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Prüfungen und Diagnostik weiterer Betriebsmittel
5.1

Extended Maintenance Intervals for On-Load Tap-Changers Require Extensive Long-Term Tests in the Development Stage

Axel Krämer, Dieter Dohnal

Maschinenfabrik Reinhausen GmbH, Regensburg

Abstract

The technical and economical demands on equipment for electrical network applications is risen continuously in the last years. Especially the discussions on availability and the push for extended maintenance intervals have to be pointed out.

In case of on-load tap-changers (OLTC), these high requirements can be fulfilled technically with introduction of the vacuum switching technology. Based on an experience of more than 20 years in vacuum switching technology, a new generation of OLTCs made by MR offers the enlargement of the common maintenance-intervals of the conventional OLTC-technique due to the utilization of the advantages of the vacuum switching technology. With the application of this technology maintenance-intervals of 300'000 switching operations without any time limit became standard for the today's VACUTAP® on-load tap-changer family for power transformers.

The promise of those extended maintenance-intervals has to be proven in a wide range during the development stage. MR has introduced a testing strategy for the new generation of VACUTAP® OLTCs, which was and will be applied in the future to the performance verification tests.

This paper will provide an insight into both the advantages of the vacuum switching technology and the technical safeguarding by testing of the remarkably increased maintenance interval.

The new introduced OLTC-maintenance-interval means for a conventional network power transformer that during an assumed service life of 30 years with an average switching number of 10'000 per year of the OLTC, the economic lifetime and the first maintenance coincide.

1 Introduction

The importance of power transformers equipped with on-load tap-changers has grown permanently in the last decades. Today, regulated power transformers are indispensable operating equipment in energy supplying networks. Main tasks of new developments are driven by the worldwide deregulations in the electric generation, transmission and distribution industry. The voltage regulation of power transformers is realized by means of on-load tap-changers (OLTCs) by which the turn ratio can be varied under load. The high-speed resistor type OLTC, based on the 1926 patent by Dr. Janssen, is the most widely used principle worldwide.

In the course of a tap-change operation the transformer load current has to be transferred from the current carrying tap to the pre-selected one. That load transfer is realized within a period of about 50 to 100 milliseconds and consists of a defined sequence of making and breaking non-arcing and arcing contacts in the diverter switch or selector switch.

In conventional OLTCs the arcing contact system within the diverter switch consists of movable and fixed copper or copper-tungsten contacts. These contacts are using the mineral transformer oil as the switching medium, with the consequence of carbonizing the fluid due to arcing. In addition the fluid is contaminated by the melting loss of contact material (contact wear). However, the arc quenching is only one duty on the transformer oil within the diverter or selector switch, the fluid is also used as insulating, cooling and lubricating medium. /1/, /2/

When debating on prolonged maintenance intervals the contact wear (Fig. 1) as well as the deterioration and contamination of the diverter switch fluid (Fig. 2) is of major concern.

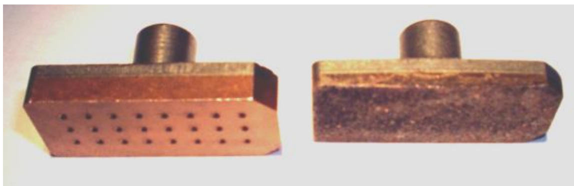

Fig. 1: Wear at copper-tungsten contacts

Fig. 2: Carbon deposits at the diverter switch insert and the oil compartment

To keep the properties for conventional OILTAP® OLTCs on a high level, maintenance has to be scheduled according to the number of operations and the service time whichever comes first.

Typical values are:

- 50’000 to 100’000 tap-change operations
- 4 to 7 years time-interval

2 Vacuum Switching Technology

During the last 30 years, vacuum switching technology has become the predominant technology for medium-voltage circuit breakers and high-current contactors. The first reactor-type OLTCs with vacuum interrupters have been developed in the early 70s. MR started producing vacuum reactor-type OLTCs in the mid 80s and, therefore, had a lot of experience with vacuum switching technology when starting in 1995 with the production of the first resistor-type OLTC with vacuum interrupters. This event was followed by the design of additional types and today a complete range of OLTCs with vacuum interrupters has been introduced, which provides, parallel to the conventional technology with arcing contacts under oil, an alternate and often better and more economical solution. /3/, /4/

The well-known arcing contacts with copper-tungsten have been replaced by vacuum interrupters. Due to the different switching conditions and requirements compared to circuit breakers, the vacuum interrupters used for OLTCs are specially designed. The unique parameters are:

- Mechanical life in transformer oil (or any other given insulating medium) for the operating temperature range and expected lifetime of the OLTC
- Switching performance
- Contact life
- Physical dimension

2.1 Benefits of VACUTAP® Technology

The vacuum interrupter is a hermetically sealed system. The arcing takes place within this sealed volume and there is no interaction with the surrounding medium, i.e. when using vacuum interrupters in OLTCs with the fluid within the diverter or selector switch compartment. The following benefits can be achieved:

- No deterioration of the fluid within the diverter or selector switch compartment due to arcing → no carbon deposits at the OLTC when using mineral transformer oil. The duty of the clean mineral oil is now concentrated on its function as insulation, lubrication and cooling medium. High dielectric strength and high lubrication properties during the service life can be gained.
- The breaking characteristic is independent from the surrounding medium → other fluids than transformer oil can be easier adopted.
- The arc drop voltage in vacuum is lower as in oil with the consequence of low energy consumption during breaking → reduced contact wear.
- High rate of re-condensation of metal-vapor on the contact surfaces → reduced contact wear.
- No aging of the arc quenching medium → constant breaking characteristics throughout the entire life span of the vacuum interrupters.
- No oxidation of the contacts → consistently low contact resistance

2.2 Maintenance Aspects of VACUTAP® Technology

As mentioned above the maintenance intervals of conventional OLTCs are in the range of 50’000 to 100’000 switching operations or 4 to 7 years time-interval, whichever comes first. To day the VACUTAP® technology allows maintenance intervals up to 300'000 switching operations without any time-based limitations. Due to the usually limited number of operations in case of most of the regulated network transformers, the vacuum technology enables a maintenance free operation of the OLTC during an average life time of 30 to 40 years. /5/

3 Performance Tests

One major topic during the development of the VACUTAP® OLTC-family was how to verify the above mentioned widely prolonged maintenance intervals. Usually the international standards reflect the technical state of the art and give guidance on the appropriate tests for validating the serviceability of electrical equipment. Often they combine design tests (dielectric performance, temperature rise, breaking capacity, short-circuit current) and endurance tests (mechanical endurance, service duty)

3.1 International Standards

The relevant International Standard for OLTCs IEC 60214-1 "Tap-changers – Part 1: Performance requirements and test methods" requires the following type tests /6/:

- Temperature rise of contacts
- Switching test
- Short-circuit current test
- Transition impedance test
- Mechanical test
- Dielectric test

These required type tests picture a combination of design tests (dielectric performance, temperature rise, breaking capacity, short-circuit current) and endurance tests (mechanical endurance, service duty). With respect to the necessary maintenance actions and the life time of the equipment especially the Switching Test and the Mechanical Test are of particular interest.

The Switching Test consists of two different parts. A service duty test with 50'000 operations at the maximum rated through-current is required and enables an extrapolation of the contact life time. Additionally, the breaking capacity has to be demonstrated with 40 operations at twice the maximum rated through-current and its relevant rated step voltage. If this step voltage is not equal to the maximum rated step voltage, a second test with 40 operations has to be carried out at the maximum rated step voltage and twice its relevant rated through-current. The main purpose of these test are the validation of the design values.

The Mechanical Test consist mainly of a mechanical endurance test, where 500'000 mechanical operations have to be accomplished. For this test the normal service conditions apply, but with the contacts not energized. If the OLTC is of liquid-immersed design, the test has to be done in the relevant liquid, of course. The OLTC has to be operated, at minimum, half the number of switching operations at liquid temperatures above 75°C. Furthermore, in case of a diverter or selector switch 100 operations at –25°C have to be performed. Normal servicing according to the manufacturer's handbook is permitted during the test.

European (EN) and North-American (IEEE) standards show in this point identical requirements.

3.2 MR's VACUTAP® Testing Strategy

The extrapolation of the contact life with the test results from the service duty test required by the IEC 60214-1 is reliable for all OLTC applications and maintenance intervals up to 100'000 operations. The number of unknown is manageable. However, when introducing higher number of operations between maintenance actions, the contact life has to be verified with higher number of breaking operations during the service duty test.

Today the VACUTAP® Technology allows not only prolonged maintenance intervals but also an enlarged diverter switch life span. All these commitments are based on numbers of switching operations and are irrespective of the service time. Table 1 gives the exceptional operation numbers, which have to be verified during the design tests.

	Number of Operations
Maintenance Interval	300'000
Vacuum Interrupter Contact Life	600'000
Diverter Switch Life Span	1'200'000

Table 1: Operation Numbers of VACUTAP® VR

Obviously these exceptional operation numbers cannot be safeguarded, when verifying the type tests only mentioned in the IEC 60214-1. For that reason MR has decided to carry out extended switching and mechanical tests. The tests described in the following paragraphs were accomplished with a VACUTAP® VR as shown in Figure 3. This diverter switch is designed for

1'300A rated through-current and a maximum rated step voltage of 4'000V. However, the testing strategy for the smaller VACUTAP® VV was identical.

Fig. 3: VACUTAP® VR diverter switch insert (shown without diverter switch oil compartment)

3.2.1 Switching Endurance Tests

The service duty test required by the IEC standard was extended to a switching endurance test with 600'000 operations at maximum rated through-current. During these operations the breaking capacity of the diverter switch was verified at two occasions. After 50'000 operations breaking capacity tests with 100 operations each were passed. One at twice the rated through-current and its relevant rated step voltage and the second at the maximum rated step voltage and twice its relevant rated through-current.

After another 450'000 operations at maximum rated through-current (overall switching number: 500'000) the breaking capacity test with 100 operations at twice the rated through-current was repeated and passed.

Figures 4 show the arcing time distribution of the first 50'000 and the last 50'000 operations of the 600'000 operations switching endurance test of a VACUTAP® VR. An established criterion for the breaking capability of a diverter switch is the length of the arcing time. Reflecting on the IEC 60214-1 an arcing time below (1.2 / 2*frequency) seconds can be stated as perfect. For a 50Hz supply frequency this value is 12ms. All arcing times are below this limit both at begin and at the end of the test.

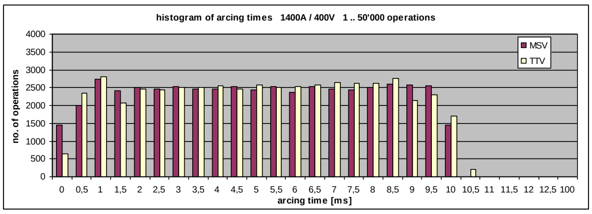

Fig. 4a: Arcing time distribution of VACUTAP® VR of the operations between 0 and 50'000 (start of test)

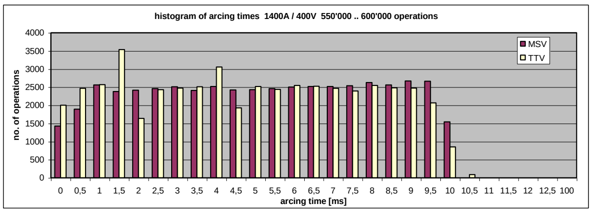

Fig. 4b: Arcing time distribution of VACUTAP® VR of the operations between 550'000 and 600'000 (finish of test)

At 500'000 operations a breaking capacity test with 100 operations at twice the rated through-current and the relevant rated step voltage was passed successfully. Figure 5 shows the arcing time distribution. Again all arcing times are within the perfect range and the distribution shows no anomaly.

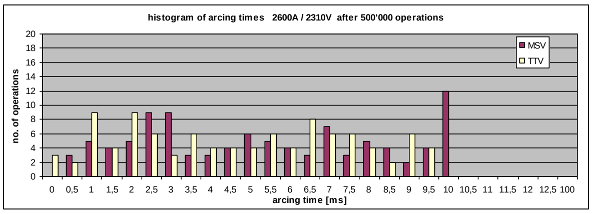

Fig. 5: Arcing time distribution of VACUTAP® VR of the breaking capacity test at 500'000 operations

By reason of the smaller number of operations and the resulting different scale of the axes, the distribution seems not that uniform as in the tests described before. However, all diagrams are showing no outliers and a constant switching characteristic can be postulated.

Besides the switching characteristics the contact wear during the switching endurance test was of substantial interest. The contact wear of the vacuum interrupters was determined after 50'000 and 600'000 breaking operations. Table 2 gives the results for the two vacuum interrupters of the VACUTAP® VR.

After 600'000 breaking operations of the VACUTAP® VR with the maximum rated through-current the contact wear is far below the permissible limits.

	Vacuum Interrupters Main path	Transition path
Permissible contact wear	4 mm	4 mm
Contact wear after 50'000 operations	Not measurable	Not measurable
Contact wear after 600'000 operations	< 2 mm	< 2 mm

Table 2: Contact wear during switching endurance test of VACUTAP® VR

3.2.2 Verfication of Exceptional Switching Conditions

The arcing contact system of a resistor type OLTC is designed for duties of ohmic nature at the breaking contacts. This means that the recovery voltage arising at the open contact distance in the current zero starts at zero with a sinusoidal wave form. Two OLTC applications are existing, where this is not true. One is the regulation with a coarse and a tap winding and the second is the use of OLTCs in HVDC transformers. /7/

When using transformer designs with coarse and tap windings a single switching operation in the cycle of operation exist, where the leakage inductance of the coarse and tap winding arrangement produces a phase angle between the switched current and the recovery voltage at the transition contact. This instance requires special consideration in case of conventional OLTCs. For arcing contacts under oil, the capability to break the current against a recovery voltage with a phase displacement at current zero is limited.

In HVDC applications the current wave form is not sinusoidal. In conjunction with the transition resistor a non-sinusoidal recovery voltage arises at the main contacts at every breaking operation. The non-sinusoidal wave form is characterized by an approximately step wave form with a high steepness. Arcing contacts have a finite recovery strength of the contact distance. If the recovery voltage is more rampant as the recovery strength the contact distance will reignite.

Because of the extraordinarily fast dielectric recovery of 10kV/µs, vacuum interrupters have the ability to handle those duties better than conventional arcing contacts under oil.

The VACUTAP® VR has demonstrated its breaking capacity with respect to these duties in breaking tests, where the phase displacement between switched current and recovery voltage was 90°. Results of these test can be taken from Table 3.

Switched current [A]	Recovery voltage [V]	Number of operations	Arcing time [ms]
500	2'100	200	< 11
500	4'000	200	< 11
1'000	4'000	200	< 11
1'500	4'000	100	< 11
2'000	4'000	100	< 11

Table 3: Contact wear during switching endurance test of VACUTAP® VR

As after the switching endurance test with 600'000 operations, all arcing times are below the above mentioned 12 ms.

With these tests the switching performance could be proven impressively.

3.2.3 Mechanical Endurance Tests

The primarily goal of the mechanical endurance test is to verify the mechanical life span of the diverter switch, selector switch or tap selector. When taking the numbers given in Table 1, a number of mechanical operations of at minimum 1'200'000 must be demonstrated and safeguarded for the relevant OLTC. Therefore, the number of operations for the mechanical endurance test for the VACUTAP® VR was raised to 1'500'000 operations (3 times the number required by IEC 60214-1). During the tests there was no failure or undue wear of mechanical parts. The recordings of the switching sequence at the beginning, at the end and on several intermediate occasions of the mechanical endurance test showed no significant difference. All relevant switching times were within the permissible values. Figures 6 show typical recordings of the switching sequence at the beginning and the end of a mechanical endurance test with 1'500'000 operations. Table 4 shows certain switching times with relevance to the correct functioning of the diverter switch.

All switching operations of the mechanical endurance test were carried out at a temperature of the fluid of 80°C. Those mechanical test were done on several test objects. Single specimen were operated up to 2’000’000 operations, but this is not a criterion for passing the test.

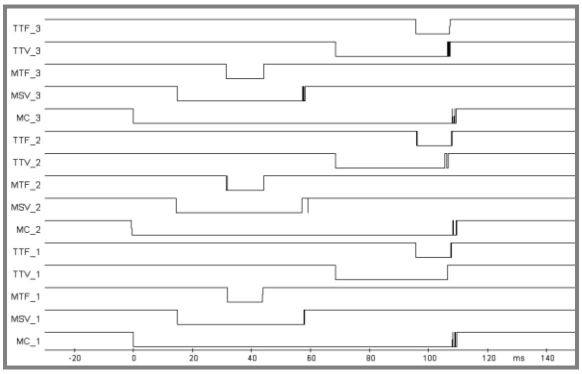

Fig. 6a: Switching sequence of VACUTAP® VR diverter switch at the beginning of the mechanical endurance test (switching direction 1→ n+1)

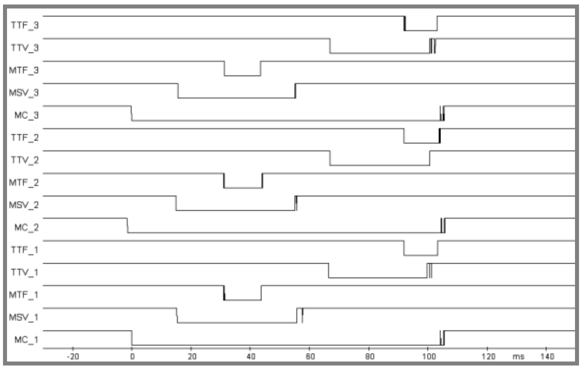

Fig. 6b: Switching sequence of VACUTAP® VR diverter switch at the end of the mechanical endurance test (switching direction 1→ n+1)

Oil temperature 80°C		**MSV opens - MSV closes**	**MSV closes - TTV opens**	**MSV opens - MTF opens**	**TTV opens - TTF opens**
Permissible timing		< 47 ms	< 15 ms	> 13 ms	> 13 ms
Timing at start of the test	#1	43.1ms	11.6ms	15.8ms	26.8ms
	#2	41.7ms	11.3ms	15.0ms	25.3ms
Timing after 1.5 million operations	#1	42.3ms	12.7ms	15.3ms	23.8ms
	#2	38.1ms	12.0ms	13.8ms	23.1ms

Table 4: Switching times of two VACUTAP® VR diverter switch at the start and the end of the mechanical endurance test

This high number of operations gives a safety margin of 25% related to the life span. With regard to the maintenance interval of 300’000 operations the tested number of operations was 5 times higher. The mechanical life span of the bellows of vacuum interrupter is quite higher and was tested separately in an endurance test with several million operations.

		MSV opens - MSV closes	**MSV closes - TTV opens**	**MSV opens - MTF opens**	**TTV opens - TTF opens**
Permissible timing at -25 °C		< 90 ms	< 20 ms	> 13 ms	> 13 ms
Timing at 25 °C (all test samples)		< 43 ms	< 11 ms	> 15 ms	> 26 ms
Timing at -25 °C	#1	< 52 ms	< 13 ms	> 19 ms	> 35 ms
	#2	< 44 ms	< 11 ms	> 17 ms	> 29 ms
	#3	< 46 ms	< 12 ms	> 18 ms	> 30 ms

Table 5: Switching times of the low temperature test of VACUTAP® VR diverter switch

The low temperature mechanical switching capability was passed with 136 operations down to –30°C. It can be taken from Table 5 that all switching operations were passed successfully.

In addition to the IEC requirements, the high temperature mechanical switching capability was also demonstrated in several tests with 136 operations at 130°C. On some test objects the high temperature test was carried out with 1’000 operations.

The right timing of the contacts could also be shown for the above mentioned temperature conditions and a supply frequency of the motor drive of 60Hz and the motor drive driven with double speed. The double speed condition is sometimes required by applications in industrial transformers, where the tap-changer has to move quick through consecutive positions.

With these tests the mechanical performance of the VACUTAP® VR could be demonstrated successfully.

3.2.4 Insulating liquids

Due to the advantages of the vacuum switching technology in OLTCs mentioned in paragraph 2.1, the use of alternative insulating liquids becomes easier. Therefore, the VACUTAP® VR was tested within different insulating liquids in addition to the conventional transformer oil. Mechanical endurance tests and dielectric tests were carried out with one liquid of the following insulating liquid families each:

- High molecular weight hydrocarbons
- Synthetic ester
- Natural ester

Due to different low temperature viscosities the low temperature limit has to be adjusted to the relevant liquid, generally spoken, the low temperature limit rises. The dielectric withstand values of the alternative liquids are different as those of transformer oil dependent on the homogeneity of the electrical field. However, the mechanical endurance can be compared to that of transformer oil.

3.2.5 Tests according to IEC 60214-1

The above mentioned tests were completed by several tests as required by the International Standard IEC 60214-1 for the Type Test.

The residual performance characteristics as "Temperature Rise of Contacts", "Short-circuit Current Test", "Transition Impedance Test" as well as the "Dielectric Tests" were proven on several test objects and under the conditions required by the Standard. All tests were passed successfully.

4 Conclusion

The vacuum switching technology enables the production of OLTCs, which meet the same life expectancy as transformers. Maintenance intervals up to 300'000 operations without any time-based restrictions can be realized.

With a special testing strategy these lifetime and maintenance expectations were proven. The accomplished tests are beyond the standard test requirements of the International Standard IEC 60214-1. Especially the switching performance, the contact wear as well as the mechanical performance are the main topics with respect to lifetime and maintenance. The VACUTAP® VR has demonstrated his performance in several endurance tests and met all the internal requirements successfully. Therefore, this OLTC is proven for service with a maintenance interval of 300'000 operations, a vacuum interrupter contact life of 600'000 operations and a diverter switch life span of 1'200'000. But still, OLTCs have to be classified as mechanical switching equipment and they are not fully free of tear and wear of the mechanical parts.

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Zusammenfassung

Die technischen und wirtschaftlichen Anforderungen an Geräte der elektrischen Energieversorgung sind in den letzten Jahren kontinuierlich gestiegen. Die Diskussionen um ihre Verfügbarkeit und das Streben nach verlängerten Wartungsintervallen sind besonders hervorzuheben.

Im Falle von Laststufenschaltern (OLTC) können solche Forderungen mit Einführung der Vakuumschalttechnik erfüllt werden. Aufbauend auf der Erfahrung von mehr als 20 Jahren in der Vakuumschalttechnik, wurde von der MR eine neue Generation von OLTCs entwickelt. Durch Nutzung der Vorteile der Vakuumschalttechnik wird eine Verlängerung der üblichen Wartungsintervalle gegenüber der herkömmlichen Stufenschaltertechnik ermöglicht. Mit dem Einsatz dieser Technologie können Wartungsintervalle von 300'000 Schaltungen ohne jegliche zeitliche Einschränkung für die heutige VACUTAP® Last

stufenschalter-Familie für Leistungstransformatoren als Standard angesehen werden.

Die Zusage solcher verlängerten Wartungsintervalle muss im Zuge der Entwicklung in weiten Grenzen überprüft werden. MR hat für die neue Generation der VACUTAP® OLTC eine Prüfstrategie etabliert, die bei der Überprüfung der Leistungsmerkmale eingesetzt wurde und in Zukunft auch weiterhin eingesetzt werden wird.

Dieser Beitrag soll einen Einblick sowohl in die Vorteile der Vakuumschalttechnik als auch in die Prüfungen zur technischen Sicherstellung der außergewöhnlich verlängerten Wartungsintervalle ermöglichen.

Aus dem neu eingeführten Wartungsintervall für OLTC ergibt sich für einen üblichen Leistungstransformator im Netzbetrieb, dass bei einer angenommenen Lebensdauer von 30 Jahren und einer mittleren Schaltzahl von 10’000 Schaltungen pro Jahr das Ende der ökonomischen Lebensdauer und die erste Wartung zusammenfallen.

Authors address

Dr. Axel Krämer

c/o Maschinenfabrik Reinhausen GmbH
Manager Test Department
Falkensteinstrasse 8
93059 Regensburg

Tel.: +49 (0) 941 / 4090-486
Fax: +49 (0) 941 / 4090-114

a.kraemer@reinhausen.com

Dr. Dieter Dohnal

c/o Maschinenfabrik Reinhausen GmbH
Director Engineering and R&D
Falkensteinstrasse 8
93059 Regensburg

Tel.: +49 (0) 941 / 4090-345
Fax: +49 (0) 941 / 4090-506

d.dohnal@reinhausen.com