IMPROVEMENTS OF TRANSITION CABLE SLEEVES FOR MASS-IMPREGNATED CABLE

J. Stolz[1*], P. Weiß[2], M. Klemm[3]
[1] Haefely Test AG, Lehenmattstrasse 353, 4052 Basel, Switzerland
[2] University of Kaiserslautern, Paul-Ehrlich-Straße 12, 67663 Kaiserslautern, Germany
[3] University of applied sciences Saarbrücken, Goebenstraße 40, 66117 Saarbrücken, Germany
Email: <stolz.johannes@haefely.com>

Abstract
Failures on transition cable sleeves from mass-impregnated cables to VPE cables lead to the researches described in this paper. Based on a detailled failure analysis of faulty transition cable sleeves the failure mechanism coud be described. To reproduce the failure in laboratoy tests, a test cylce of a new and an aged transition cable sleeve was used, which represents the thermal load cycle of a cable in service. In the following, improvements regarding to the optimization of dielectric field strength control and the reduction of unavoidable micro-bubbles were done. Comparative tests show the improvement of the performed changes. The test specimen did not fail in test. Long-time tests in service are pending.

1 INTRODUCTION

Mass-impregnated cable were no longer produced for quite some time. Nevertheless, they are still in operation in many cases due to their long life time. In case of a failure, the conventional repair method is a transition cable sleeve to a VPE insulated middle voltage (MV) cable. This leads in old cable runs to very often splitted cable sections with many transition cable sleeves from mass-impregnated cable to VPE and vice-versa. The main aspect for the transition cable sleeve is now to fullfil all the requirements regarding to electrical, dielectrical, thermal, chemical and mecanical stress. To guarantee a long operation period, the transition cable sleeve must guarantee a life time of 40 years or more.

Frequent failures show the contrary. After a operation period of three to seven years, several transtion cable sleeves fail and make an additional repair necessary. The additional costs of the repair but considerably more the penalty due to not delievered electrical energy lead to a detailled failure research.

2 STATUS QUO, BOUNDARY CONDITIONS

Due to the small failure rate of one to three units per year, in the past the failure was assumed in a poor assembling. The harsh boundary conditions in the cable trench with a high pollution of earth and the possible assembling of several sand grains into the transition cable sleeves was the long assumed defect reason. Defect transition cable sleeves were replaced and directly disposed. Only an accumulation of two defects in a short period lead to a rethink. The faulty transition cable sleeves were “dissected” layer by layer to analyse the defect. Both sleeves show the same failure behaviour: a phase-to-earth-fault in the transition area in the middle between the crimped conductor and the expansion of the three phase mass-impregnated cable. Figure 1 shows the failure in detail.

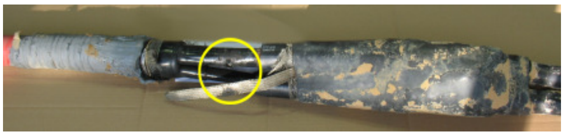

Figure 1: general view of the failure of the transition cable sleeve

The next failed unit verified the failure behaviour of the former two. To consider several failure procedures a research was done. Researches in the assembling documentation of the utility, the load cycle reports and a short delievery cross check showed, that the insulation breakdown was not correlated to the load current cycle, season, assembling or a poor material charge. Three years old terminations with an almost continous load cycle fail as well as seven years old terminations in spring time.

3 THEORETICAL EXPLANATIONS

The failure behaviour was clear defined, the failure reason was unknown. Hence, another detailled research of the sleeve construction, the mechanical assembling and a repeated detailled “dissection” of faulty sleeves were performed. The construction of the transition sleeve is shown in figure 2:

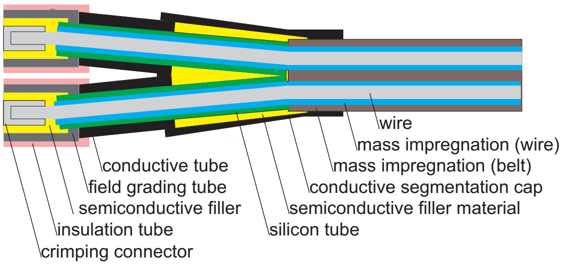

Figure 2: construction sketch of the cable sleeve

The copper or aluminium wire is wrapped by the mass impregnated paper. The paper serves only to maintain the mechanical dimensions, the electrical insulation is nearly exclusively done by the oil impregnation. Every mm³ of missing mass impregnation leads to micro-bubbles in the insulation liquid. To avoid or minimize the latter, a mechanical pressure is done by the steel armor over the copper screen of the three phase cable. In the transition sleeve, the transition from the expanding of the three phases to the crimping connector the mass-impregnated cable has no armor, only a silicon tube to avoid the dissipation of the impregnation liquid. In the direct environment of the cimping connector an additional semiconducting tape is used to control the electrical field strength. This is fixed by a mechanically very strong tube to ensure a reproducable mechanical environment.

The existence of micro-bubbles in mass-impregnated cable is only part-wise critical. It is right, that they lead to partial discharges and with this to a slightly destruction of the insulation material. The impregnation degrades and carbon black particles occur. Also the partial discharges affects the impregnated paper. The cellulose fibres were cracked and degenerates also to carbon black particles. This will lead to a conducting film which usually build current bridges between each layer of the paper wrapping.

But oil impregnated cables have a significant advantage: The insulation material is not solid, it is semi-fluid with a decreasing viscositiy at higher temperatures. The thermal differences lead to a thermal flux and hence to a movement of the micro-bubbles in the cable. Due do this, the slightly destruction of the partial discharges is distributed over the complete cable.

And just this effect leads to the defect in the transition sleeve: Existing micro-bubbles in the mass-impregnated cable move due to the thermal flux. They are under pressure, as long as they reside in the mass-impregnated cable with the external circumjacent steel armor. But if they move near to the transition sleeve, the mechanical pressure is missing. This leads to micro-bubbles with increased volume and less pressure. The partial discharge starts significant earlier, because the pressure is reduced. This is not an exciting new effect, this was described by the law of Paschen in 1889. If the micro-bubbles move further to the crimping connector, there is also a mechanical pressure around the insulation, which generates the same effect as the steel armor around the cable. Hence, the micro bubbles were pushed both from the origin mass impregnated cable and from the crimping connector in the transition section of the cable sleeve. Here they stay in a very closely bounded area. The occuring partial discharges in the low pressure micro-bubbles can damage the mass-impregnated paper insulation significantly accelerated than in the cable due to the described reduced movement flexibility.

Two other effects amplify the micro-bubble movements:

Position of the cable sleeve

Typically, the cable sleeve is positioned after the cable was assembled. This leads to the fact, that the cable sleeve is higher positioned to ground than the genuine cable. Due to thermal movements of the mass impregenation the micro-bubbles collate in the cable sleeve. It is the same effect like air bubbles in a heating radiator. The air bubbles collate at the top of the radiator – in the cable the the micro-bubbles collate in every local maxima like the higher laid cable sleeves, see figure 3.

In addition, there is a lower static preasure of the impregnation liquid than in the lower, original insulated parts of the cable. The difference of the static pressure is very small but constant existing. With this, the movement direction is clearly defined.

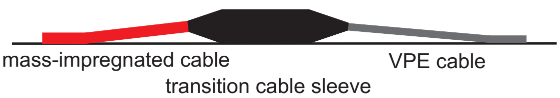

Figure 3: sketch of arrangement in the cable trench after assembling with minimum height differences between cables ans sleeve

Thermal load current cycle

Typically cables were charged with a specific load cycle. This leads to different temperatures in the conductor, the insulation, the shield and the armor. During a high current, first the expansion of the conductor bears a pressure to the impregnatation liquid and the armor. The existing micro-bubbles were pressed and they suffer a higher inner pressure by a simultaneously lower volume. During a cooling down-process caused on the load current reduction, the conductor shinks and reduces the partial pressure in the micro-bubbles correspondingly. Each one of this two thermal procedures (heating and cooling) is typically the start of a movement process of the micro-bubbles in the mass-impregnation.

But the movement of the micro-bubbles into the transition area of the cable sleeve explains the failure only partwise. To generate partial discharges in the micro-bubbles, the prevalent field strength is an important factor. At a field strength below the partial discharge inception level, nothing occurs – even if micro-bubbles exist in the critical area. Hence, the field configuration has to be analyzed too.

4 REVIEW OF THE INSULATION COORDINATION

The comparison of the three important cross sections

- cable
- transition area in the cable sleeve and
- crimping conductor of the cable sleeve

shows clearly the differences, like shown in figure 4 to figure 8.

Mass impregnated cable

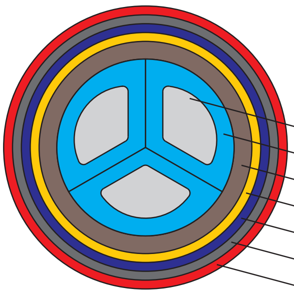

Figure 4: cross section of the mass impregnated cable

Mass impregnated oil paper is the only insulation material between the inner conductor and the copper screen. Hence, the radial field strength is very simple to calculate: If one assumes a uniform dielectricum the well known equation for a coaxial cylinder with a single dielectricum can be used.

$$E_{cable} = \frac{U}{d \cdot \ln\left(\frac{d_a}{d_i}\right)}$$

(The difficulties of micro-bubbles were discussed in the clauses before and can be neglected here for a better understanding).

Aggravatingly for this effect the used cable was a sector cable. So each phase conductor is shaped like a triangle with rounded egdes. The consequence is a quite higher field strength at this rounded egdes than on the surface of an single phase coaxial cable with the same diameter. The observed damages verified this, see figure 10.

Crimping connector

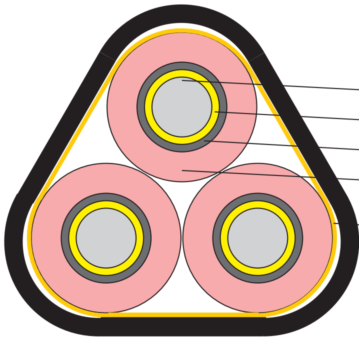

Figure 5: cross section of the cable sleeve crimping connector area

The crimping connector increases the diameter of the inner electrode. The circumjacent semiconducting tape can be described as a parallel connection of a resistor (R_1) and a capacitance (C_1) in the equivalent circuit diagram. The circumjacent silicone tube is both a dielectricum (C_2) and a mechanical pressure. Hence, the equivalent circuit is as follows:

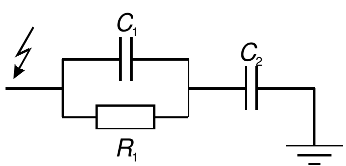

Figure 6: equivalent circuit diagramm of the cross section of cable sleeve in the range of the crimping connector

Here, the dielectric stress to the field grading material is mostly critical regarding to thermal stress due to the semiconducting behaviour. But this is not the focus on this paper. The series operation of the two capacitances is here not critial too, due to the higher permittivity of the field grading material.

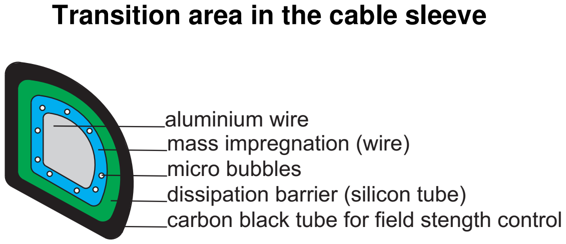

Figure 7: cross section of the cable sleeve in the critical transition area

The transition area consists of two dielectrica: the mass impregnated cable and the silicon tube (instead of the genuine belt insulation) to avoid dissipation of mass impregnation. Hence, two dielectrica are in series operation. To calculate the electrial field strenght relations, one has to consider the permittivities of the two materials. Mass-impregnated paper has a permittivity of 2.4, the silicone tube of 5 (based on manufacturer information). According to the electric law, the displacement current density $\vec{D}$ is in series operation the same.

$$\vec{D}_1 = \vec{D}_2$$
$$\varepsilon_1 \cdot \vec{E}_1 = \varepsilon_2 \cdot \vec{E}_2$$

It is obvious, that the material with the lower permittivity is exposed to a higher electric field strength. In this case, the mass-impregnated insulation $(\varepsilon = 2{,}4)$ is considerably higher stressed than the silicone rubber $(\varepsilon = 5)$. This is only due the constance of the displacement current density. If one consider also, that the highest field strength in a coaxial arrangement occurs at the surface of the inner electrode, the mass-impregnated insulation is stressed twice. Finally, the sectorized conductor cross-section leads to additional local dielectric stress which has also taken in account.

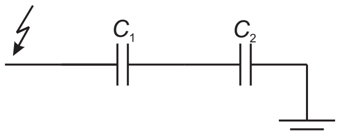

Figure 8: electric circuit diagram of the transition area

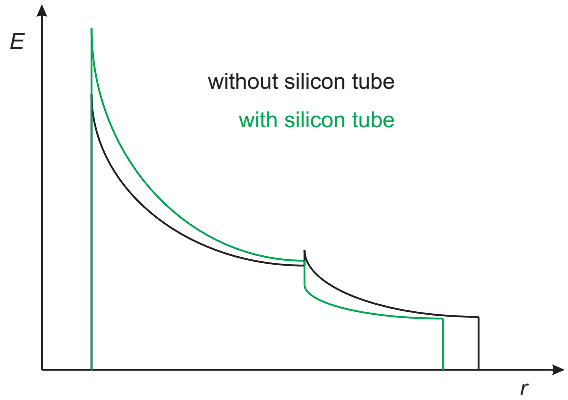

Figure 9: schematic electric field strength process with and without the additional silicone tube.

Unfortunately, the breakdown-voltage of a mass-impregnated insulation is significantly lower than the one in the silicone composite material.

An impact of the axial electric field strength on the degradation and the following breakdown could not bee seen in all of the analyzed failure scenarios. The often discussed failure scenario of a creeping electrical tree in the enlargement area from the three phase arrangement to three single phase arragements was not observed here. The following figure shows the typical failure, in which a pure radiated breakdown leads to the damage of the material. It can be seen clearly, that the degradation starts directly at the rounded corner of the sectorized cable, the point with the highest dielectric stress.

Figure 10 a: typical failure scenario


Figure 10 b: typical failure scenario

Very high attention should be also paid to the fact, that this failure occurs NOT due to non-appropriate testing of the termination sleeve. The termination sleeves passes excellent all routine and type test in the manufacturing process. The crux of the matter is the missing adjustment from old technology (mass-impregnated cable) to new technology (heat-shrinking silicon tubes) under the boundary condition of non-ideal effects like movements of micro-bubbles and superimposing dielectric stress in conjunction with missing mechanical pressure as they are described above.

5 IMPROVEMENTS

Based on the detailled failure analysis and the theoretical explanations a combination of measures were taken:

- Reproducing the failure behaviour for finding an application oriented testing procedure
- Modification of the mechanical design to improve the insulation coordination and to avoid the researched failure mechanisms

Application oriented testing procedure

The main question is here: “How can stresses be modelled of a cable in service which occur over several years with a laboratoy test procedure within several days/weeks?” The idea was testing with increased nominal values to get an accelerated ageing. The test was done in the following cycle:

- High-voltage test with PD measurement and following dissipation factor (tanδ) measurement (initial measurements)
- High-current test to generate the thermal flux process inside the specimen (High-current-test:150% I_N test for 2 hours)
- Comparative measurements of PD and tanδ relating to the initial measurements (high-voltage test)

These tests were done with one new cable sleeve and two cable sleeves aged in service, which were demounted from the net especially for this test.

The test cylce was done several times for each specimen. All test specimen failed after 3...5 test cycles with a breakdown from one phase to earth. The two aged test specimen fail one to two cylces earlier than the new one. To avoid an assembling failure, the assembling was done under clean laboratory conditions and under attendence of assembling experts from the utilities.
The similarity of the occured failures under laboratoy testing and the ones which occured in service operation verifies the chosen test cycle procedure.

At this point, the failure procedure both can be reproduced and explained. The last two missing points are now to improve the arrangement and the verification the improvements.

Mechanical design changes

In the preceeding clauses, the need of a mechanical redesign regarding to the improvement of insulation coordination and the suppression of the low pressured micro-bubbles was described in detail. But the two needs for the mechanical design change have to be considered separately, because they cannot improved by a single changement.

Improvements on insulation coordination:
As described, the main problem in the insulation coordination is the mis-relationship of the two dielectrica regarding to their permittivity and their corresponding breakdown field strength. To improve the insulation coordination, two approaches were made:
The silicon tube to avoid the dissipation of the impregnation liquid has a permittivity of 5. It should be changed with a corresponding tube with a permittivity, which is lower than 2.4 – the permittivity of the mass-impregnation. Due to chemical requirements this was not possible. Hence, an additional tube with insulating characteristics and a low permittivity was mounted around the silicon tube. On this additional tube the field control tube was mounted. With this, the field strength at the outer diameter of the sectorized conductor

could be decreased. The impact by this measure will be very low, so that additional measures are necessary.

The second approach is the decrease of the dimensions of the micro-bubbles by applying mechanical pressure at the arrangement. By applying a silicon tube with a high mechanical pressure, the tube archieves in the critical transition area of the cable sleeve the same effect as the steel armor in the mass-impregnated cable. The existing micro-bubbles suffer a higher mechanical pressure, this leads to smaller dimensions and a simultaneously higher inner-partial pressure. According to Paschens law the breakdown field strength will increase. It is very important, that the mechanical pressure tube conserves its high pressure during a long time for guaranteeing a long lifetime of the cable sleeve. At the other hand, it has to be flexible enough to perform a small mechanical expansion without bursting due to thermal stress occuring from the load cycle.
It is absolutely clear, that the mechanical pressure tube can not keep the pressure up the whole distance, especially the end sections are highly critical. Therefore, the transition areas to the expansion of the three phase cable and to the crimping connector have to overlap with the existing mechanical pressure tubes.

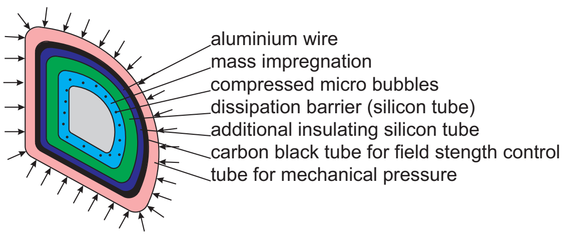

Figure 11: schematic diagram of the improvements

Verification of improved arrangement

Two cable sleeves with small design deviations were assembled to test the efficiency of the performed improvements. One was mounted with an additional insulation tube around the silicon tube, one without. Both specimen were assembled with an additional silicon tube, wich is used for keeping up the mechanical pressure in the transition area of the cable sleeve.

Comparative tests with the testing procedure showed that the two improved specimen did not fail – even if there were exposed more than ten cycles to the application oriented testing procedure. During the researches, no failure at the two test specimen can be provoked. Even at breakdown tests the two specimen did not fail – here the breakdown occured in all cases at the cable termination.

6 SUMMARY

Based on an accumulation of failures of transition cable sleeves from VPE to mass-impregnated cables researches were made. It was found, that the problem not consists of a weak transition cable sleeve – it fulfills excellent all routine tests according to the standards. In fact, the combination of old and new technology (mass-impregnated cable and VPE cable) does not fit. Researches on faulty cable sleeves show the failure, which could be reproduced in the laboratory. The reason for the failure is based on a weak insulation coordination and an accumulation of micro-bubbles with low inner partial pressure in the transition area from the mass-impregnated three phase cable to the crimping connectors. An additional insulation tube for the improvement of the dielecrical coordination was mounted. Forthermore, a surrounding silicon tube was mounted, which applies high mechanical pressure to the cable sleeve. This decreases the diameter of the micro-bubbles and increases the inner partial pressure and leads to the increase of the PD inception level. A test cycle procedure with high current tests following high voltage tests was done to reproduce the load current behaviour.
The changes were tested again in comparative tests. The considerable higher cycle time in laboratory tests leads to the constituted assumption of a significant higher life time in service.
The modified cable sleeves are in service since two years to generate more application know-how.

7 REFERENCES

[1] E. Peschke, R.v.Olshausen: Kabelanlagen für Hoch- und Höchstspannung, Publicis MCD Verlag, 1998
[2] W. Ehlers, H. Lau: Kabel-Herstellung, Springer, 1956
[3] A. Schwab: Hochspannungsmeßtechnik, 2. Aufl., Springer, 1981
[4] D. Kind, H. Kärner: Hochspannungs-Isoliertechnik, Vieweg, 1982
[5] L. Heinhold, R. Stubbe: Kabel und Leitungen für Starkstrom, 5. Aufl., Publicis MCD Verlag, 1999