical performance and their low life-cycle costing they dominate the power distribution market. So far this technology has been predominately used in distribution networks up to 52 kV. Now some manufacturers have started to expand this technology to the electrical power transmission networks. The vacuum switchgear technology represents in this case a natural extension of the existing SF6 circuit breaker portfolio. The expansion of the breaker portfolio to include vacuum circuit breakers can offer customers genuine added value. The first step is a prototype of an outdoor circuit breaker for 72.5 kV which uses a vacuum interrupter for arc-quenching and nitrogen gas for dielectric insulation of this vacuum interrupter. A common spring drive mechanism is used to switch the vacuum interrupter unit inside of the three pole columns. The developed live-tank prototype circuit breaker was delivered to three pilot customers in Europe to gather joint operational experience under realistic network conditions. In order to offer these pilot customers the highest quality standards and the highest degree of security for their energy supplies, the manufacturer carried out a complete set of type tests for the 72.5 kV live-tank prototype circuit breaker. The circuit breaker conforms to the specifications of the latest edition of the International Electrical Commission standard (IEC 62271-100, 2008-04). This paper deals with the basic information about the circuit breaker design. The results of the IEC type test will be presented. In this context the vacuum interrupter unit provides a slightly different switching characteristic in comparison to other arc-quenching media. The minimum arcing times for most IEC test duties are shorter. Due to the excellent recovery of dielectric strength, the circuit breaker copes with severe values of di/dt and du/dt. It is quite clear that this different switching behaviour could influence the existing grid configurations. In addition to a successful type test, field experience is necessary to establish the vacuum technology on the sub-transmission voltage levels. The three pilot customers describe their initial experience with the prototype circuit breakers. This refers to the kind of applications, the number of switching operations and their early experience. Furthermore, the expectations of these utilities with respect to high-voltage vacuum circuit breakers are set out.

KEYWORDS

High-Voltage – Switchgear – Vacuum Interrupter – Pilot Customer – Operational Experience

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INTRODUCTION

Over the last four decades, the vacuum interrupter has conquered distribution networks (up to 40.5 kV) due to its outstanding performance and low life-cycle costs. The other media used to extinguish switching arcs have become less important for distribution networks. This sustained success of vacuum switchgear suggests that the technology could be a promising extension of the existing high-voltage switchgear portfolio.

The technical feasibility of this kind of application has been provided by several studies and pilot projects [1], [2], [3], [4].

Vacuum switchgear technology easily handles 10,000 operations at rated normal currents and more than 30 operations at full fault current, and this without the need for contact replacement. Long operational life and minimal maintenance are superb features of vacuum circuit breaker technology. It is unaffected by low temperatures; it is therefore ideally suited to cold climate areas.

Thus, the expansion of the circuit breaker portfolio to include high-voltage vacuum circuit breakers offers customers genuine added value. The first step is a prototype of an outdoor circuit breaker for 72.5 kV using one vacuum interrupter for each pole column. In our case, the vacuum interrupter is responsible for arc-quenching purposes, and the nitrogen gas filling for the dielectric insulation of this vacuum interrupter inside the pole column.

This paper is based on the cooperation between a circuit breaker manufacturer and three European utilities. They have started working on the examination of the influence of vacuum switchgear on the transmission networks. Prototype circuit breakers have been placed in the sub-transmission voltage range of 72.5 kV. In 2010 a three-year trial period started.

LIVE-TANK CIRCUIT BREAKER DESIGN AND TECHNOLOGY

The 3AV1FG - 72.5 kV prototype is a three-pole outdoor circuit breaker with one common spring drive mechanism. The force required to actuate the three contacts in the pole columns is supplied to the pole column corner gears by the spring drive via the operating rod and the coupling rod.

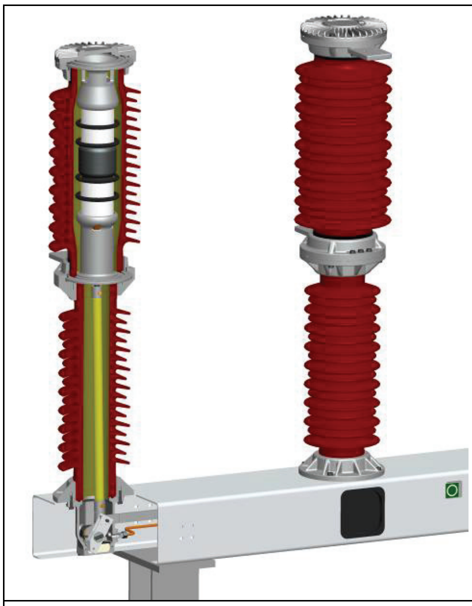

Figure 1 : Sectional view of one pole column

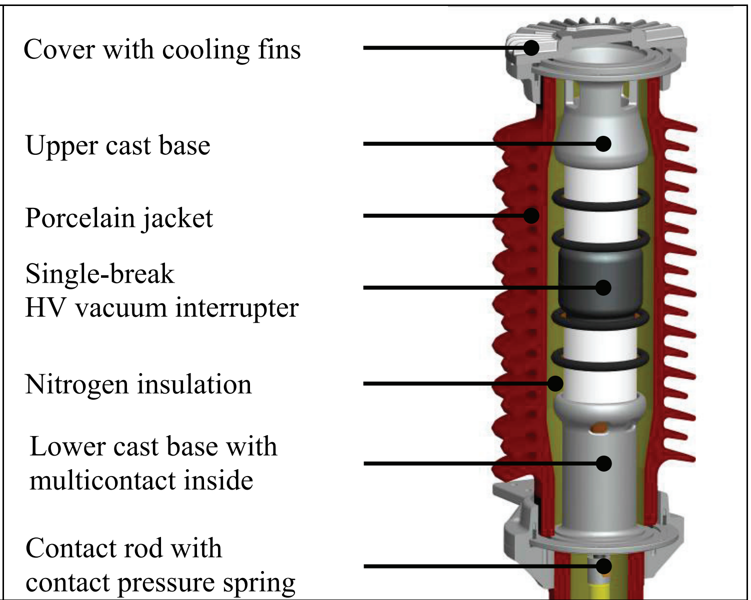

Figure 2 : Sectional view of a breaker pole

The kinematic chain offers a specific characteristic in comparison to conventional gas circuit breakers. To ensure that the contacts remain in the closed position, the blow-apart forces caused by a current flow through the contact structure have to be balanced by a contact spring (contact pressure spring). The three pole columns are connected by tubes to one gas compartment. The density of the gas in this compartment is checked by a monitor and the gas pressure is indicated by a gauge.

The vacuum interrupter itself is defined as "sealed-for-life". These switching elements are enclosed in porcelain jackets. An additional insulation medium is required to improve the outer dielectric strength of the vacuum interrupter, because of the compact size of this element in withstanding the dielectric demands. The three pole columns of the circuit breaker are insulated by nitrogen to withstand this high-voltage stress. The design is dimensioned for a gauge nitrogen pressure of 0.21 MPa. Figure 1 shows a sectional view of one pole column. Figure 2 essentially shows the basic interior of the porcelain circuit breaker pole.

Typically, vacuum circuit breakers do not provide two contact systems for carrying normal current and for short-circuit current interruption, as is the case with gas-insulated circuit breakers. One contact system masters both demands. At the contact areas, the contact resistance produces energy input. The thermal conductivity of the fixed and moveable contact rods leads this thermal heating out of the vacuum interrupter. Convection inside the vacuum interrupter is not possible. A multicontact system is attached to the moveable contact to enable the transfer of current and heat to the lower base. A side cover with cooling fins, attached to the fixed contact, helps to radiate the heat into the atmosphere.

The inner design of the vacuum interrupter is optimized to withstand the transient recovery voltage after arc interruption and the fundamental high-voltage demands (withstand voltages).

The preferred arc control system for comparatively large contact distances is the Axial Magnetic Field (AMF) contact geometry. The second most widely-used system is the Radial Magnetic Field (RMF) contact. The interrupting capability of the RMF system is much better for lower contact distances. The RMF system is preferable for a contact stroke of less than 15 mm. The AMF system provides significant advantages as from 20 mm [5]. In our case, an AMF system with a unipolar, self-induced magnetic field is used. Over the past few decades numerous experiments and theoretical simulations have been implemented to improve the contact design of the AMF systems [6], [7]. Such experience has been essential in expanding this plasma control system to enable contact strokes of more than 20 mm, which are necessary for high-voltage vacuum applications. Numerical simulations of magnetic flux density effectively support the development work and enable us to broaden the switching capability limits more and more. Figure 3 and Figure 4 show the results of such a simulation tool. The interpretation and the comparison of these results with experimental data are essential. All of this together represents the value of such extremely helpful tools. Additionally, these investigations have to take into consideration that not only the switching performance is important, but also the ability to carry the nominal current in a sufficient way. The AMF arc-extinguishing performance for the larger contact distances of a 72.5 kV vacuum interrupter is excellent and the arc behaviour is up to the highest short-circuit current values not in the constricted plasma phase. This reduces local overheating of the contact surface by distributing the arc energy over the entire copper chromium (CuCr) contact plate surfaces. Contact erosion and density of metal vapour will be reduced by this system, therefore enabling fast and reliable recovery of the dielectric strength after current zero. Consequently, it was possible to carry out the short-line fault tests (L90 and L75) with a line-side time delay of less than 100 ns, even if this exceeds the IEC standards.

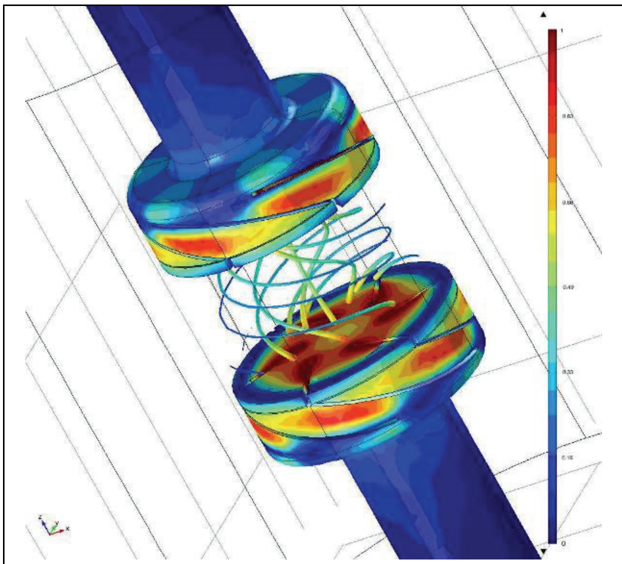

Figure 3 : Simulation of magnetic flux density for the AMF contact system

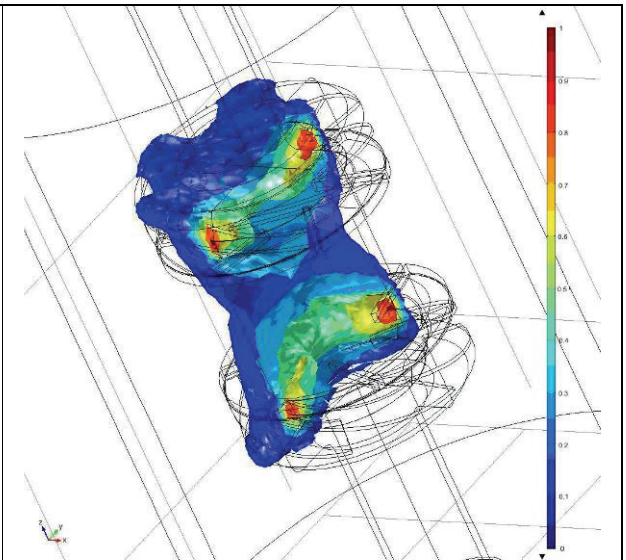

Figure 4 : Equipotential areas of magnetic flux density for the AMF contact system

IEC TYPE TEST

Pilot utilities will enjoy maximum reliability although the test phase for pilot vacuum circuit breakers is for a limited number of units. The manufacturer offers the same technical test documentation quality as with its other high-voltage switchgear product portfolios.

Rated voltage	72,5 kV
Rated short-duration power-frequency withstand voltage	140 kV
Rated lightning impulse withstand voltage	325 kV
Rated frequency	50 Hz
Rated normal current	2500 A
Rated duration of short circuit	3 s
Rated short-time withstand current	31,5 kA
Rated peak withstand current	85,1 kA
Rated short-circuit breaking current	31,5 kA
First pole-to-clear factor	1,5 p.u.
Capacitive voltage factor	1,4 p.u.
Capacitive class	C2
Insulation medium	N_2
Temperature range	-30…+40 °C
IEC 62271-100 (2008), IEC 62271-1 (2007)	

Figure 5 : Basic ratings for 3AV1FG – 72.5 kV prototype

Figure 6 : PEHLA type test of 3AV1FG – 72.5 kV prototype

The 3AV1FG - 72.5 kV prototype was fully type-tested and certified by the independent institute PEHLA. The type tests were in strict accordance with the latest standards of the International Electrical Commission (IEC) (e.g. power, dielectric, mechanical, temperature rise, low and high temperature tests). This includes also the necessary test concerning the potential emission of X-rays. In general, the emission of X-rays was fundamentally investigated for the available vacuum interrupter portfolio [8]. Consequently, the vacuum interrupters do not pose dangers to people or the environment under the specified operating conditions. This also applies in the case of a high-voltage vacuum interrupter.

The basic ratings of this circuit breaker are listed in Figure 5. The tests were carried out predominantly for a power frequency of 50 Hz. The photograph in Figure 6 was taken during the high-power type test, and shows the circuit breaker connected to the test circuit.

INITIAL EXPERIENCE WITH THE PROTOTYPES

The conscientious development activities and a successful type test are only preliminary requirements to ensure safe operation of high-voltage vacuum circuit breaker equipment. Three European utilities agreed to implement the circuit breaker in their network configurations. The necessary test phase was started in August 2010.

In this context, frequently operated feeder bays with sufficient meshed configurations were preferred to produce the necessary field experience under load conditions. However, this was not always possible, so the number of operations for the respective prototype circuit breakers varies considerably. In this initial test phase critical applications like capacitor banks and shunt reactor switching (switching of small inductive currents) were avoided.

Table 1 gives an overview of the different pilot circuit breakers, their locations, the number of switching operations and the kind of applications.

Experience of utility A:

Circuit breakers have been installed in the 63 kV network. The feeder bays have been selected in three duplicate busbar substations situated in different parts of France, including near the sea. The first circuit breaker was installed at the end of 2010 and the last one in mid-2011.

For these circuit breakers, maintenance operations are frequency-based. Circuit breakers are visually inspected at least twice a year and no-load operations are performed at the same frequency. Moreover, N2 gas density is permanently monitored and spring charging time is monitored with each operation. Since commissioning of the circuit breakers, they have switched off several short-circuit currents. So

far, no abnormalities have been observed on the circuit breakers, nor on the equipment in the vicinity. So far, utility A has provided positive feedback on switching and fault-clearance events.
The commissioning and the first months in operation of the three vacuum circuit breakers have been carefully analyzed and allow determining of the points that will have to be adapted when considering the installation of vacuum circuit breakers on a larger scale, such as factors regarding operation, inspection and maintenance procedures of the circuit breakers (gas pressure handling, maintenance schedule,…).

Experience of utility B:

The circuit breaker is installed in a double busbar substation in the 65 kV grid. The selected bay feeds a connection between two double busbar substations. The circuit breaker completed over 1800 operations under charge since September 2010 without any malfunction. Moreover a continuous analysis of recordings of voltages and currents during switching operations are fulfilled to verify if this type of circuit breaker causes fewer sags and swells. The circuit breaker has not switched off any short-circuit currents up to now, nevertheless no abnormalities have been observed.

Experience of utility C:

Utility C has not so far observed any abnormalities. The circuit breaker has not yet switched off any short-circuit currents.

Table 1 : List of pilot circuit breakers

Utility/circuit breaker	Location of pilot circuit breaker	Type of applications, switching requirements	Number of switching operations (up to 12-2011)
Utility A, circuit breaker 1	France, Lion D'Or (Atlantic Ocean)	Outgoing feeder circuit breaker	20
Utility A, circuit breaker 2	France, Moru	Outgoing feeder circuit breaker	90
Utility A, circuit breaker 3	France, Ormes	Outgoing feeder circuit breaker	20
Utility B, circuit breaker 1	Luxemburg, Esch-sur-Alzette	Outgoing feeder circuit breaker	1841
Utility C, circuit breaker 1	Denmark, Haslev	Circuit breaker for changing busbars	200

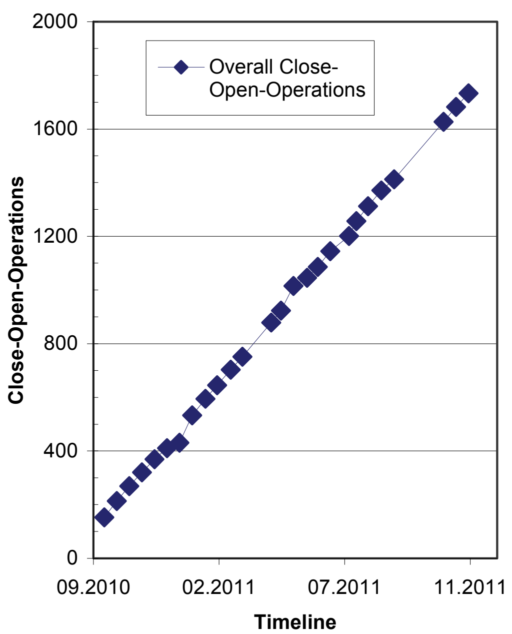

Figure 7 : Utility B, trend of total switching operations for the pilot circuit breaker

Figure 8 : Photograph of the pilot circuit breaker at utility C

Figure 7 shows the trend of the switching operations for utility B's circuit breaker in the course of the test phase. Figure 8 shows a photograph of utility C's circuit breaker, taken at the site where it is in use.

Overall, these five prototype circuit breakers have so far carried out more than 2,200 switching operations.

PROSPECTS OF THE PILOT UTILITIES

The reasons for the utilities to take part in the initial test phase of the vacuum technology for the sub-transmission voltage levels are diverse. A comparatively low contact erosion allows an increased breaking capacity for the normal current and the short-circuit current. The vacuum circuit breaker introduced here offers 10,000 operations for the rated normal current and 30 interruptions for the rated short-circuit breaking current. This results in a further improvement in performance for the high-voltage switchgear applications.

The maintenance schedule and the service procedures for the vacuum technology could differ from the existing gas circuit breaker technology. This could result in benefits for users.

Additionally, the technology offers the possibility to create a high-voltage circuit breaker without the use of greenhouse gases, which represents a major challenge for utilities. It is also an opportunity for utilities to show their interest in promoting investigations on new and less polluting technologies.

Finally, the current pilot test phase gives an opportunity to discuss the question of IEC type tests: Do we need new IEC standards for this new application of vacuum technology?

In general, utilities and manufacturers derive benefit from the experience gained in the test phase of the prototype circuit breakers in realistic high-voltage grid configurations. This experimentation allows us to consider whether widespread installation of high-voltage vacuum circuit breakers within a few years might be possible.

Further to this pilot project, some utilities are already looking forward to installing vacuum circuit breakers at higher voltages (e.g. in a 90 kV network).

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