A FIELD CHECK ON THE CONDITION OF VACUUM INTERRUPTERS AFTER LONG PERIODS OF SERVICE

Martin LEUSENKAMP *
Martin BINNENDIJK**
Bert TER HEDDE**
Eaton – China*/The Netherlands
Martin.Leusenkamp@Eaton.com

Theo VAN RIJN
Alliander – The Netherlands
Theo.van.Rijn@Alliander.com

ABSTRACT

In modern medium voltage distribution networks Vacuum Circuit Breaker (VCB’s) play a vital role in the safety and reliability of the grid. The key components in VCB’s are the Vacuum Interrupters (VI’s). Medium Voltage switchgear and the VI’s are designed for a long service-life. The first VI’s were introduced in medium voltage breakers half a century ago, and many were in service for decades. In collaboration with several utilities a status check has been carried out on a number of VI’s which had been in service up to 25 years. The result of this work provides valuable information on the reliability of VI’s after long periods of service and is useful for asset management of distribution networks.

INTRODUCTION

The first generation switchgear systems equipped with VCB’s are now approaching their fiftieth anniversary in service which is well past the typical design life of thirty years. In practise, the vast majority of switchgear systems is decommissioned or had a major overhaul well before it has been in service for forty years. Switchgear with an extended operation well beyond the original intended service life, that could not be decommissioned and/or replaced by a newer system due to some specific reason, the circuit breakers, are normally replaced well before their fiftieth year in service. In general the number of switchgear systems with over fifty years of service equipped with the original breakers is relatively small. This gives more or less an indication of the maximum expected operating life of a breaker and hence the minimum required design life of a VI. Figure 1 shows a typical VI, VCB and Switchgear System used in Medium Voltage distribution networks.

To get a better insight in the aging of VI’s a status check has been carried out in collaboration with several utilities. In the Dutch Alliander MV-network more than 25,000 VI’s are in service. Based on this population, and to check for a reliability of 90% with a margin of error of maximum 10%, a sample size had been determined of 68 VI’s. The actual sample size taken out of service for this investigation was eventually 54. This smaller sample size would result in an 11% margin of error looking at the original aim. Those VI’s had been in service for up to 25 years. A second group of interrupters manufactured in the late 80’s came from decommissioned switchgear in the UK which had been in service for about 20 years.

Various tests including full short-circuit tests on some units have been carried out to get a full understanding of the status of the VI’s. A number of units were opened for visual inspection of the interior to get a better insight in the actual severity of interruptions a VI would see during its service life. This paper discusses background information first, followed by results of the tested VI’s.

VI – LIFE AND FAILURE PROBABILITY

Basic expectation is that an ideal Vacuum Interrupter maintains its original vacuum level forever. Practice of 50 years with huge installed base supports this so far, as outlined in this paper. Of course ‘forever’ has an end in practice, and any real vacuum system presents a rise in pressure eventually. This may be due to gas penetrating through leaks, outgassing of internal parts and permeation of gases through the enclosure. This paper provides results from the field showing that by proper design, processing and quality control a VI’s end-of-life point vastly exceeds any (extended) service life requirement of any VCB. VI’s passing the leak check during the final inspection in manufacturing are sealed for life.

Life definitions

The minimum service life of VI’s complies to the preferred values mentioned in the IEC 62271-1 [1] which are 20, 30 and 40 years. The typical service life for switchgear systems is 30 years. The service life is the period of useful life in operation with normal repair and maintenance.

Fig.1: From left to right: VI, VCB & Switchgear System
The original intended service life of a system is usually less than the asset's physical life which is the duration that piece of equipment is able to perform business operation. Therefore it is not uncommon that switchgear systems are kept in service well beyond the stated design life of the equipment manufacturer. Most VI manufacturers never stated any life information on their product data-sheets as it was considered that the life of a VI would greatly exceed the typical 30 years’ service life of a breaker. However, some VI manufacturers’ data-sheets mention a storage or shelf-life which is not to be confused with service life. When a VI is unpacked from its original packing material and installed in a breaker, or merely left in storage, placed in pre-expended bins, or held as bench stock, storage life or shelf-life ends and service life begins [2]. The various life definitions are illustrated in figure 2.

Life prediction

The end of a VI’s physical life depends on various factors. One of them is the vacuum level inside the interrupter. The initial vacuum level of factory new VI’s is roughly around $P_0=1\times10^{-6}$ mbar.

When exceeding the critical pressure of $P_{crit}=0.01$ mbar, the excellent voltage withstand capabilities of a VI starts to decrease, as shown in figure 3.

During VI design a very conservative safety factor over the critical or end-of-life value is used ( $P_{crit}=0.01\times P_{act}=10^{-3}$ mbar). This to determine ample “getter” amount and to set a conservative pass criteria during the production vacuum measurement. A proper designed VI has a getter, which is a type of capture pumping device normally made of a sintered-powder matrix of metal alloys which chemisorb active gases. Getters are activated during the high temperature brazing process just before the VI is sealed-off. The amount of getter material is chosen such that tiny leaks, permeation or outgassing or any other source that could contribute to an excessive pressure rise during life is fully eliminated.

Eaton VI’s have a vacuum design life of at least 100 years which is more than twice the maximum expected operating life of a VCB.

As the installed base of older VCB’s starts to increase the question raises whether remaining life prediction of VI’s would be possible and would make sense or not. The following information may guide asset management.

![Figure 3: Paschen curve](image)

**Fig.3**: Paschen curve

![Figure 4: Remaining VI life determined x-years after the manufacturing date assuming a constant leak-rate](image)

**Fig.4**: Remaining VI life determined x-years after the manufacturing date assuming a constant leak-rate

Figure 4 can be used to estimate the remaining VI’s vacuum life when performing a pressure measurement 5, 10, 20 or 40 years after the manufacturing date when assuming a constant leak rate during its entire life starting the day the VI was sealed and that the unit was manufactured without a getter.

As an example, a VI that would have an internal pressure of $1\times10^{-4}$ mbar 20 years after the manufacturing date would take another 200 years to reach $10^{-3}$ mbar and a staggering 2000 years to reach the critical pressure of $0.01$ mbar. Both numbers are well beyond any realistic service life expectation of a VCB.

The assumption of a constant leak-rate over the entire life is however not realistic nor are any commercial available VI’s manufactured without a getter. With the getter type, amount of getter material and saturation state unknown it would be impossible to make reliable life predictions.
ones a VI is in service. Besides that, any leak that could jeopardize life would have been caught during the final production testing. This means that the moment a serious breach of integrity would have occurred is at a later date. It must be noted that pressure measurement of sealed units in the field is complicated and with, e.g., fixed switchgear often impossible. The measurement requires sophisticated measurement equipment and is only useful when the calibration curves of the specific VI type are known. These curves are only available to the original VI manufacturer.

Practise has shown that a VI should never be removed from a breaker with the intention to put it back in service. The risk of failure due to, e.g., twisted bellows, especially when performed by others than the OEM, is very high and strongly discouraged. Figure 5 shows an X-ray picture from a VI of which the removal from the breaker caused a twisted bellows.

In general, no specific tightness tests are required during life for vacuum interrupters since their tightness is verified during manufacturing and proven to be sealed for life. Any breach of integrity during life would be easily captured by an AC-withstand test during the normal breaker maintenance intervals.

**Failure probability**

VI’s are a high-tech industrial component and each unit has gone through a rigorous set of quality checks prior to shipment. The vacuum tightness is one of the topmost priorities. A proper designed and processed VI is sealed for life. Any leakage that could shorten the intended life would have been detected prior to shipping. Vacuum production testers have proven to be extremely accurate over the last decades and able to detect any product that would be liable to fail during its life in service.

Based on Eaton’s almost 50 years of VI manufacturing experience early “infant mortality” failures have shown to occur shortly after shipment due to, e.g., transport damage, poor storage, incorrect handling, improper mounting into the breaker etc. Those failures are however easily detected by an AC-withstand voltage check at either the standard routine test or during commissioning of the entire switchgear system. After commissioning the field failure rate of VI’s has been proven to be extremely low. In general, a VI in service for 5 years or more has a very low probability to fail during its remaining service life. Figure 6 shows the hypothetical failure rate vs. time for VI’s.

**MEASUREMENT RESULTS**

Eaton received a total of six VI’s manufactured by VIL, UK around 1989 which were identified as Type V803. Those VI’s were part of an extended study conducted by the Energy Network Association in the UK [3].

After general investigation and vacuum measurement five units were sent to the Eaton High-Power lab in Horseheads, NY to validate the switching performance based on the original data-sheet specification. Three units have been used for short-circuit switching tests and two have been cut open to investigate the interior after being in actual service for over 20 years. The remaining VI was used to prepare a calibration curve for the vacuum measurement. Another set of 54 interrupters were manufactured by Eaton and involved both Load-Break Switch VI’s type VA14 as well as Circuit Breaker VI’s types VB12 and VB20. This set of VI’s was taken out of service by Alliander, a large utility in the Netherlands, specifically to check for any signs of aging. Those VI’s had been in service varying from 5 – 25 years.

The following tests were performed on all units:

- Visual inspection
- X-ray
- Power-Frequency Withstand test (PFWV-test)
- Lightning Impulse test (BIL)
- Resistance measurement
- Vacuum Measurement

![Fig.5 : X-ray of VI with twisted bellows](Image)

![Fig.6 : Bathtub curve – Hypothetical failure rate vs. time](Image)
Three V803 units had additional short-circuit testing and several VI’s from both groups were opened to visually inspect the interior.

**Visual inspection**
Upon arrival the boxes containing the VI’s were inspected for any signs of transportation damage. The VIL VI’s were bare and were carefully inspected to look for any signs of damage, contamination, oxidation or any other signs of aging. In general these 25 year old VI’s appeared to be in mint condition. The Eaton VI’s came from encapsulated pole units and most of them were still in a pre-casting, as shown in figure 7, which had to be removed for further testing.

![Fig. 7: Eaton VI’s in epoxy pre-casting](image)

**X-ray inspection**
To check the interior for any signs of distress without damaging the VI envelope all VI’s were inspected by X-ray. It was noticed that from the 60 VI’s 8 had a twisted/damaged bellows ranging from slight to severe deformation. A twisted bellows could severely reduce the mechanical life of a VI and/or result in leakage. It is likely that the damage occurred during the disassembly of the VI’s from the breakers. Besides the bellows damage, no signs of severe arcing, internal contamination due to switching or shield damage was observed. This was confirmed later when a number of the units were opened.

**Power Frequency Withstand Voltage test**
The V803 type VI is a 17.5kV interrupter which should withstand, according the IEC standard, a 1-min PF WV of 38kVrms. Once in service only 80% of this value is required to pass. The V803 data-sheet however gave a maximum withstand voltage of 50kVrms. The VI’s passed testing up to 110% of the data-sheet value (55kVrms) at a 8mm gap.
The Eaton interrupters were tested at a 10mm gap at 50kVrms for the VA 14 type interrupters and at 38kV for the VB12 and VB20 type interrupters. All interrupters tested passed the PF WV-test without any issues.

**Lightning Impulse test**
Only on the V803 interrupters lightning impulse tests were performed as the Eaton type interrupters under test were not designed to withstand the lightning impulse voltage without external insulation applied. The required lightning impulse voltage for new 17.5kV interrupters is 95kVpeak. The VIL tested units passed without any issues the 95kV rating and even up to 110% of the rating. Higher test voltages were not attempted to not damage the units due to possible external flashovers. In later tests in Eaton’s High Power lab in Horseheads, NY the units that were used for switching tests were tested under oil and tests at higher impulse voltages up to 150% of the rating were performed successfully.

**Resistance measurement**
For all units the DC-resistance was measured and compared to the values on the product data-sheet. No abnormalities were observed indicating that the interrupters most likely did not see any high fault currents. Later this was confirmed by visual inspection of the contacts when several of the units were opened.

**Vacuum Measurement**
All units were tested in the Eaton’s VI production vacuum tester in the Suzhou, China facility. The tester is based on the Penning/Magnetron measurement principle.

![Fig. 8a: First pressure measurement via penning method of 4 furnace batches of 100 VB20 units each.](image)

![Fig. 8b: Measurement results of 54 Eaton type VI’s.](image)
The 54 Eaton VI's measured had internal pressures in the range of factory new VI's.
In figure 8 the results are presented. Figure 8a shows a typical measurement result of several VI furnace batches of total 400 new VI's of the type VB20, whereas figure 8b shows the results of the returned VI's.
From these test results it can be seen that no noticeable pressure rise was evident and that all units would have passed the test criteria for factory new VI's and would have surpassed from vacuum perspective any practical service life requirement.
For the V803 type VI's no calibration curve was available and we had to use one unit to prepare it to be able to perform accurate pressure measurements. The 5 tested VI's had a pressure of 2.9x10^{-6} mbar, 4.6x10^{-5} mbar, 2.2x10^{-5} mbar, no-start and 4.2x10^{-6} mbar, respectively. The no-start normally indicates a very low pressure outside the measurement range of the tester.
For all measured VI's we can safely state that they were sealed for life.

Short-circuit switching tests
Three V803 VI's underwent a series of short-circuit tests in Eaton’s High Power Lab in Horseheads, NY at the designated rating according the data-sheet. All tests were single-phase interruptions. In order to show the basic short-circuit capability of the VI’s a 14 shot sequence was conducted at the rated short-circuit current of 17.5kV-25kA@50Hz.
The interruption performance observed was acceptable for an E1 electrical switching life as described in the present edition of the IEC circuit breaker standard.
Testing continued up to a total of 30 full short-circuit shots to investigate the suitability for an E2 extended electrical life which seems to be beyond this designs capability.
Looking at the applicable standards back in 1989 the VI’s performed excellent.

Visual Inspection of VI interior
Two V803 VI’s were cut open to look at the VI interior after being in service for 20 years. No significant arcing on the contacts, nor any other signs of aging has been observed. During the life in service these VI’s only saw a limited number of (very) low current interruptions. In figure 9 the contacts of a V803 and VB20 are shown which both are in new state after many years in service. Similar results were seen with the other Eaton type interrupters cut open.

CONCLUSION
A VI is a high-tech industrial component going through a rigorous set of quality checks before being shipped. The vacuum tightness is with no doubt one of the topmost priorities. Each interrupter is checked individually and

Fig. 9 : Contacts of VI's after 20+ years in service; both in new state. (Left: V803 contact; Right: VB20 contact)

has a unique serial number for traceability. Eaton has been manufacturing VI’s for almost 50 years at first part of Westinghouse as well as Holec and now part of Eaton. We have always considered the life of a VI to exceed 30 years, the typical service life of a breaker. Based on Eaton’s almost half a century manufacturing experience with millions of units in service we can say that properly processed VI’s are hermetically sealed for life.

Based on the outcome of this extensive investigation in collaboration with various utilities where a substantial number of VI’s was taken out of service to get a statistical insight in their status after years in service, it has been concluded that aging of VI’s with respect to internal pressure rise, that eventually could lead to failures, is not a major concern. None of the tested VI's showed an excessive pressure rise that could impose a limiting factor for the remaining life expectancy of the switchgear system. The risk of failure of properly designed, processed and checked VI’s due to natural leakage is virtually nil.
Based on the outcome of this study the life expectancy of VI’s has been determined to exceed 100 year and therefore forms no increased risk in relation to the service life of a switchgear system.

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REFERENCES