CONTINUOUS VACUUM MONITOR FOR AIR INSULATED VACUUM CIRCUIT BREAKERS

Hans SCHELLEKENS Christophe PREVE Venanzio FERRARO François Bonnard
Schneider Electric BU Energy, Medium Voltage Products, Grenoble, F-38050 cedex 9
hans.schellekens@schneider-electric.com

ABSTRACT

The Continuous Vacuum Monitor presented improves the availability of the Vacuum Circuit Breaker left without maintenance from 99.9% to as much as 99.999 9% and the functional safety to 99.999 999% as nearly immediate warning reduces the risk to operate a VCB with a leaky Vacuum Interrupter. The physical operating principal of the CVM is based on a capacitive sensor detecting partial discharges occurring inside the VI as its dielectric strength falls below the network voltage. A microcontroller measures these discharges and analyses their characteristics to reduce the risk of false identification of a loss of vacuum. The degree of interference due to PDs from other sources is discussed using a numerical analysis.

INTRODUCTION

The first continuous vacuum monitor (CVM) is proposed as an option in Japan only since 2006, about 50 years after the introduction of vacuum circuit breakers [1,2]. This poses the following questions:

Why did it take such a long time?

Firstly, vacuum interrupters are conceived as *sealed for life* products. One of their strengths is they are maintenance free: *install and forget*. Manufacturers underscore this aspect by referring to the excellent Mean Time To Failure of more than 45000 years of the installed vacuum interrupters [3]. Secondly, it has been argued that monitoring is counterproductive as any vacuum pressure measurement device reduces the reliability of the VI. Therefore today all VCB's are without vacuum monitors.

Why should the CVM be installed?

The trust users convey to the VCB based on the MTTF values is only permissible for applications with minimized and accepted risks and respecting maintenance procedures; MTTF doesn't mean *fail free*. In all other cases monitoring of the vacuum on a regular basis is mandatory. This is exactly what the CVM does. It surveys the VI continuously and gives an alarm within minutes after loss of its functionality. It permits the network to adapt the protection of the network to the new situation and to coordinate the replacement of the circuit breaker.

When should the CVM be installed?

There are 3 priority applications for the CVM:

- Improvement of service continuity through reducing risk of equipment damage: Critical applications where the cost of loss of functionality is very high and exceeds by far the cost of monitoring.
- Extension of the operating life of existing VCB beyond their original operating life without exceeding the maximum number of allowed mechanical and electrical operations.
- Functional safety improvement through reducing internal arc risk due to VI loss of vacuum.

In the following paragraphs a detailed description will be given of the CVM clarifying questions like: Why doesn't the CVM impact the reliability of the VI itself? How does it detect the loss of vacuum and why is interference from other partial discharge sources excluded? How can an availability of 99.999 9% be realized on the functionalities of the vacuum interrupters like the nominal current carrying, the short circuit interrupting and the dielectric capability?

PHYSICAL OPERATING PRINCIPAL

In [4] a detailed description is given about the differences of the 4 main types of vacuum measurement applicable to sealed vacuum interrupters in VCB's. They are presented in the diagram of fig. 1 and will be briefly discussed below. Users of VCB's commonly use the HiPoT (high potential test) or dielectric withstand test

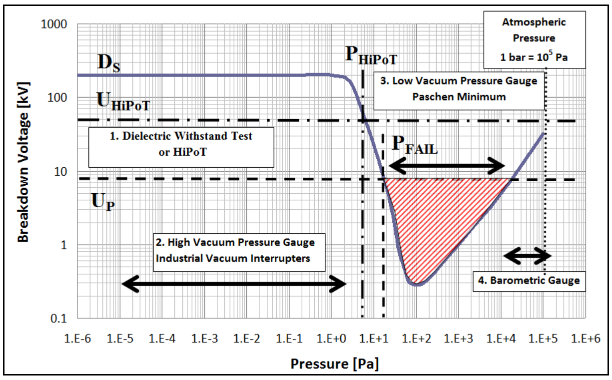

Fig.1. Dielectric strength DS of a VI with 1cm contact gap. Features of the figure are outlined in the text. Hashed area is region with PDs inside VI.

(indicated in Fig.1 as (1)) to test the vacuum condition. The voltage U_{HiPoT} is sufficiently high to provoke a breakdown at atmospheric pressure if vacuum is lost. When no breakdown occurs then the pressure in the VI is lower (or better) than P_{HiPoT}. This test is only possible during a maintenance overhaul as the VCB need to be disconnected and racked out from the switchgear cubicle. Three other techniques exist to evaluate the vacuum condition and which can be performed in a continuous way when the VCB is online potential.

The high vacuum pressure gauge (indicated in Fig.1 as (2)) measures in the operating range of vacuum interrupters and can be used to predict the remaining life time. This gauge needs access to the inside of the VI and electronics at line potential. The barometric gauge (indicated in Fig.1 as (4)) needs an additional bellow for pressure measurement. Both methods have been disregarded as they impact negatively the reliability of the VI.

A low vacuum pressure gauge (indicated in Fig.1 as (3)) measures at pressures around the Paschen minimum above P_{FAIL}. The VI has a dielectric strength below the nominal network voltage and has lost its current interruption and voltage-withstand characteristics. This results in continuous breakdowns, called PDs between the energized current conductors and the electrically floating shield inside the VI, irrespective whether the VI is in open or closed position. These PDs can be measured by a capacitive sensor placed between the VI and a grounded conductor (for instance the housing of the CB drive). The CVM discussed here uses this principle. Although the monitor doesn't give any warning for upcoming loss of vacuum, the signal of failure is directly linked with the loss of the vacuum interrupter characteristics. The VI needs to be at the network voltage for an operational detector, which is the case for most distribution switchgear applications.

The parameters $T_{RESPONSE}$ and T_{BLIND_SPOT} are related to VI failure modes and are calculated using the minimum and maximum leak rate values reported in [3]. In case of a big leak, the pressure will rise fast to atmospheric pressure. $T_{RESPONSE}$ is the time available to detect the leak before measurement becomes impossible; the available response time is in excess of several hours. In case of a very small leak the monitor suffers from a blind spot where T_{BLIND_SPOT} is the time when the VI has lost its characteristics and the detector can detect the loss of vacuum; this time is less than some tens minutes. These times are compatible with the intrinsic measurement time of the CVM of several minutes.

These low vacuum pressure gauges are considered an optimal engineering choice for the CVM as they don't require any specific adaptation to the VI; hence the reliability of the VI is not affected.

Table I: Comparison of the 4 types of vacuum monitors.

	Type of vacuum monitor			
	HiPoT	**High Vacuum Pressure Gauge**	**Low Pressure Gauge**	**Barometric Gauge**
Measurement Range	**2.10^0 to 10^5 Pa**	**2.10^{-4} to 5.10^{-1} Pa**	**10^1 to 10^4 Pa**	**10^4 to 10^5 Pa**
Predictive	**No**	**Yes**	**No**	**No**
Adaptation of VI	**No**	**Yes**	**No**	**Yes**
Continuous monitoring	**No**	**Yes**	**Yes**	**Yes**
$T_{RESPONSE}$	**Periodicity of Maintenance**	**2 sec.**	**3 Hours**	**Unlimited**
T_{BLIND_SPOT}		**Non**	**40 Minutes**	**46 Days**

TECHNICAL REALISATION

The CVM consists of 2 main parts, a capacitive sensor and an electronic module coupled by a cable. The installation of the CVM is shown in fig.2. It shows the sensor positioned between the circuit breaker poles containing the vacuum interrupters and the mechanism housing and fixed against the latter. The Electronic Interface Device, or EID, is placed on DIN-rail on the front panel of the circuit breaker. The Electronic Interface Device implements the following functions:

- Analogue signal conditioning card, which contains an EMC filter, the Partial Discharge filter, amplifiers and power supply.
- A Micro Control Unit (MCU) for signal analysis, communication and data storage.
- A Human Machine Interface

A detailed view of the Electronic Interface Device is given in fig. 3. Communication is either through Modbus

Fig. 2. CVM installation on VCB type HVXO² 17.5kV-31.5kA-1250A
The green panel is the epoxy support with the sensor
The insert shows the electronic interface device.

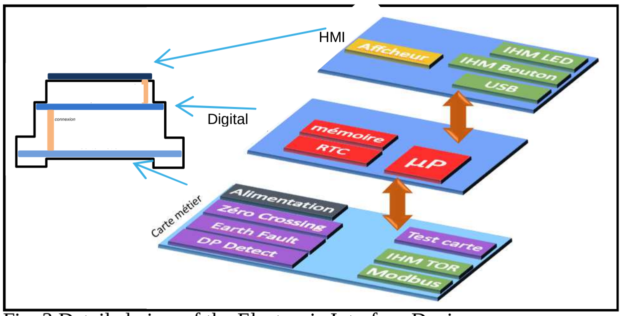

Fig. 3 Detailed view of the Electronic Interface Device.

or by ZIGBEE dongle connected to the USB port. As the probability to have a leaky VI is very low, it is of utmost importance to be sure that the CVM is functioning correctly and to avoid false alarms.

The CVM incorporates the following functionalities:

1. Continuous self check of the system :
   Before each measurement cycle the MCU controls:
   - the correct connection of the sensor to the EID, and
   - the electronic chain of detection by injecting a pulse into each sensor.
2. Detection of leaky VI: Measurement cycle is set at one minute interval. Although one cycle is sufficient to acknowledge a loss of vacuum; the standard procedure is to signal the presence of a leaky VI only after confirmation over 5 consecutive cycles. Detection of loss of vacuum is based on recognition of the characteristic signature of the PDs produced in the VI's in front of the CVM sensors.
3. Filtering out signals not coming from the VI's. PDs might arise from other sources. The detection algorithm is robust to avoid such interference (see below).
4. Signalling the presence of leaky VI to the operator. LEDs placed on the EID on the CB inform the operator in front of the CB of the presence of a leaky VI. In this case the CB shall not be manoeuvred. This signalisation can be duplicated on the Cubicle using the dry contacts.
   Four signals are commonly presented:
   - CVM operates : Blue
   - CVM failure : Orange
   - Vacuum Leak : RED
   - Communication : Yellow
5. Sending an alarm to the network operator. Modbus allows full dialog to the SCADA system. The data that can be transmitted are the 4 status signals of the CVM as well as the measured PD signature. All data are stored in a local memory FIFO that retains the history of the last 70 days.

DETECTION OF LOSS OF VACUUM

Detection of loss of vacuum is based on recognition of the characteristic signature of the PDs. The characteristic signature of *loss of vacuum* is determined using a special test setup, where the pressure in a VI is varied in an artificial way. The VCB is connected to a 3 phase power supply with a nominal voltage of 10kV. One of the VI's on the CB is connected to a pumping system. The pressure can be varied reproducibly from 1 Pa to 10^5 Pa, which covers the whole zone where PDs can occur, fig.1.

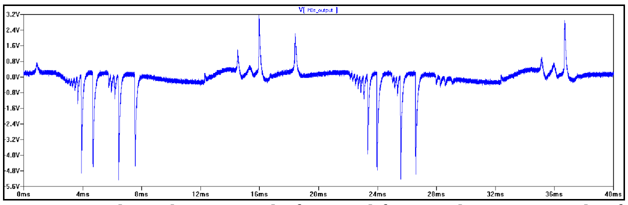

Fig. 4. Partial Discharge signal after amplification during 2 periods of 50Hz. Pressure is about 20 Pa.

A typical time recording of PDs due to a high gas pressure of 20 Pa inside the VI is given in fig. 4. Notice that the signal is reproducible, the number of positive pulses is less than the number of negative pulses, and that the peak values are not identical.

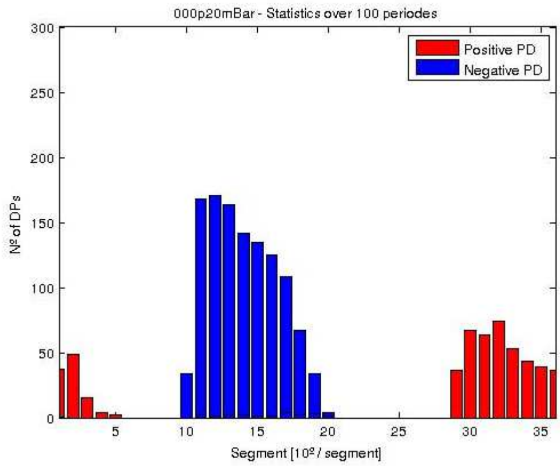

Fig.5. Partial discharge signature. Number count of positive and negative partial discharges.

In order to have a statistically representative number of discharges, the positive and negative PDs are counted during 100 power frequency cycles. Measurements are synchronized with the power frequency. Number count of positive and negative PDs are shown in fig. 5. The signature of the PD is characterised using statistical and spectral analysis. These characteristic signatures of the PDs which depend on pressure are factory stored in the memory of the EID.

SENSIBILITY TO PD INTERFERENCE

PDs may come from **other sources** than loss of vacuum and might interfere with the detection algorithm. The extent to which is investigated by the following numerical simulation:

a. [5] Describes the positive and negative PDs by Pearson distribution functions and gives for each the statistical variations for 2 parameters: skewness and kurtosis, as well as for Q the ratio between positive and negative PDs.
b. Matlab® is used to create in randomly PD pulses

according to Pearson distribution. The resulting partial discharge signature is then analysed by the CVM algorithm resulting in a measured phase angle.

c. The statistical nature of the parameters is taken into account. The amplitude and the phase information are calculated using a design of experiments approach (in this case a 3rd order Central Composite Design) varying the 5 parameters. A Monte Carlo calculation using Oracle® yields the probability distribution for the amplitude and the phase information in the frequency domain.

d. The χ^2 test with k degrees of freedom is used to test **goodness of fit** for the hypothesis H_0: "the observed signature is identical to the signature of *loss of vacuum*". The distance D^2_k between an observed parameter μ and the associated parameter of *loss of vacuum* u:

$$D_k^2 = (u_k-\mu_k)^2/\sigma_k^2 \quad (1)$$

Here μ and u are any of the statistical parameters [5] and amplitude and phase information in the frequency domain.

e. The probability that the signature of an observed PD is mistaken for a *loss of vacuum* (incorrect rejection of H_0: Type I error) can now be calculated; see table II.

Interference is negligible as table II shows. The probability to have a false reading is low for "Corona in Air" at 0.01% to very low (<0.0003%) for all other PDs of [5]. PDs caused by loss of vacuum in another VCB connected to the same bus or cable are also effectively discriminated. As detection of PDs is phase sensitive, the CVM has the information which phase has lost the vacuum; this information is not exploited as the VCB has to be exchanged anyway. In conclusion, the CVM is very selective PD detector, detecting only a loss of vacuum inside the VI's installed on the VCB being monitored.

Table II : Interference or the probability to mistake a PD [5] for loss of vacuum.

PD - source	P(loss of vacuum)
1. Corona in Air	**0.01%**
2. Surface discharges in Air	<0.0001%
3. Surface discharges in SF6	<0.0001%
4. Floating parts in Air	<0.0001%
5. Corona in Oil	**0.0002%**
6. Surface discharges in Oil	<0.0001%
7. Discharges in cavities (dielectric bounded)	**0.0001%**
8. Discharges in cavities (electrode bounded)	<0.0001%
9. Treeing initiated by point-plane	<0.0001%
10. Treeing initiated by a cavity	**0.0003%**
11. Vacuum leak on another CB	<0.0001%

CUSTOMER BENEFITS

The problems caused by a loss of vacuum in a VCB are:

- Oxidation of the contacts in case of prolonged exposure to air, which for fully nominal current loaded CB's leads inevitably to overheating of the circuit breaker, loss of contact pressure and arcing.
- Immediate loss of short circuit interrupting capability, which becomes only evident upon solicitation of the function and causes the next higher protection to intervene. The consequence is a substantially increased number of consumers or loads affected in power outage [6].
- Immediate loss of dielectric strength, which becomes only visible upon opening of a disconnecting CB; for example in "fast current transfer" schemes and in bus-bar couplers using 2 CB's in series. The consequences are a total loss of functionality in these critical applications.

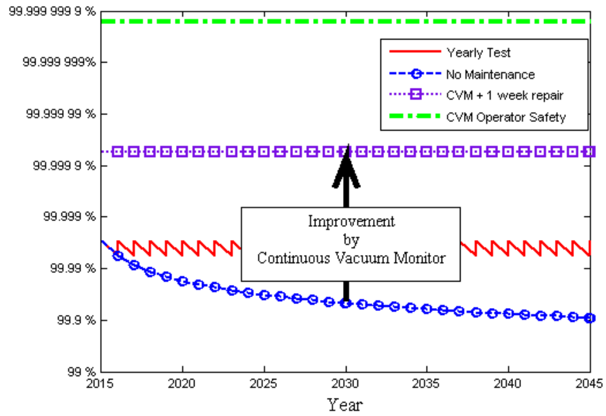

Fig. 6: Availability of a VCB during 30 year interval as function of maintenance policy (yearly or non) compared to VCB with CVM.

Yearly test of the vacuum condition limits these risks to about 1 in 15000, as the test permits to replace VCB's with VI's that lost their vacuum, which corresponds to an availability of 99.995%. Yet in absence of any test the number of faulty devices will increase over time to about 1 in 500 after 30 years, which corresponds to an average availability of 99.9 %. The variation of the availability of a VCB with time is shown in fig. 6.

The CVM brings the following advantages:

- No need any more for the yearly test of the vacuum condition; the CVM takes over this function entirely. It informs the operator of the state of the VI and of its proper condition every minute.
- Functional safety [7] is increased. Operation of a leaky VI might evolve into an internal arc hazard. The risk to operate a VCB with a leaky VI is drastically limited by a reduction of the detection delay from 1 year to some tens of minutes (table 1). The operator in front of the VCB is informed immediately and the risk to operate a VI with an unexpected leaky VI is reduced. The functional safety increases to 99.999 999% (eight nines).
- The availability of the CB function is increased. The network operator is informed nearly immediately. He will organise a planned maintenance operation and he can prohibit the opening of the breaker. In this way malfunction during a planned operation or during an emergency operation is avoided. The resulting availability of the VCB mounts to 99.9999% (six

nines) for a repair time of one week.

The availability does not depend entirely on the condition of the VI, but on the whole chain of detection and action: current transformer, over-current relay, mechanism and VI's. Yet from the network operator perspective, the CVM increases the availability of the VI on the VCB to 99.9999% compared to 99.9% for a CB left without maintenance.

CONCLUSION

Vacuum technology is a key for the future. Despite its reliability has been demonstrated and appreciated for decades up to now, monitoring its performance shall bring additional benefits to the energy availability and maintenance optimization.

The continuous vacuum monitor surveys the VIs on a VCB continuously and gives an alarm within minutes after loss of its functionality. It permits the network operator to adapt the protection of the network to the new situation and to coordinate the replacement of the circuit breaker. The operating principle, its construction and the detection algorithm are described. The degree of interference due to PDs from other sources is discussed based on a numerical analysis. The continuous vacuum monitor brings 3 main advantages to the network operator:

- It replaces the yearly test of the vacuum condition.
- It increases functional safety against the risk to operate a VCB with an unexpected leaky VI to 99.999 999%.
- It increases the availability of the functionality of the VCB to 99.999 9%

Its prime interest is for critical network conditions and for extension of operating life. Demonstrated here above on VCB, it could be implemented as well on any current or future devices using vacuum technology.

MISCELLANEOUS

Acknowledgements

The authors express their thanks to Marcos Crozzolo and Maxime Durand for their decisive impact in the development of the Electronic Interface Module, and to Yvon Rebiere for his mathematical guidance in the analysis of PD interference.

REFERENCES

[1] M. Kamarol, 2007, "Diagnostic Technique of Insulation Performance in Vacuum Interrupter Based on Partial Discharge", Proc. Int. Symp. EcoTopia Science 2007, Nagoya

[2] K. Miyagi, 2008, “Trend of New Technologies for Insulation Diagnosis and Monitoring of Substation Equipment”, AE POWER SYSTEMS REVIEW, vol.1, 2008.8

[3] R. Renz , 2007, “Vacuum Interrupters – Sealed for Life”, 19th CIRED, paper 0159

[4] H. Schellekens, 2014, "Continuous Vacuum Monitoring in Vacuum Circuit Breakers", *Proceedings ISDEIV conference*, vol.2, 465-468, Mumbai, India

[5] E. Gulski, 1991, “Computer-Aided Recognition of Partial Discharges using Statistical Tools”, thesis, Delft University Press, Delft, Netherlands

[6] H. Schellekens, 2010, “Impact of vacuum switch-disconnectors on reliability of MV distribution networks”, CICED, Nanking

[7] IEC-61508, “Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems“