A 50 Hz AFTER LAYING TEST FOR HIGH-VOLTAGE EXTRUDED INSULATION CABLES

G. C. Paap
Power Systems Laboratory
Delft University of Technology
P.O.Box 5031, 2600 CD Delft, The Netherlands

A. N. Verveen
Rijnland Energy Company
P.O.Box 111, 2300 AC, Leiden, The Netherlands.

ABSTRACT - In this paper a 50 Hz after laying test for high-voltage extruded insulation cables is proposed. This test, which takes place in the network during normal operation, has successfully been carried out twice. One fault was detected. The paper presents the circumstances under which the tests were made, the considerations of the possible risk-factors and the results.

Keywords - site test, cable, extruded insulation, a.c. voltage, transients.

1. INTRODUCTION

At the 32nd Cigre Congress in Paris in 1988, at the meeting of group 21 -HV insulated cables - it was established that the results of the d.c. test for high-voltage power cables with extruded insulation were not satisfactory [1]. Other tests, such as the 0.1 Hz test and the oscillating wave test, were put forward as solutions to the problem. During the meeting it was also suggested [2] to test at service voltage for one month.

The purpose of the test is the detection of defects in the assembling and accessories of the installed cable. Cable failure is detected by means of the a.c. tests after fabrication. Laying damage, or after laying damage if you will, is detected throughout the entire circuit by the carrying out of the routine d.c. site test on the protective oversheath after each cable installation, and also after assembly.

In this paper a 50 Hz after laying test is proposed in which the high-voltage power cable is submitted to $\sqrt{3}U$ where U is the service voltage. The cable to be tested is connected to the network in normal operation by means of a power transformer of which the neutral point of the secondary wye is not grounded. By this measure the short-circuit power is also diminished. Upon connecting one phase of the cable to ground during a previously determined period, the other two phases will be exposed to $\sqrt{3}$ times the nominal voltage with respect to earth. Through cyclically changing the phase to be earthed, each phase is tested twice for the determined period. The optimal length of time of the test is still a point of discussion which has two sides to it:

- 1) How much time is sufficient to detect defects in the cable and accessories.
- 2) How long is it allowed to expose the network components, which are used in normal operation of the network, to the increased voltage.

The test transformer in particular plays an important part in this. If this transformer is designed for a system with grounded wye, which is the case here, it is subject to faster dielectric ageing through this test. This after laying test has now been put into practice twice.

91 SM 514-0 PWRD A paper recommended and approved by the IEEE Insulated Conductors Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1991 Summer Meeting, San Diego, California, July 28 - August 1, 1991. Manuscript submitted May 29, 1990; made available for printing June 21, 1991.

Figure 1: Schematic diagram of test circuit 1

2. THE FIRST AFTER LAYING TEST

The first after laying test [3], November 1988, concerned a three-phase 50 kV high-voltage connection, consisting of three single-phase cables with extruded insulation and with a length of 3 km. The test was carried out for a 30 minute period per cycle. This means that each phase underwent the test voltage of $\sqrt{3}U$ for one hour. The switching protocol, used in this test is shown in figure 1. The after laying test proceeded as follows:

- Station A circuit-breaker B1 "in". Test bus is connected to the 50 kV network voltage.
- Station A circuit-breaker B2 "in". Test transformer energized.
- Station B circuit-breaker B3 "in". Test transformer parallel with 10 kV bus.
- Station A circuit-breaker B1 "out". Test bus now under load from 10 kV from station B. Short-circuit power of test circuit is lowered.
- Station A circuit-breaker B4 "in". Test cable is energized.
- Station A circuit-breaker B5 "in". One of the phases is connected to earth, the remaining two phases now have the voltage $\sqrt{3}U$ to earth.
- After a fixed time, in Station A circuit-breaker B5 "out", next phase to ground, and circuit-breaker B5 again "in" etc.
- After ending the test, disconnect the test circuit.

In this test full use was made of the available network system. Prior to making the test, possible risk factors were reviewed. Simple calculations showed that the frequencies of this circuit are in

the order of from 500 to 800 Hz, which was a reason to block the voice-frequency system (500 Hz) for metering etc. during the test. The 10 kV circuit-breaker of the power transformer used in the test is not reignition free. It had to be ensured that this circuit-breaker did not switch off the test system if there was no fault current in the system. If there is no fault a capacitive current in the order of 200 A would be interrupted. This can lead to undesirable overvoltage. Partly because of this, surge diverters were fitted to the 10 kV side. The times of the current relays of the various circuit-breakers were so adjusted that the 50 kV circuit-breaker would be the first to experience interruption. The function of the 10 kV circuit breaker was reduced to a back-up function. Ferroresonance, due to the saturation in the voltage transformer, was not expected because of the 4 km long 50 kV cable between stations A and B. In practice, the phenomenon was not observed.

In this test no defects of the cables or accessories were detected and another after laying test of a new three-phase cable system with a length of 13 km was planned. In extensive discussion with the transformer manufacturer, it was decided that the second test could be carried out with a cycle time of one hour, thus, in this way, each phase could undergo the test voltage for two hours. The cycle time of one hour was determined as follows: The test voltage for a used transformer is 3 times the service voltage during one minute. When the test voltage is $\sqrt{3}$ times the service voltage, the time t , it can be applied to the transformer, is calculated from:

$$(\sqrt{3} \cdot t)^9 = (3.1)^9$$

which yields 140 minutes.

Figure 2: Schematic diagram of test circuit 2

3. THE SECOND AFTER LAYING TEST

This test took place in December 1989 and concerned a 13 km long double three-phase 50 kV connection, also consisting of the same single-phase cables with extruded insulation. These cables will, for the coming five years, be used in the 10 kV network and have thus not yet been introduced into a 50 kV installation. It was, therefore, not possible to make use of existing network

components in carrying out the test. For this reason it was decided to construct a mobile test unit, which can also be used for future tests.

The renovation of an old 50 kV substation delivered sufficient components for the building of this test unit.

Model calculations

For this test the transients, which appear during the switching in the network, were simulated with the help of a computer model. Figure 2 shows the schematic diagram. In this figure the test unit is outlined. Preliminary studies led to the decision to make use of a circuit breaker B5 to perform the closing to earth of the separate phases. This way of grounding will prevent the appearance of ferroresonance should the voltage transformer in the test unit be energized without the test cable being connected.

From figure 2 and the component data, as given in the appendix, the model in figure 3 is derived. In figs.4a and 4b. the curves

Figure 3: Diagram for model calculations

Figure 4: Switching sequence of test circuit

for the phase voltages $U_{A,B,C}$ and the currents $I_{A,B,C}$ are given for the complete switching sequence. In the source voltage E , with peak value $e = 1$ pu, a 5th harmonic component of 1.6% is taken into account. The presence of this harmonic followed from measurements of the source voltage of the network in normal

operation and must therefore be ascribed to the regular consumer loads, such as six-phase rectifier bridges, in the 10 kV network.

At $t = 0$ circuit breaker B4 is closed and the cables to be tested are energized. The steady-state phase current is mainly determined by the capacitance of the cable to be tested: $i_A = \omega C_e = 0.13 \text{ pu}$ ($= 64 \text{ A}$). The peak values of the phase voltages become a little larger than 1 pu because of the capacitive load.

At $t = 0.1 \text{ sec.}$ circuit breaker B5 is closed and phase A is grounded. In the steady state the voltages U_B and U_C become $\sqrt{3} \text{ pu}$ and the voltage of the neutral $U_0 = 1 \text{ pu}$.

For the currents it holds: $i_B = i_C = \sqrt{3}\omega C_e = 0.22 \text{ pu}$. The current in the earthed phase $i_A = 3\omega C_e = 0.4 \text{ pu}$. The resistance R, which stems from the regular 12 MW consumers load connected to the 10 kV bus bar, mainly determines the damping for the transients of the positive sequence components.

At $t = 0.2 \text{ sec.}$ - in practice after one hour - B5 is opened. The neutral voltage U_0 disappears via the voltage transformer, of which the primary wye is connected to earth. The high inductance of the voltage transformer together with the big capacitance of the cables yields a transient with a low constant frequency while saturation of the voltage transformer is not taken into account here.

At the end of the test - in the simulation at $t = 0.5 \text{ sec.}$ - B4 is opened. The frequency of the transient is determined by the inductance of the voltage transformer and the small parasitic capacitance C_1 . This situation is, in the case of asymmetries, sensitive to ferroresonance and needs therefore special attention.

Figure 5: Trailer with test unit.

The site test in practice.

The terminations of the cables and connections between the test transformer and the test unit were only used for this test. The end of each cable was stripped of its outer protective sheath, lead alloy sheath and outer semiconducting screen over a length of 60 cm. A stress cone was constructed. No problems were met when the cables to be tested were energized by closing circuit breaker B4. However, on the initial induction of the one-phase earthing of phase C by closing circuit breaker B5, there was a flash-over at the end of the cable between phase A and earth. This two-phase short circuit was immediately switched off by B4. The weather was very damp and there was considerable wind. In spite of the fact that the terminations had been thoroughly cleaned and were

Figure 6: The defective temporary termination.

Figure 7: Switching off a 2-phase earth fault.

protected by a tent covering, the flash-over occurred. Since the flash-over appeared in the first instant, it is likely that the reflection of the transient voltage at the open end of the cable also contributed to this fault.

In fig.7 the phase voltages and the voltage at the open delta winding U_0 of the voltage transformer are given. At $t = T_1$ phase C is connected to earth, at $t = T_2$ an overstrike occurs in phase A and at $t = T_3$ circuit breaker B4 opens. It can be seen that through this two-phase earth fault, at opening circuit breaker B4, a ferroresonance effect is generated in the remaining part of the 50 kV system which is still energized. The frequency of U_0 is approximately 25 Hz. From the tripping of the current relays, it was possible to establish that the 10 kV currents were in the order of 4 kA. The 50 kV short-circuit current thus had a value of approximately 800 A. The switching off of the fault took approximately 70 msec. The damage to the defective termination was therefore so limited that the cause of the flash-over could be clearly established: the connection between the semiconducting screen and the stress cone introduced the flash-over.

This incident proves that weak points (due to the temporary terminations here) are indeed recognized by this test.

After this event all terminations were equipped with an extra insulator and the test was continued without encountering any problems worth mentioning. Fig. 8 shows the voltage and current curves when B4 is closed to energize the cables to be tested. Note that the scales in the figures of the measurements differ from those used in the calculations. Because of the capacitive character of unloaded cables the influence of the small 5th harmonic component in the source voltage is significantly amplified.

From the figs. 9 and 10 it appears that no problems arose neither when phase A was connected to ground nor during the removing

Figure 8: Closing B4: cables energized.

Figure 10: Opening B5: phase A released.

Figure 9: Closing B5: phase A connected to earth.

Figure 11: Opening B4: phase A not connected to earth.

of this "fault". During the test period of one hour, that phase A was grounded and the voltages in the phases B and C were $\sqrt{3}U$, no defects were encountered.

In fig. 10 a temporary decrease in the amplitude of the voltages is observable during the transient after opening B5, which could be explained by the slowly declining voltage of the neutral, measured over the open delta winding of the voltage transformer. A low frequent voltage performs a higher saturation in the voltage transformer; the secondary voltage is distorted.

After the test circuit breaker B4 is opened. In fig. 11 the actual case is presented, where there is no connection to earth. This action does not yield any problems. Only a low frequent transient appears with a relative small damping. The frequency is

Figure 12: Opening B4: phase A connected to earth.

determined by the circuit, which consists of the inductance of the voltage transformer and parasitic capacitance C_1 , and deals with the zero-sequence component. In fig. 12 the result is given when B4 is opened while one phase (A) is still connected to earth, which could be an option to save the use of one circuit breaker, B5. Then the grounding of the separate phases can be performed by a load breaking switch, while the cable to be tested is not energized. However, in this asymmetrical case a much more chaotic transient is observable and even the introduction of ferroresonance could be expected. In this case, where indeed for a moment a 25 Hz frequency appears, the transient disappears finally and the normal steady-state remains. During the tests no complaints were received from consumers, which were also connected to the 10 kV-bus bar. The two-phase earth fault at the start of the tests was the cause of one complaint.

4. CONCLUSIONS

1. The method of applying the after laying test as a sufficient discriminatory commissioning test was found to be perfectly feasible.
2. From the results of the measurements, it has been shown that this manner of testing does not involve any extra risks to the supplying network.
3. From the experience with two tests, we can conclude that this manner of testing certainly brings weak points of the system to light. However, more tests of this kind are necessary to obtain a complete insight into the value of this procedure. The determination of the duration that the cable to be tested has to be exposed to the test voltage for a satisfactory result, is still an open question. However, since the first test in 1988, six after-laying tests have been performed, three for cable systems of 50 kV and three for 150 kV. Since these tests were performed all these connections are still in operation without breakdown.

5. ACKNOWLEDGEMENT

The authors wish to thank prof. dr. ir. F. H. Kreuger for his support and helpful discussions.

6. REFERENCES

1. H. Auclair, W. Boone, M.S. Papadopoulos: "Development of a new after laying test method for high voltage power cable systems", *International Conference on Large High Voltage Electric Systems*, Cigre 1988.

2. F.G. Kreuger, Discussion in *Proceeding of the 1988 Session of CIGRE Group 21, HV Insulated Cables*, pp. 36-37.

3. A.N. Verveen: "Een 50 Hz opleveringsbeproeving aan een 50 kV kunststofkabelcircuit." *Elektrotechniek* 67 (1989) 3 (maart).

BIOGRAPHY

Gerardus Chr. Paap was born in Rotterdam, the Netherlands on February 2, 1946. He received his M.Sc. from Delft University of Technology in 1972 and his Ph.D. from the Technical University of Lodz in 1988. From 1973 he has been with the Faculty of Electrical Engineering of the Delft University of Technology. First, from 1973 to 1985, with the Electrical Machines and Drives Division where he lectured on the fundamentals of

electrical machines and from 1985 with the Power Systems Laboratory as Assistant Professor. His research interests include power systems transients and the dynamics of electrical machines.

Arie N. Verveen was born in Arnhem, the Netherlands on April 30, 1936. He received his M.Sc. from Delft University of Technology in 1961. From 1965 he has been with the Rijnland Energy Company in Leiden, the Netherlands, supervising the 50 kV transport systems of the company. In this field he was confronted with the problems concerning DC site tests for high-voltage extruded insulated cables.

He introduced and put into practice the first $\sqrt{3}U$ after laying test in the Netherlands.

7. APPENDIX: DATA OF NETWORK COMPONENTS

The network data of the network in fig.3 is:

Base MVA $S_b = 20$ MVA, base voltage $U_b = 50 \cdot \sqrt{2/3} = 40.8$ kV. Base current $I_b = 490$ A, base impedance $Z_b = 83.3$ ohm.

$e = 1$ pu.

$Z_{T1,2,3} : X_{T1,2,3} = 0.228$ pu, $R_{T1,2,3} = 0.0055$ pu.

$Z_{T4} : X_{T4} = 0.198$ pu, $R_{T4} = 0.005$ pu.

$R = 2.4$ pu, $C_1 = 2.34 \cdot 10$ pu.

The cables to be tested are 38/66 kV EPR-insulated cables. The cross-section is built up as follows: a solid aluminium conductor with a cross-section of 21.7 mm, then an inner semi-conducting screen, the EPR insulation, an outer semi-conducting screen, a lead-alloy screen and a PVC jacket. The diameter of the cable without the PVC jacket is 43.7 mm.

The cables to be tested consist of 15 sections of approximately 900 meters. The sections are connected with taped joints.

The parameters of the complete cable system are:

$C = 412.10$ pu, $X = 0.0099$ pu, $R = 0.0062$ pu.

Correction to "Contamination Performance of Silicone Rubber Cable Terminations"¹

In the above paper, 1 the following closure was missing. This page should have appeared after page 1373.

(R.S. Gorur, L.A. Johnson and H.C. Hervig): The purpose of the paper was to better understand silicone's hydrophobic characteristics, including recovery, by varying test conditions of the salt fog tests to achieve better correlation with its excellent service history in severe field environments, including seacoast areas.

Fortunately, the industry has the luxury of having service history of over fifteen years with various polymeric terminations and insulators. (Silicone tape terminations go back to the early 1960's). When test procedures contradict each other as shown in Table 1 of the paper and also reported in another work [1] where silicone outperformed EPDM at low salinities (250 $\mu\text{S}/\text{cm}$) and the reverse reported at high salinities (750 $\mu\text{S}/\text{cm}$), it becomes obvious more research is needed to explain the inconsistencies and have better correlation to actual service.

Five hundred hours duration for test procedures of this type has shown to generally provide meaningful results in a relatively short convenient time span. It is not meant to be an acceptance test, but a learning tool and no claims have been made otherwise. As to running tests at very high salinities (16-22000 $\mu\text{S}/\text{cm}$), we disagree that it is "well known little surface degradation occurs," as 16,000 $\mu\text{S}/\text{cm}$ test levels are required in at least one national standard in Europe.

Twenty-four hours of dry time was chosen to follow normal cycles of dew formation, or in some areas fog. This is more plausible than assuming fog or rain will continue for 500 or 1000 hours (40 days and nights) at a salinity of 1000 $\mu\text{S}/\text{cm}$ when average salinity of coastal rain has been quoted as in the 30-50 $\mu\text{S}/\text{cm}$ range and decreases to lower values as rain continues. Even in severe environments, long periods of time (several hours to several months) occur where there is insufficient wetting to form electrical discharges. We believe the 24 hour rest time is consistent with the real world. This procedure has also been used by other [2] with meaningful results.

Both laboratory aged and service aged EPDM and silicone insulators have been analyzed for recovery of contact angle with similar results [3, 4, 5] in other studies. Results were consistent with silicone formulations being able to recover their hydrophobicity over a long time period. The EPDM's studied did not. Because semi-crystalline materials more closely resemble EPDM's chemically than silicone, we believe the semi-crystalline materials would behave more like EPDM.

The discussers reference to a paper by Gubanski reporting that when using a "merry-go-round" test that EPDM has a lower surface leakage than silicone and it would be hard to choose between silicone and epoxy.

The above references (including Gubanski), however, show silicone to have lower surface leakage. Also, a recent Hungarian paper shows epoxy to be very poor compared to silicone after six years of service [6]. We believe this inconsistency is a good example on why test procedures must be designed to correlate with service results and actual climatic conditions. For example, adjustments to allow for a 24 hour test is within a daily cycle, but 48 hours is not.

Our work does apply to other silicones, although actual test times would vary depending on specific formulations and methods. This would also be true for EPDM's and polymers in general as various additives can affect performance greatly.

REFERENCES

- [1] R.S. Gorur, E.A. Cherney, R. Hackman, T. Torbeck, "The Electrical Performance of Insulating Materials Under Accelerated Aging in a Fog Chamber," IEEE/PES 87 WM 147-2 PWRD
- [2] S.H. Kim, E.A. Cherney, R. Hackam, "The Loss and Recovery of Hydrophobicity of RTV Silicone Rubber Insulator Coatings," IEEE/PES 90 WM 024-0 PWRD
- [3] S.M. Gubanski, A.E. Vlastos, "Wettability of Naturally Aged Silicone and EPDM Composite Insulators," IEEE/PEX 1990 Winter Meeting 90 WM 025-7-PWRD.
- [4] S.M. Gubanski, J.G. Wankowicz, "Distribution of Natural Pollution Surface Layers on Silicone Rubber Insulators and Their UV Absorption," IEEE Transactions on Electrical Insulation, Vol. 24, No. 4, Aug. 1989.
- [5] E.M. Sherif, A.E. Vastos, "Influence of Aging on the Electrical Properties of Composite Insulators," Fifth International Symposium on High Voltage Engineering, 24-28 August 1987, Federal Republic of Germany
- [6] M. Paulusz, "Tracking and Erosion Resistance of Composite Insulators," Institute of Electrical Power Research, Hungary

Manuscript received September 20, 1990.

¹ R.S. Gorur, L.A. Johnson, and H.C. Hervig, *IEEE Trans. on Power Delivery*, paper 90 WM 074-5PWRD, vol. 6, no. 4, pp. 1373-1366, October 1991.