Field Measurement and Calculation of Electromagnetic Transients Due to Faults in a Cross-bonded 400 kV Cable System

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Abstract - **Previous transients studies of a newly installed 380 kV underground cable system of 7.5 km length at the Bewag, Berlin, were presented at the IPST '95. One object of that former study was to compare measurements and simulations of the transmission line parameters with different line models. Since all the sheaths were not cross-bonded during these measurements, the effect of cross-bonding remains to be further investigated. It is the objective of this paper to investigate the transient propagation properties of the 380 kV underground cable with reference to the stress of the surge arresters.**

Keywords: cross-bonding, surge arresters, energy absorption, EMTP, electromagnetic transients.

I. INTRODUCTION

In 1994, measurements of transient wave propagation on a 400 kV cable of 7.5 km length were performed to serve as a basis for a comparison of different simulation models [1]. One object of that former study was to compare measurements and simulations of the transmission line parameters with different line models. Since all the sheaths were not cross-bonded during these measurements, the effect of cross-bonding remained to be further investigated.

Meanwhile we encountered a line-to-ground fault in the substation at one end of the 7.5 km cable system with a series of multiple re-igniting small fault currents and their corresponding transient overvoltages which, at instants when the circuit was being shorted, triggered all sheath surge arresters at once and, consequently, destroyed them as a result of accumulated heat. This caused us to investigate the transients due to this type of fault more closely and to draw our attention to:

- The effect of small short-circuit currents
- Sheath surge arrester stress.

II. ELECTROMAGNETIC TRANSIENTS DUE TO INTERMITTING FAULT CURRENTS

In general, power system protection is designed to prevent equipment from enduring major impacts and stresses. Peak short-circuit currents are thus considered according to their electromagnetic forces and effects, while, in the case of sustained short-circuit currents, the main attention is drawn to the effects of overheating.

However, small short-circuit currents qualify for neither category and may cause entirely different effects due to their continuous extinction and re-ignition. Especially for sheath surge arresters, this behaviour may be fatal since with a heat absorption energy of about 20 to 40 kJ they might withstand such discharge

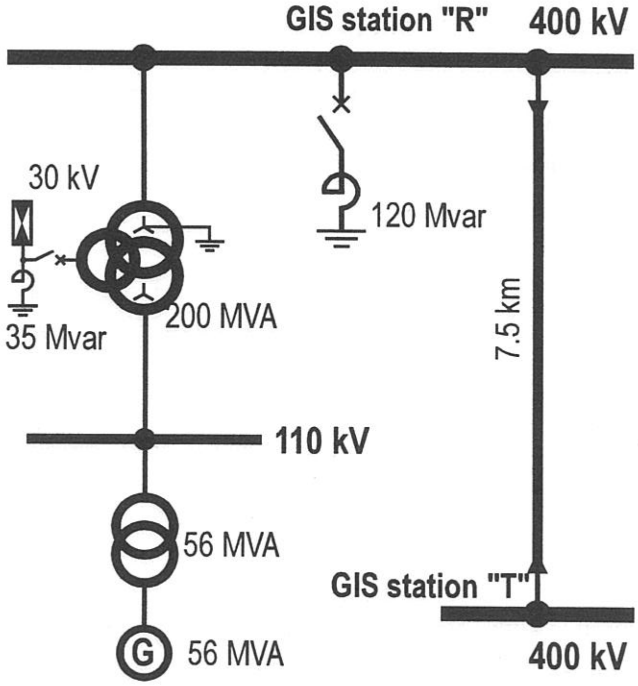

Fig. 1. Test facility

currents only once or twice before they require a sufficient cooling period. During each discharge period, the temperature of the conducting path inside the arrester increases by approximately 60 K.

The described effect was observed in a test circuit (Fig.1) including an unloaded 400 kV cable (Table I) which was operated at 1.5 p.u. of rated voltage. Intermitting short-circuit currents of varying magnitudes up to 200 A (Fig. 2) were induced from the interconnected gas-insulated switchgear "T".

Table I. Dimensions of the cable

Oil pipe diameter of	22.0 mm
Core diameter	46.5 mm
Thickness of paper insulation	25.0 mm
Thickness of Al sheath	3.6 mm
Outer diameter of sheath	115.9 mm
Thickness of PE jacket	4.0 mm
Diameter over all	129.0 mm
Core cross section (Cu)	1200 mm^2
Permittivity of outer insulation	2.3
Permittivity of main insulation	4.17

From the readings of a digital protection unit, we were able to reconstruct the entire short-circuit sequence: The first flashover took place at full operating voltage while the consecutive flashovers occurred at a lower voltage level due to the damaged internal insulation of the GIS.

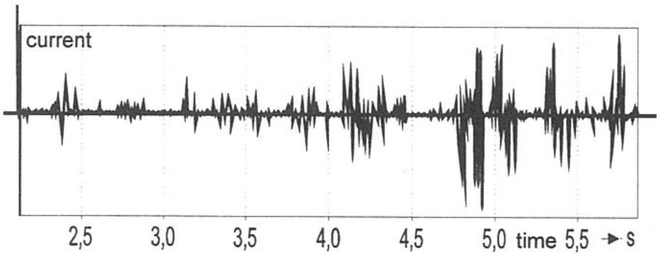

Fig. 2. Intermitting short-circuit currents

Due to their initial operating voltage of 1.5 times its normal value, the arresters endured a higher-than-average energy absorption of about 19 kJ per strike. For strikes at lower voltages, the energy values were correspondingly smaller.

III. OBSERVED EFFECTS OF THE FAULT ON THE SHEATH SURGE ARRESTERS ALONG THE ENTIRE CABLE

The arresters closest to the fault location undergo the severest stresses because, at this location, the transit time of the surge wave through the cable is the longest. According to [2], if the cable were considered to be composed of one major cross-bonding section, the ratio of energy absorption in the first cross-bonding point compared to the second one is 2:1.

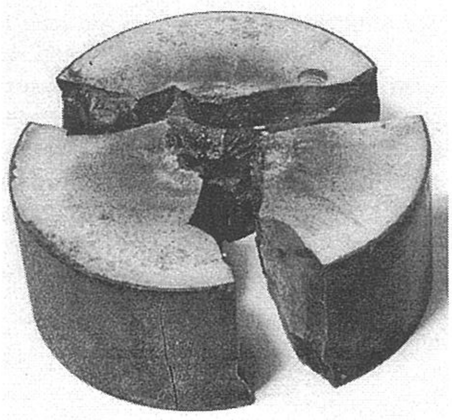

Fig. 3. Burst surge arrester

The heat dissipation of the surge arresters into the environment becomes negligible due to short fault repetition times of only a few milliseconds. Thus, the absorbed energy in the arresters will add up over the course of time and their internal temperature will rise accordingly. Afterwards conducted metallurgical investigations showed that metal parts inside the surge arrester's housing box had experienced a surface temperature of about 300 degrees Celsius. The disks inside the metal-oxide varistors (MOV) showed even higher stresses due to overheating which eventually caused them to burst (Fig. 3).

After the destruction of a surge arrester its internal resistance drops to values between 20 Ohms to 30 kOhms (Table II). It had been observed that:

i. The smaller the internal resistance of a destroyed arrester, the less is its heat absorption.
ii. Due to the alloyed connection inside a broken arrester, the two sheaths at the cross-bonding point can be regarded as one interconnected sheath.
iii. The arresters closest to the fault location will be destroyed completely, while the ones farther away survived with reduced internal resistances.

Table II. Measured resistance (Ohm) of the damaged MOVs

No of cable joint	L1	L2	L3
1	+	+	+
2	+	+	+
4	+	+	450
5	118	+	100
7	220	850	150
8	10000	1100	5000
10	0	30300	230
11	1300	300	7000
12	250	300	300
14	180	500	120
15	500	320	1600
17	40	200	7000
18	70	150	20

\+ no measurements due to destruction

According to these observations, all sheath voltage arresters had been successively destroyed until the cable remained without any effective cross-bonding. Since this alters the positive sequence impedance of the cable, it may also endanger the well-functioning of connected protective impedance relays.

The large deviations of the measured values in Table II can be explained considering the mechanical condition of the resistive arrester material after dismantling. Heavily affected parts even crumbled into pieces while taking the measurements. However, all resistance values are smaller than under normal operating conditions. The possibility of increased resistance of an arrester after having been exposed to such stresses is excluded by the manufacturers. Hence, the cable will be furthermore protected against surge voltages.

IV. STUDY OF THE FAULT SURGE OVERVOLTAGES AT THE MOST CRITICAL CROSS-BONDING POINT

A. Test setup

After all destroyed sheath surge arresters had been replaced, the transient behaviour of the 7.5 km cable system (Fig. 5) was examined again [1] under low voltage conditions. A single phase fault was imitated by short-circuiting the cable 1 at the terminal of GIS station "T" (sending end) after the cable had been precharged with dc +30 Volts (Fig. 4a).

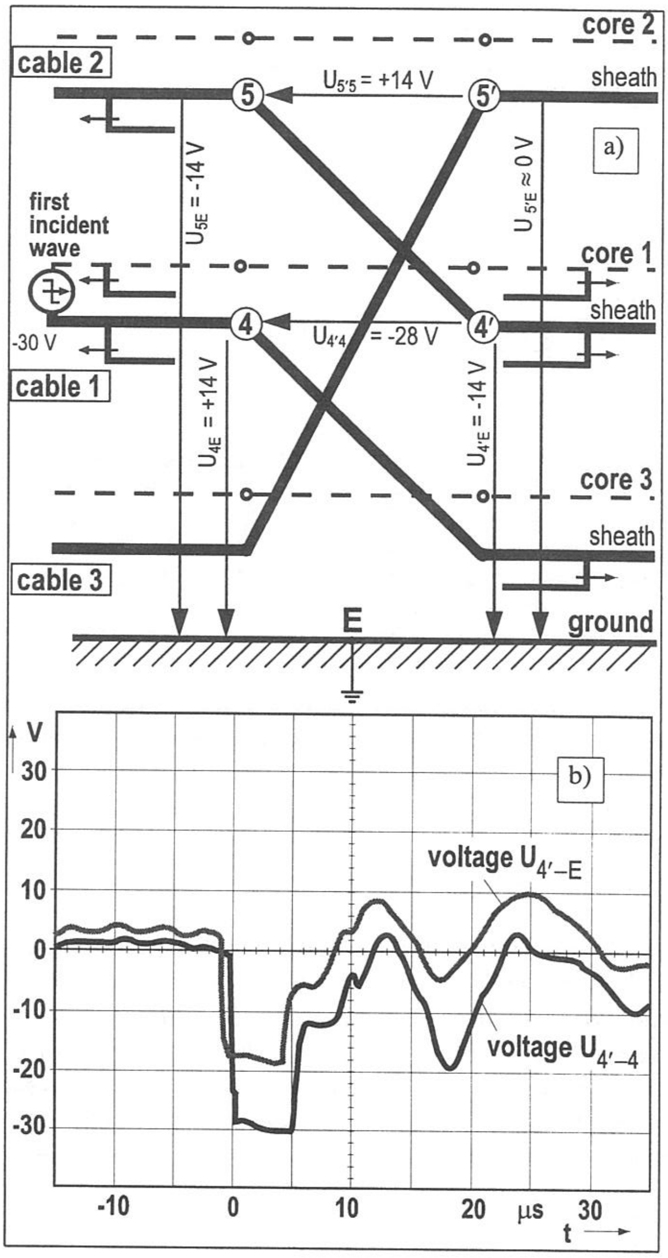

Fig.4. a) Overvoltages at the most critical cross bonding point immediately after the arrival of the first incident wave

b) Oscillograhp of voltages at point 4'

The GIS station "R" (receiving end) as well as all other cable terminals were open-ended, all sheaths were cross-bonded, and all sheath surge arresters installed.

The measurements were performed at the first cross-bonding point which is the most critical [2,3,4,5]. It is located only 0.385 km from the fault location at station "T". The cable joints with the cross-bondings are situated in passable cable vaults under ground, where the MOVs are connected directly to the sheaths with very short bonding leads.

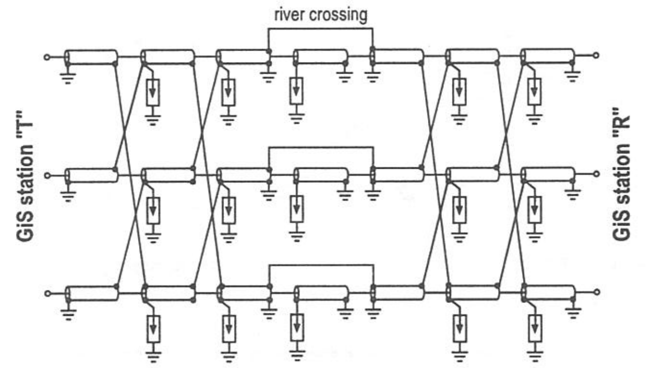

Fig. 5. The cross-bonded cable system. Both sides of rivercrossing reduced to 1 instead of 3 major sections

B. Field measurements

The test voltage was far below the threshold voltage of the surge arresters such that we could investigate the propagation of transient overvoltages without triggering the MOVs. Fig. 4b shows the transient wave form of the sheath-to-ground and sheath-to-sheath voltages in the time interval between the arrival of the first incident travelling wave and the return of the first reflected wave. Concerning our study, this time interval is of importance because it contains the highest overvoltages which would cause the response of the sheath surge arresters.

Cross-bonding causes the travelling waves to leave the cable. They behave according to the refraction index, i.e. the ratio of the low surge impedance of the coaxial part of the cable, 26 Ohms [1], to the high surge impedance behind the cross-bonding point. As a result, high transient overvoltages ccur between the sheaths and ground as well as between different sheaths. The refracted waves continue travelling in both directions along the cable. The propagation of the refracted waves becomes obvious in Fig. 4b.

The dominant first impulse ends with the arrival of the reflected wave returning from the sending end inside cable 1 back to point 4. It returns after twice the travelling time of 5.1 µs of this particular cable section (l=385 m, v=151 m/µs). The magnitude of the voltage signed in Fig. 4a are valid for this dominant time interval. They are the result of a simple voltage divider function of all surge impedances involved at this cross-bonding point.

C. Comparison between measurements and calculation

For comparison, we performed simulations with the Electromagnetic Transients Program EMTP. The cables were modelled using L.Martí's model [6]. Fig. 6 shows for example the sheath-to-ground overvoltage at point 5 of Fig. 4a. Within the time interval of the first impulse at the cross-bonding point, the simulation results matched our measurements reasonably well.

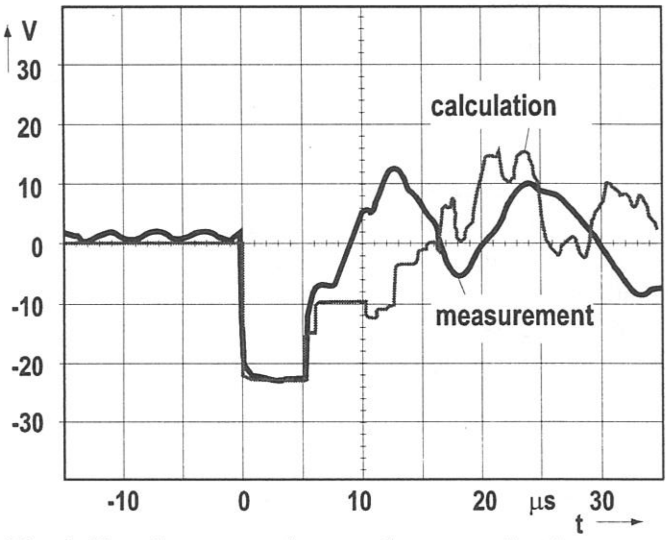

Fig. 6. Sheath-to-ground overvoltage at point 5

It should be emphasised that, in order to expect sufficiently accurate results, the cable had to be modelled in detail, including all major and minor cable sections. In this case, there were 19 sections, i.e. six major sections plus one river-crossing section without cross-bondings (Fig. 5). We found that simplifications made by reducing the number of modelled cable sections are not permissible for these types of study, where sheath voltages, currents and MOV energy at the first cross-bonding point are investigated.

V. SIMULATION OF SHEATH SURGE ARRESTER STRESS AT THE MOST CRITICAL CROSS-BONDING POINT

With the experiences from the measurements, we now wanted to simulate the voltage and current waves for the fault case studied in chapters 1 and 2. Of particular interest were voltage stressing and energy absorption capabilities of the sheath surge arresters which were modelled by means of their non-linear resistance. For calculating the energy absorption, a block-oriented representation was realised employing the „Models“-module in the EMTP. The results from chapter 4 demonstrate that it becomes necessary to model the cable in detail with all cable sections, each having a length of approximately 0.4 km. For each section, we used the frequency dependent cable model implemented in the EMTP.

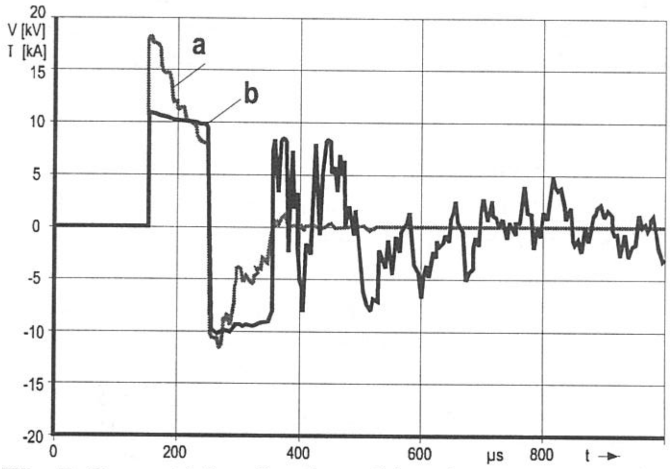

Fig. 7. Current (a) and voltage (b) at the most stressed sheath voltage arrester

The simulations were performed with sheath surge arresters of a residual voltage of 10 kV at 10 kA (wave shape 8/20 µs). The single phase short was applied to the terminal "T" of cable 1.

All simulations showed that due to the behaviour of the travelling waves, the stress on a sheath surge arrester was higher, the closer it was located to the fault at terminal "T". The farther its distance from the fault location, the shorter became the time interval between the first incident voltage and current waves and their reflections; and, consequently, the less energy was absorbed by the arrester. Fig. 7 shows the voltage and current waves across the most severely stressed sheath surge arrester which is situated at the first cross-bonding point. Throughout the simulations, the short was applied at 1.5 times the crest value of rated voltage (see chapter II).

Our special interest in the simulation of the travelling waves was devoted the energy absorption of the sheath surge arresters. Their rated energy absorption limit was 37 kJ. As described in chapter III, an exposure to higher energy levels might well lead to their destruction. The simulation of the circuit behaviour under short-circuit conditions enabled us to calculate the energy that was absorbed by the arresters while being subjected to voltage and current travelling waves. The absorbed energy is given by:

$$W = \int v(t)\, i(t)\, dt$$

where v(t) and i(t) are the instantaneous voltage and current, respectively, across the surge arrester. The integration time is the time interval between fault begin and the time, by which either v(t) or i(t) have permanently decreased to zero. A comparison between the actually absorbed energy and the rated energy shows whether or not a surge arrester had been overstressed.

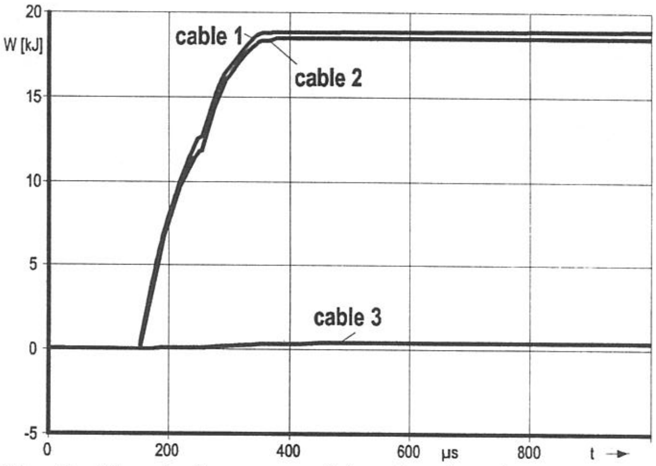

Fig. 8. Absorbed energy of the sheath voltage arrester at the first cross-bonding point

Fig. 8 shows the absorbed energy for each of the three sheath surge arresters at the first cross-bonding point next to the fault location. The arresters of cables 1 and 2 experienced the severest impacts of 19 kJ each. Considering a rated energy of 37 kJ, this means that each of the arresters might withstand up to two consecutive faults. However, any further re-ignition would lead to the destruction of the arresters.

The simulations confirm our observations from chapter III and also quantify the impact of a single phase fault on all partaking sheath surge arresters. It is clear that the fault conditions described in chapter II would lead to their destruction.

VI. CONCLUSION

Sheath surge arresters are usually designed for fault cases with severe impacts. However, also during small intermitting short-circuit currents, they are repetitively exposed to full material stress, and will eventually fail when their energy absorption limit has been exceeded. For surge arresters closest to the fault location, this limit may be already reached after the second or third discharge since, due to very short pause times between the intermitting faults, the absorbed heat cannot be dissipated in the environment.

Fault surge overvoltages at the most critical cross-bonding point were investigated. Due to the cable discontinuity at the cross-bonding point, the first incident travelling wave is reflected, branched, and refracted. The paper presents systematically the distribution of the different transient overvoltages between the cable sheaths and ground. Kirchhoff's law must hold true at any instant. The measurement results are compared with calculations and reveal sufficient accordance.

VII. REFERENCES

[1] M.Ermel, J.Pannicke, M.Henschel: "Field measurements and modelling of the transients propagation properties of a 380 kV cable system of 7.5 km length at Bewag Berlin", *Proc. IPST'97*, Lisbon, 3.-7. September 1995, pp 82-86.

[2] H.G. Dabringhaus: *Transiente Überspannungen auf Hochspannungskabeln*, Dissertation, Universität Duisburg, 1983.

[3] L.Martí, L.H.Brierley, T.E.Graininger: "Analysis of Electromagnetic Transients in cross-bonded cable systems using frequency dependent cable models", *Proc. IPST'95*, Lisbon, 3.-7. September 1995.

[4] L.M.Wedepohl, D.J.Wilcox: "Estimation of transient sheath overvoltages in power cable transmission systems", *Proc. IEE,* Vol 120(8), pp877-882,1973

[5] A.Ametani, C.T. Wan: "Sheath overvoltages due to faults on an EHV Cable", *Proc. IPST'95*, Lisbon, 3.-7. September 1995.

[6] L.Martí: *Simulation of electromagnetic transients in underground cables with frequency-dependent modal transformation matrices*, PhD thesis, University of British Columbia, Vancouver, Canada, Nov. 1986.