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THERMAL BEHAVIOUR OF ZnO SURGE ARRESTERS IN POLLUTED CONDITIONS

by

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Abstract - The thermal performance of ZnO surge arresters were studied in the laboratory and in the field. Results from two natural pollution test sites are presented in terms of temperature rise and charge accumulation. The feasibility of reproducing the thermal stress on the arresters in the laboratory by means of the salt fog method and the slurry method, is discussed.

Keywords - surge arrester, ZnO, metal-oxide, thermal performance, artificial pollution, natural pollution

1. INTRODUCTION

ZnO surge arresters operating in polluted areas may be subject to an environmental stress causing an increased risk of flashover, internal partial discharges (PD) and increased varistor temperature. Regarding the risk of flashover, service experience has shown that the risk of flashover may be kept at a sufficiently low level if the requirements on the external insulation are based on the actual pollution severity, i.e. a minimum specific creepage length for a given pollution level.

Internal PD may appear in the surge arrester during a pollution event, caused by the difference between the internal and external voltage distributions. Today, however, ZnO varistors can be efficiently protected from the consequences of internal PD.

The third basic phenomenon related to ZnO surge arresters operating in polluted conditions is the temperature rise that may occur due to the uneven voltage distribution created by the surface leakage currents. This phenomenon is of great interest today and it has been thoroughly studied in the field and in the laboratory within a collaboration between ABB, TransiNor, and EDF. Artificial and natural pollution tests results have been compared on the basis of pollution severity, maximum varistor temperatures and charge of leakage currents. It was found that the accumulated external charge per hour is a good measure of the thermal stress imposed on the arrester during polluted conditions.

The first results of these studies were published in Reference 1. In this paper, further results from the field tests are presented. It is also shown how the laboratory test parameters can be varied in order to obtain the desired pollution conditions. Furthermore, it is discussed how to incorporate the effect of uneven heating into the standardized type tests for surge arresters.

2. LABORATORY AND FIELD TESTS

The ZnO arresters subject to pollution tests in the laboratory and in the field were standard arrester types for 245, 300 and 420 kV systems. General data for the arresters are presented in Table I, and the arresters are shown in Figure 1.

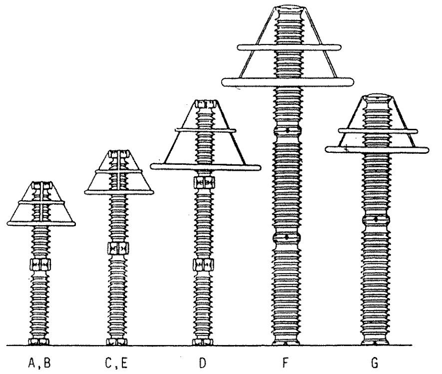

Figure 1. Surge arrester types used for the tests.

2.1 Laboratory test methods

Four different artificial pollution test procedures were studied in the laboratory:

- Salt fog method
- Solid layer method
- Partial wetting method
- Slurry method

The salt fog and solid layer methods are standardized procedures as per IEC 507, originally intended for studies on the flashover performance of insulators. The partial wetting method is a standardized test procedure for ZnO surge arresters according to

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Table I. General data for the surge arresters.

Surge arrester type	No. of units	System voltage kV	Rated voltage kV	Test voltage kV	Creepage distance mm	Specific creepage distance mm/kV	IEC line discharge class	Varistor diameter mm	Average housing diameter mm
A	2	245	192	141	5430	22	3	62	210
B	2	300	216	173	5430	18	4	75	210
C	2	300	216	173	6780	23	4	75	210
D	3	300	216	173	8148	27	4	75	210
E	2	245	192	141	6780	28	3	62	210
F	3	420	360	243	12510	30	4	75	326
G	2	420	360	243	9340	22	4	75	326

ANSI/IEEE C62.11-1987. The slurry method is a non-standardized test method consisting of repetitive applications of slurry to the complete arrester [1]. Up to ten consecutive applications of slurry were used in these tests.

2.2 Natural pollution test sites

The Martigues pollution test station is located in the south of France, very close to the seashore (about 10 meters) in the vicinity of an industrial area with oil power plant, steel industries, oil refineries and chemical industries. The test voltages are 24/√3, 245/√3 and 420/√3 kV. The surge arresters tested at Martigues includes two 245 kV arresters (A and E) and two 420 kV arresters (F and G).
The predominant winds at Martigues follow the Rhône Valley, blowing from the north through the nearby industrial area. Winds also blow from the sea, especially during storm periods, but also during long periods of low wind speeds. Based on previous experience, the conditions at Martigues correspond to pollution zone 3 according to the IEC standard.

Two arresters (A and F) are equipped with fiber-optic sensors for temperature measurements. The other two arresters (E and G) were equipped with thermo-strips along the varistor column. The internal (varistor) and external (surface) currents were measured on all four surge arresters.

The Lista test site is located on the south coast of Norway and exposed to salt pollution from the sea. The predominant wind directions are south and south-west. The test site is an ordinary 300 kV open-air switchyard located about 500 meters from the seashore. Previous experience indicates that the pollution conditions at Lista correspond to IEC zone 3. The arresters (C and D) have different specific creepage distances in order to study the influence on the pollution performance.

The temperature measurements at Lista are restricted by the fact that the arresters are connected to the 300 kV system. The thermo-strips can not be checked until the arresters are finally taken out of operation and removed from the test site. Measurements of internal and external charge are carried out on both arresters.

3. RESULTS FROM LABORATORY AND FIELD TESTS

Results from data acquisition at the field test sites and from the laboratory studies, were reported in Reference 1. A short description of the laboratory test results are given below. The results from the field tests have been significantly extended; up to four years of charge accumulation information is now available.

3.1 Results from Martigues

3.1.1 Temperature measurements

The maximum varistor temperatures recorded for the four surge arresters are summarized in Table II. For arrester types E and G, the maximum temperatures are those indicated by the thermo-strips after the test period was completed. For arrester types A and F, monthly maximum values are given in Table II. The monthly maximum temperature rise above ambient was calculated and presented in Table III.

Table II. Maximum varistor temperature at Martigues (°C).

Month	Arrester A	Arrester A	Arrester E	Arrester E	Arrester F	Arrester F	Arrester F	Arrester G	Arrester G
	Top Unit	Bottom Unit	Top Unit	Bottom Unit	Top Unit	Middle Unit	Bottom Unit	Top Unit	Bottom Unit
Jui 89	36	34	↑	↑	•	•	•	↑	↑
Aoû 89	35	34	↑	↑	•	•	•	↑	↑
Sep 89	29	29	↑	↑	•	•	•	↑	↑
Oct 89	28	46	↑	↑	•	•	•	↑	↑
Nov 89	25	23	↑	↑	•	•	•	↑	↑
Déc 89	•	•	49	49	•	•	•	40	40
Jan 90	•	•	↓	↓	13	17	17	↓	↓
Fév 90	37	31	↓	↓	40	17	25	↓	↓
Mar 90	28	34	↓	↓	21	21	24	↓	↓
Avr 90	18	22	↓	↓	17	17	18	↓	↓
Mai 90	27	28	↓	↓	24	27	25	↓	↓
Jui 90	30	30	•	•	27	27	26	•	•
Jui 90	33	43	•	•	32	31	30	•	•
Aoû 90	32	34	•	•	32	31	30	•	•
Sep 90	29	30	•	•	26	25	24	•	•
Oct 90	52	28	•	•	25	25	23	•	•
Nov 90	19	22	•	•	17	19	•	•	•
Déc 90	•	•	•	•	•	•	•	•	•
Jan 91	12	•	•	•	16	17	16	•	•
Fév 91	17	17	•	•	16	17	15	•	•
Mar 91	21	18	•	•	20	18	17	•	•
Avr 91	21	19	•	•	22	19	19	•	•
Mai 91	25	31	•	•	24	25	40	•	•
Jui 91	32	31	•	•	27	27	26	•	•
Jui 91	34	35	•	•	47	35	47	•	•
Aoû 91	38	35	•	•	•	32	27	•	•
Sep 91	33	33	•	•	29	30	27	•	•
Oct 91	30	29	•	•	27	27	25	•	•

It can be noted that significant temperatures have been recorded in all surge arrester units. However, a detailed analysis of the temperature recordings showed that at times of significant temperature rise in one unit of an arrester, no temperature rise was observed in the other unit(s) of that arrester.

Table III. Maximum varistor temperature rise at Martigues(°C).

Month	Arrester A Top Unit	Arrester A Bottom Unit	Arrester F Top Unit	Arrester F Middle Unit	Arrester F Bottom Unit
Jui 89	<5	5	•	•	•
Aoû 89	<5	5	•	•	•
Sep 89	<5	7	•	•	•
Oct 89	7	>27	•	•	•
Nov 89	9	5	•	•	•
Déc 89	•	•	•	•	•
Jan 90	•	•	<5	<5	<5
Fév 90	12	16	25	<5	10
Mar 90	12	14	<5	<5	<5
Avr 90	<5	<5	<5	<5	<5
Mai 90	<5	<5	<5	<5	<5
Jui 90	<5	<5	<5	<5	<5
Jui 90	5	13	<5	<5	<5
Aoû 90	<5	7	<5	<5	<5
Sep 90	9	5	<5	<5	10
Oct 90	33	5	<5	<5	10
Nov 90	5	<5	<5	<5	•
Déc 90	•	•	•	•	•
Jan 91	13	•	<5	<5	<5
Fév 91	<5	<5	<5	<5	<5
Mar 91	<5	<5	5	<5	<5
Avr 91	<5	<5	<5	<5	<5
Mai 91	<5	5	<5	<5	18
Jui 91	<5	<5	<5	<5	<5
Jul 91	<5	5	17	<5	22
Aoû 91	16	<5	•	<5	<5
Sep 91	<5	<5	<5	<5	<5
Oct 91	7	<5	<5	<5	<5

3.1.2 Charge measurements

The charge measurements for the complete test period in terms of the monthly maximum internal and external charge per hour with a duration of 2 and 6 hours, are presented in Tables IV and V. The durations were selected on the basis of typical pollution events observed during the tests. The thresholds for the internal and external currents were 2 mA_{peak}. (The threshold for the external currents given in Reference 1 is erratic.)

The internal charge values were well correlated with the temperature rises in the bottom unit of the surge arresters. A comparison of Tables III, IV and V shows that high maximum internal charge values were recorded when a significant heating in the bottom unit was noticed. Thus, the internal charge is a representative value of the temperature rise which appears in a unit due to pollution activity.

A close comparison of the external charge curves for the four surge arresters indicated that high external charge activity events took place at the same time on all arresters. The simultaneous nature of the high-charge events confirms that they were caused by pollution phenomena.

3.1.3 Influence of specific creepage distance

The influence of the specific creepage distance on the external charge can be studied in Table V. As seen, the external charge per hour is very similar for arrester types A and E, which have the same housing diameter but different creepage distances.

Table IV. Maximum charge during 2 hours at Martigues (As/h).

Month	Arrester A Qint	Arrester A Qext	Arrester E Qint	Arrester E Qext	Arrester F Qint	Arrester F Qext	Arrester G Qint	Arrester G Qext
Jul-89	0.00	0.00	0.00	0.08	*	*	0.24	0.07
Aoû-89	0.40	4.40	0.65	3.99	*	*	0.09	7.77
Sep-89	0.70	5.40	*	*	*	*	0.14	7.96
Oct-89	1.80	3.20	4.44	3.20	*	*	1.30	7.30
Nov-89	0.60	1.60	0.81	1.78	*	*	0.71	4.49
Déc-89	0.60	4.30	1.53	4.45	*	*	0.79	11.16
Jan-90	0.60	4.80	0.82	6.04	*	*	1.10	7.56
Fév-90	1.30	4.60	1.58	4.95	*	8.12	0.76	7.64
Mar-90	0.20	6.70	0.98	5.70	*	7.62	0.80	7.99
Avr-90	1.45	4.86	3.37	4.66	*	8.88	1.10	10.26
Mai-90	0.18	1.70	0.05	1.70	0.02	2.77	0.01	6.10
Jul-90	0.60	1.90	*	*	0.02	[3.71]	*	*
Jul-90	5.50	6.33	*	*	0.46	[7.91]	*	*
Aoû-90	2.39	4.48	*	*	*	[7.45]	*	*
Sep-90	2.76	4.72	*	*	*	*	*	*
Oct-90	2.33	7.06	*	*	*	*	*	*
Nov-90	0.73	3.70	*	*	1.72	8.56	*	*
Déc-90	1.21	7.94	*	*	0.99	14.86	*	*
Jan-91	0.13	1.54	*	*	*	5.99	*	*
Fév-91	0.66	1.27	*	*	1.54	*	*	*
Mar-91	0.64	3.53	*	*	0.43	12.86	*	*
Avr-91	0.09	2.02	*	*	0.03	8.82	*	*
Mai-91	3.86	2.34	*	*	*	6.13	*	*
Jui-91	1.30	6.50	*	*	1.01	14.50	*	*
Jui-91	0.68	4.86	*	*	1.39	7.49	*	*
Aoû-91	1.04	3.47	*	*	0.52	7.48	*	*
Sep-91	2.34	2.36	*	*	0.21	8.63	*	*
Oct-91	0.75	4.45	*	*	0.37	6.73	*	*

Table V. Maximum charge during 6 hours at Martigues (As/h).

Month	Arrester A Qint	Arrester A Qext	Arrester E Qint	Arrester E Qext	Arrester F Qint	Arrester F Qext	Arrester G Qint	Arrester G Qext
Jui-89	0.00	0.00	0.02	0.08	*	*	0.19	0.07
Aoû-89	0.20	2.80	0.33	2.93	*	*	0.08	7.01
Sep-89	0.40	3.90	*	*	*	*	0.09	6.47
Oct-89	1.50	1.70	4.20	1.46	*	*	0.88	4.70
Nov-89	0.40	1.40	0.60	1.43	*	*	0.55	3.79
Déc-89	0.50	3.40	1.09	3.36	*	*	0.64	9.15
Jan-90	0.30	4.50	0.65	5.24	*	*	0.91	7.20
Fév-90	1.10	4.30	1.20	4.11	*	7.54	0.47	7.13
Mar-90	0.10	5.90	0.83	4.27	*	6.55	0.40	6.73
Avr-90	0.75	3.53	2.22	2.74	*	7.20	0.38	7.52
Mai-90	0.08	1.44	0.03	1.45	0.01	2.40	0.01	4.85
Jui-90	0.47	1.73	*	*	0.01	[2.82]	*	*
Jul-90	5.18	3.89	*	*	0.22	[7.43]	*	*
Aoû-90	1.64	3.68	*	*	*	[4.85]	*	*
Sep-90	2.43	3.19	*	*	*	*	*	*
Oct-90	2.11	6.21	*	*	*	*	*	*
Nov-90	0.63	2.97	*	*	0.74	6.12	*	*
Déc-90	0.60	5.83	*	*	0.53	10.38	*	*
Jan-91	0.08	0.73	*	*	*	[2.35]	*	*
Fév-91	0.49	1.06	*	*	1.21	[4.02]	*	*
Mar-91	0.21	1.91	*	*	0.14	5.04	*	*
Avr-91	0.08	0.86	*	*	0.01	3.95	*	*
Mai-91	3.43	1.50	*	*	*	2.40	*	*
Jui-91	0.85	3.19	*	*	0.67	6.28	*	*
Jui-91	0.58	3.52	*	*	1.15	6.93	*	*
Aoû-91	0.97	2.71	*	*	0.52	6.83	*	*
Sep-91	0.96	1.77	*	*	0.11	6.76	*	*
Oct-91	0.69	2.42	*	*	0.20	5.07	*	*

3.1.4 Influence of housing diameter

The effect of housing diameter on the external charge can be seen in Table V by comparing the external charge values for arrester types A and G. These arresters have the same specific creepage distance and the same number of arrester units, but different housing diameters. By assuming that the charge is proportional to the diameter of the housing (see Table I), it can be seen that the charge values for type A and G are similar when normalized to the same diameter.

3.1.5 Flashover performance

Flashovers occurred on three of the surge arresters during polluted conditions. It should be noted that two of these arresters are actually intended for pollution zone 2, while the pollution level at Martigues sometimes reaches zone 3. The specific creepage distance is the main parameter explaining the flashovers; most of them occurred on surge arresters A and G, which have a short specific creepage distance, however, one flashover also occurred on arrester type E.

In conclusion, the external charge appears to be a representative value of the pollution activity on the surge arrester, when the effect of the housing diameter is taken into account. Thus, charge measurements on different types of surge arresters can be compared if the charge levels are normalized to the same average housing diameter. Simultaneous measurements of leakage current amplitudes showed that the maximum peak level of external leakage current was linked with the flashover performance of a surge arrester. At the same time, the amplitude of the internal current could not be linked with the thermal behavior of the arrester.

3.2 Results from Lista

3.2.1 Charge measurements

The charge measurements at Lista have been going on for more than four years. The threshold for the internal current has been 2 mA_{peak}. For the external current, both 0.4 and 2 mA_{peak} thresholds have been used [1]. To facilitate a comparison with the results from Martigues, only the results with the 2 mA_{peak} threshold are presented in Table VI.

Table VI. Maximum charge during 2 and 6 hours at Lista.

Arrester type	Duration h	Int. charge As/h	Ext. charge As/h
C	2 6	0.5 0.5	2.5 0.8
D	2 6	0.3 1.5	3.5 1.7

3.3 Results from laboratory tests

3.3.1 Salt fog method

The main characteristic of the salt fog method is the possibility of high thermal stress on the arrester and the large scattering in results obtained during repeated tests under the same conditions. No correlation could be found between salinity and temperature rise; high temperatures were reached also for low salinities. Usually, the highest temperatures were reached in the top unit, however, significant temperature rise was noticed also in the bottom unit. The thermal stress on one unit is maintained on the same unit during the entire test period.

3.3.2 Solid layer method

The solid layer method gives a considerably lower external charge accumulation compared to the other test methods, and the temperatures reached during the tests were very moderate. No correlation was found between the maximum temperature rise and the salt deposit density of the pollution layer.

3.3.3 Partial wetting method

The partial wetting method differs considerably from the other test methods; the location of the temperature rise in the upper half of the arrester is predetermined by the wetting procedure, and a very high temperature rise may appear in very short time.

3.3.4 Slurry method

The main characteristic of the slurry method is that the temperature rise may appear in any arrester unit with about the same probability. The external charge depends on the number of test cycles included in the test. The temperature rise varies from one cycle to another, reflecting the variations in the voltage grading obtained after each application of slurry. The external charge is not correlated to the specific creepage distance.

4. DEVELOPMENT OF LABORATORY TEST PROCEDURES

For the purpose of selecting an appropriate laboratory test method, it is necessary to identify the most characteristic properties associated with thermal stress on surge arresters during natural pollution.

The results from the field tests show that:

- The external charge is up to about 10 As/h for the large-diameter housing, and up to about 6 As/h for the small-diameter housing, with a 6 hour duration. These charge levels were obtained in Martigues using a threshold of 2 mA_{peak} for the external current.

- Significant temperature rise due to pollution may appear in any unit of a multi-unit arrester, but only in one unit at a time.

- The influence of the specific creepage distance on the accumulated external charge is negligible within the range studied.

Based on these findings, it is possible to determine the corresponding requirements on the laboratory test methods:

- The test method should be able to establish an external charge activity of sufficient intensity and duration, e.g. up to 6 As/h during 6 hours on the small-diameter housing using a current threshold of 2 mA_{peak}.

- Significant temperature rise should be able to appear in any unit of a multi-unit arrester.

- External charge accumulation should be practically independent of the specific creepage distance.

A comparison of the test results from the field and from the laboratory shows that the solid layer method is not capable of providing the desired external charge levels. Furthermore, with the partial wetting method, temperature rise can only occur in the upper half of the arrester.

Of the four test methods investigated, it is only the salt fog method and the slurry method that are able to fulfill the requirements on a suitable test method. In order to develop these methods so that the required test severity may be expressed more precisely in terms of laboratory test parameters, further studies have been carried out. These studies include charge measurements on test insulators in natural pollution, calibration of the salt fog method with regard to salinity, air pressure and saline flow rate, and calibration of the slurry method with regard to the slurry resistivity.

4.1 Charge measurements on insulators at Martigues

The severity of the pollution conditions, as far as the thermal behavior of ZnO surge arresters is concerned, may be expressed in terms of accumulated external charge per hour. Therefore, it is necessary to carry out charge measurements on a site to characterize its actual severity. In order to determine if the charge accumulation on insulators is representative also for surge arresters, a series of charge measurements have been carried out at Martigues on various types of insulators. The measurements were made on four insulator strings (see Table VII). Insulator no. 1 is a typical long-rod insulator, while no. 2, 3 and 4 are typical cap-and-pin insulators.

The results of the charge measurements are presented in Figures 2 to 4. For surge arrester A, the external charge values are given. To account for the different diameters, the charge values have been normalized to an average housing diameter of 1 meter. All the measurements presented were obtained with a current threshold of 2 mA_{peak}.

Table VII. General data for test insulator strings

String	Type	Material	Average Diameter (mm)	Specific creepage length (mm/kV)	Number of insulators per string
1	Long rod	porcelaine	129	25.4	2
2	Cap and pin standard profile	glass	160	17	13
3	Cap and pin open profile	glass	210	18.5	12
4	Cap and pin standard profile	glass	160	25	19

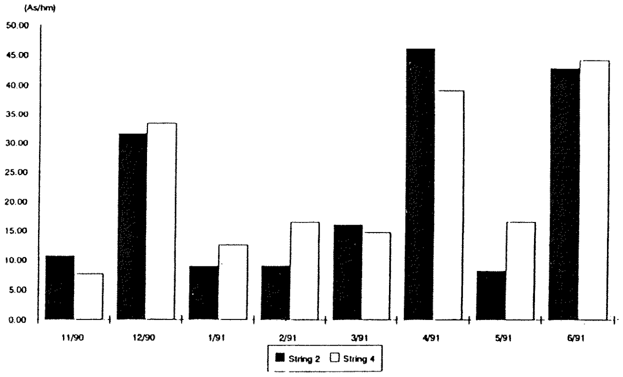

Figure 2. Normalized maximum charge during 2 hours for insulators no. 2 and 4.

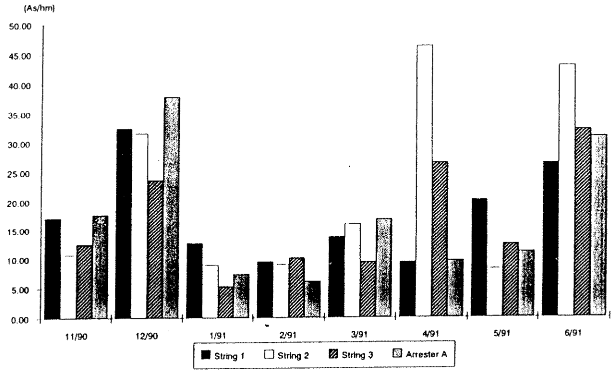

Figure 3. Normalized maximum charge during 2 hours for insulator no. 1 - 3 and arrester A.

4.1.1 Influence of specific creepage length

Insulator strings no. 2 and 4 have the same technical characteristics (test voltage, shed profile, glass insulators) except the specific creepage length (17 mm/kV for string no. 2 and 25 mm/kV for string no. 4). The comparison of the normalized charge results obtained on these two insulators is presented in Figure 2. No significant influence of the specific creepage length can be observed; this conclusion is similar to the one obtained for surge arresters. During natural pollution events, higher current impulses were recorded on insulator no. 4 than on no. 2. However, the influence of the high amplitude current impulses is not significant for the charge measurement, and the charge values are close for the two insulator strings.

4.1.2 Influence of the shed profile

Figure 3 presents the charge results for arrester type A and insulator strings no. 1, 2 and 3. As seen, the results obtained for surge arrester A and insulator string no. 1, are very similar. On the other hand, significant differences are noted for the two other insulator strings (mainly in November, April and June).

To explain the differences observed in Figure 3, it can be supposed that the influence of the insulator profile is very significant. The shed profiles of surge arrester A and insulator no. 1, are very similar. As a consequence, the pollution deposits and the wetting/washing mechanisms are similar for these two test objects. More specifically, the sheds are not deep and the washing by the rain is fast, even during low intensity rainfalls. It has been noticed that a significant charge is recorded on these two objects only at the beginning of a pollution event.

On the other hand, the charge accumulation remains significant during a longer time for insulator string no. 2. This is due to the underribs of the sheds, which may be washed only during high precipitation events. In this case, the time needed for natural cleaning is longer, and the pollution collected in the underribs stays on the sheds for a longer time. The result is that the measured charge is higher than for insulator string no. 1. This effect is even more pronounced for 6-hour charge measurement periods.

For insulator string no. 3, the open profile favors the self washing of the insulator by the wind, and limits the quantity of deposits collected on the bottom of the sheds. But, as for insulator string no. 2, very efficient washing of the bottom of the sheds is provided only by a strong rainfall bouncing on the top of the sheds underneath. As a consequence, during a pollution event observed in April, 1991 (a heavy rainfall of 56 mm on April 25, after a dry period of 3 weeks), the time necessary to obtain a complete washing of the insulator was shorter than for insulator string no. 2.

The influence of the insulating material (glass or porcelain) is difficult to establish from the tests at Martigues. However, it is most likely that the main differences are related to the shed profiles of the various insulators.

4.1.3 Validity of charge measurements on insulators

It appears that the charge values measured on insulator no. 1 and on surge arrester A are in very good agreement when normalized to the same average diameter. During an 18 month test period, the only significant difference was recorded in March, 1990 (Figure 4). Therefore, it seems possible to get a good estimation of the pollution site severity, as far as the thermal behavior of surge arresters is concerned, by measuring the charge flowing on the surface of a test insulator. The results obtained do not depend strongly on the specific creepage length of the insulator, but its shed profile must be as close as possible of the shed profiles of the surge arresters. As a consequence, the test insulator can also be used to calibrate laboratory pollution test methods.

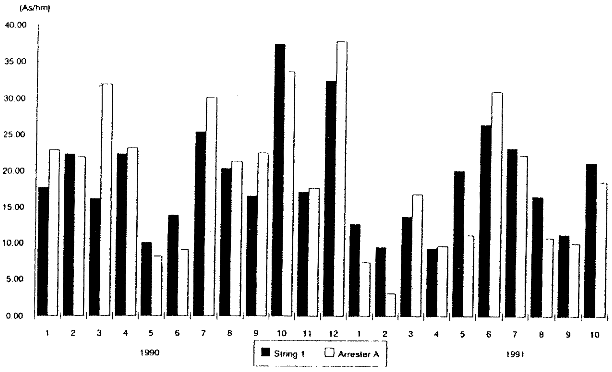

Figure 4. Normalized maximum charge during 2 hours for insulator no. 1 and arrester A.

4.2 Calibration of the salt fog test method

Charge values measured on the surge arresters and on insulator no. 1 during natural pollution tests at Martigues were in very good agreement. It was therefore decided to carry out further investigations in the salt fog chamber on this insulator. Extensive artificial pollution tests made in various countries have indicated that the salinity of the fog is not a good indicator of the severity of a salt fog test, as far as the thermal behavior of surge arresters is concerned. Thus, it was also decided to investigate the influence of other test parameters with regard to the severity of a salt fog test. The aim was to calibrate the salt fog test method, i.e. to determine the values of some test parameters in order to obtain the required test severity.

4.2.1 Influence of the test salinity

In this part, the salt fog tests were carried out in accordance with IEC publication 507: compressed air at a relative pressure of 7 bars, and a flow of solution of 0.5 dm^3/min. The test duration was fixed at two hours. The test voltage was 140 kV, equal to a specific creepage distance of about 24.2 mm/kV for the insulator.

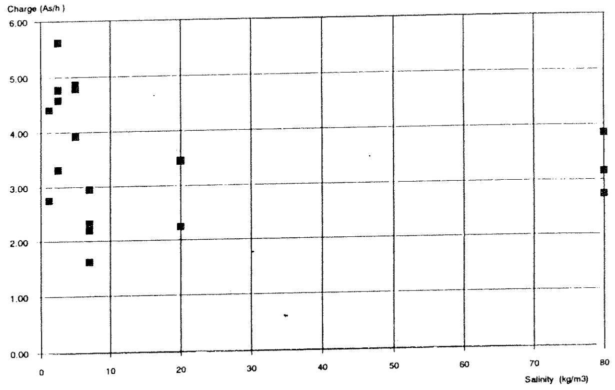

Figure 5. Average charge vs. salinity in salt fog tests on insulator no. 1.

Figure 5 presents the average charge per hour as a function of the test salinity for different tests with a threshold of 2 mA_{peak}. During most of the tests, the evolution of charge versus time is linear. It appears that the measured charge values are nearly constant when the salinity is 20 kg/m^3 and above, and that the charge values for low salinities (below 5 kg/m^3) are higher than for high salinities. During tests carried out at high salinities (above 20 kg/m^3), the maximum peak values of the leakage current are higher; nevertheless, the number of leakage current pulses is limited; there is not a continuous activity of leakage currents, but a succession of bursts of pulses followed by periods with no significant current pulses (i.e. above the threshold value).

For low salinity tests, on the other hand, significant values of leakage currents were continuously recorded, but the amplitude of the maximum leakage current remains rather low (a few tenths of mA). It may be supposed that in this range of salinities (i.e. of leakage currents), an unstable equilibrium may be created between the wetting and the renewal of the pollution layer on one hand, and the drying of the pollution layer due to the leakage currents on the other hand. This explains the wide scattering of the charge results recorded for low salinity tests, and the apparent sensitivity of these results to the test salinity. This also suggests that it is possible to obtain a higher charge value for low salinity tests than for high salinity tests, if the heating of the pollution layer due to the Joule effect well balances the wetting and the renewal of the pollution layer. As a consequence, it is recommended to use test salinities above 7 kg/m^3 for tests on surge arresters, in order to keep the test conditions as reproducible as possible. At the same time, the salinity should be low enough to avoid flashovers.

4.2.2 Influence of the spraying system parameters

As the salinity is not a good parameter to define the severity of a salt fog test carried out to study the thermal behavior of surge arresters, the influence of other parameters was investigated. Two tests series were carried out to evaluate the influence of the air pressure and of the flow of saline solution to the spraying system. The air pressure was varied between 6 and 8 bars (nominal pressure: 7 bars), and the flow of saline solution was varied between 0.17 and 0.67 dm^3/min (nominal flow: 0.5 dm^3/min). The test salinity was fixed at 10 kg/m^3.

Results are presented in Figure 6. The influence of the air pressure and of the flow of saline solution is very significant. In some cases the scattering of the results is large, but as a general trend, the following conclusions can be drawn:

- The higher the air pressure, the higher the measured charge values.

- The higher the flow of saline solution, the lower the measured charge values.

It appears that, except at the nominal flow, it is possible to increase the measured charge values by increasing the air pressure.

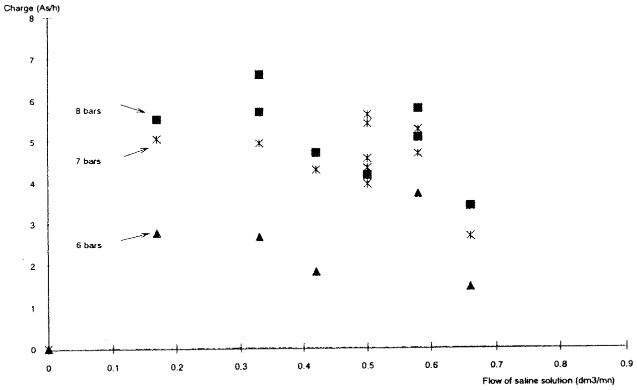

Figure 6. Average charge vs. flow of solution and air pressure in salt fog tests.

4.2.3 Correlation with results from Martigues

Figure 4 presents charge values measured on the same insulator string (no. 1) tested at the Martigues natural pollution test station. The values given in Figure 4 is the normalized monthly maximum charge per hour during 2 hours.

Normalized charge values between 10 and about 45 As/hm were measured in the salt fog tests; corresponding charge values ranging from 9 to 38 As/hm were recorded during the 18 month test period at Martigues using the same current threshold. This shows that it is possible to choose salt fog test conditions, i.e. air pressure and flow of saline solution, which are representative of field conditions. Thus, for calibration of the salt fog test parameters, a long-rod insulator (e.g. test insulator no. 1) or an empty surge arrester housing, can be used.

4.3 Calibration of the slurry test method

The severity of the slurry test in terms of average external charge per hour can be varied within a broad range by the number of slurry applications during a specified time, the duration of the test cycle and the resistivity of the slurry.

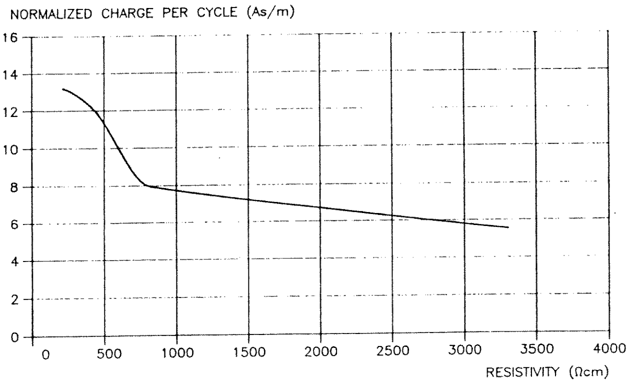

Figure 7. Normalized average charge per test cycle vs. slurry resistivity.

The slurry resistivity prescribed in the ANSI/IEEE standard is 400 Ωcm. Results from tests performed on a single arrester unit of type A, and with the resistivity of the slurry varied between 200 to 3300 Ωcm, are shown in Figure 7. The charge values are normalized to a housing diameter of 1 meter. By changing the resistivity within this practically obtainable range, the charge per hour can be varied by the factor two.

In the slurry tests described in [1], the time for slurry application was around 10 minutes, followed by a drip-off period of 3 minutes, and voltage application during 10 or 15 minutes. However, for a given housing diameter, the charge per test cycle is, in average, almost constant. It is therefore possible to increase the average charge per hour with the slurry method by reducing the time for application of the slurry and, thus, be able to perform more test cycles per hour. Experience has also shown that the major part of the charge is accumulated during the first 5 minutes of energization. The charge per hour can therefore be increased even more by shortening the time for voltage application.

The number of test cycles necessary for a required charge per hour with a normalized 1 meter housing diameter, are shown in Figure 8. The values are based on the test results presented in [1], using an external current threshold of about 1 mA_{peak}. The slurry resistivity is used as the parameter, with values taken from Figure 7.

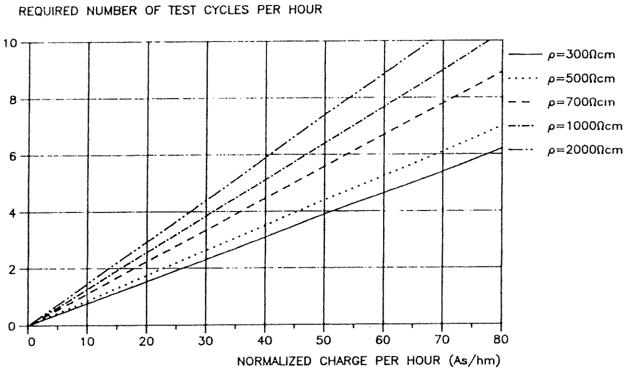

Figure 8. Required number of test cycles per hour vs. the required normalized charge.

The actual service stress during pollution, based on the field tests at Martigues and Lista, and expressed in terms of the external charge per hour for a normalized housing diameter of 1 meter, is shown in Table VIII. In order to represent the actual pollution stress in the field by a slurry test in the laboratory, the necessary number of slurry test cycles is indicated in Table IX, based on the information in Figure 8.

Table VIII. Normalized external charge levels at Martigues and Lista.

Test site	Duration h	Max. charge As/hm
Martigues	2	45.6
	6	31.8
Lista	2	16.7
	6	8.1

The number of test cycles given in Table IX are based on charge measurements with a lower current threshold (1 mA_{peak}) and should therefore be used as a guidance for selecting the slurry test parameters. Before a slurry test on a complete surge arrester is carried out, a calibration and adjustment of test parameters should be done by performing a test on a long-rod insulator (e.g. test insulator no. 1) or an empty surge arrester housing.

Table IX. Slurry test parameters to represent pollution conditions at test sites.

Test site	Duration h	Slurry Ohmcm	No. of cycles
Martigues	2	700	10
	6	700	21
Lista	2	700	4
	6	700	6

5. REPRESENTATION OF UNEVEN HEATING IN THE TYPE TEST

The thermal stability of a ZnO surge arrester is verified in the operating duty cycle test as a part of the standardized type test. The starting temperature for this test is chosen with regard to the assumed maximum ZnO temperature that may appear in service, before any heating due to energy absorption occur. To cover the influence of ambient temperature, solar radiation and some influence of pollution, the starting temperature is generally +60°C.

The effects of ambient temperature and solar radiation are expected to give the same temperature in all arrester units. Heating by pollution, on the other hand, generally results in uneven heating. In a multi-unit arrester, only one unit is heated, as discussed previously. It is important to notice that for multi-unit arresters, the thermal performance is determined by the actual temperatures appearing simultaneously in the different units. It has therefore been a discussion on what starting temperature to use in the operating duty cycle test to represent the effect of uneven heating due to pollution.

5.1 Theoretical models

In the following, it is assumed that the arrester has been unevenly heated and has reached the maximum temperature at the end of a pollution event. As a consequence, it is assumed that no significant external currents exist, i.e. the resistive current is the same in all units of the arrester.

5.1.1 Weighted mean varistor temperature

A first approximation would be to use a weighted mean value for the temperatures appearing simultaneously in the different units, taking the actual distribution of ZnO varistors into account. Hence, the weighted mean value may be is expressed as:

$$Twm = \sum_{i=1}^{n} Ti \cdot Uri/Ur \qquad (1)$$

where Uri is the rated voltage of unit i
Ur is the rated voltage of the arrester
Ti is the ZnO temperature in unit i
n is the number of arrester units

5.1.2 Power loss and voltage distribution

However, the power loss of ZnO varistors is actually not proportional to the temperature, as suggested in Eq. 1, but shows an exponential behavior which can be approximated as:

$$P = U \cdot I \cdot a \cdot e^{kT} \qquad (2)$$

where U is the voltage
I is the resistive current
a is a constant of proportionality
k is a material constant
T is the ZnO temperature

Tests on heated ZnO varistors have shown that k=0.025/°C for the range of temperatures discussed here.

For a complete arrester, the power losses can then be expressed as:

$$P = U1 \cdot I \cdot a \cdot e^{kT1} + U2 \cdot I \cdot a \cdot e^{kT2} \qquad (3)$$

where U1 is the voltage across the heated unit
U2 is the voltage across the unheated unit(s)
T1 is the temperature of the heated unit
T2 is the temperature of the unheated unit(s)

The voltage distribution between the units (U1 and U2) during unevenly heated conditions is generally unknown. Accurate calculations of the voltage distribution can be carried out by modelling very precisely the thermal behavior of the arrester. However, considering that the resistive currents during these conditions are in the mA-range, it may be assumed that the unheated unit(s) are exposed to a voltage stress which is above the continuous operating voltage, but below the rated voltage of that unit(s). As a first approximation, the average of these voltages is therefore used in the following. Hence, the voltage across the different units may be expressed as:

$$U2 = Ur2 \cdot (1+COV)/2 \qquad (4)$$

$$U1 = COV \cdot Ur - U2 = COV \cdot Ur - Ur2 \cdot (1+COV)/2 \qquad (5)$$

$$COV = (U1+U2)/Ur \qquad (6)$$

where Ur2 is the rated voltage of the unheated unit(s)
Ur is the rated voltage of the complete arrester
COV is the continuous operating voltage in p.u. of Ur

5.1.3 Equivalent varistor temperature

As a refinement of the weighted mean temperature, the concept of an equivalent temperature is introduced. The equivalent temperature is defined as an even temperature during which the power loss is, theoretically, the same as for unevenly heated conditions. The power loss at the equivalent temperature can then be expressed according to Eq. 2:

$$Peq = (U1+U2) \cdot I \cdot a \cdot e^{kTeq} \qquad (7)$$

where Teq is the equivalent ZnO temperature

From the definition of equivalent temperature, the power losses are the same as for the unevenly heated arrester, so that:

$$U1 \cdot I \cdot a \cdot e^{kT1} + U2 \cdot I \cdot a \cdot e^{kT2} = (U1+U2) \cdot I \cdot a \cdot e^{kTeq} \qquad (8)$$

Inserting (4) and (5) into (8), yields:

$$(COV \cdot Ur - Ur2 \cdot (1+COV)/2) \cdot e^{kT1} + (Ur2 \cdot (1+COV)/2) \cdot e^{kT2} = COV \cdot Ur \cdot e^{kTeq} \qquad (9)$$

Solving for Teq:

$$Teq = \ln((1-b) \cdot e^{kT1} + b \cdot e^{kT2})/k \qquad (10)$$

$$b = Ur2 \cdot (1+COV)/(2 \cdot Ur \cdot COV) \qquad (11)$$

5.2 Results from laboratory measurements

The concept of an equivalent temperature was tested on a two-unit arrester (type A) in the laboratory. The arrester was heated to temperatures that may be expected after a heavy pollution event with a subsequent energy absorption equal to the rated energy of the arrester. Starting from +20°C, which is a reasonable ambient temperature during conditions of pollution, one arrester unit was heated to +95°C to simulate worst possible uneven heating by pollution. Following the heating of one unit, both units were heated by an additional 75°C to simulate a temperature rise due to absorption of the arresters rated energy. The arrester was then energized at a COV of 0.80 p.u. of rated voltage while cooling down. The resistive current was measured along with the ZnO temperature (by fiber-optic thermometers) in the center of each arrester unit.

Three different tests were carried out on an unevenly heated arrester. In test no. 1, the top unit was heated to simulate pollution effects as described above. In test no. 2, the bottom unit was heated instead. In test no. 3, the top unit was heated to +195°C without any heating of the bottom unit. Test no. 3 is in no way representative of conditions in the field, but was performed only to study the concepts of weighted mean and equivalent temperatures under extreme conditions.

The results from tests no. 1 - 3 are shown in Figures 9 - 11. The top and bottom unit temperatures for the first hour are shown along with the calculated weighted mean temperature from Eq. 1 and the equivalent temperature determined from Eq. 10.

The true thermal performance of the arrester is represented by the "even" temperature curve shown in Figures 9 - 11. This curve represents an evenly heated arrester which has the same resistive current and the same power loss as the unevenly heated arrester under test. The basis for the even temperature curve, i.e. the relationship between resistive current and temperature for an evenly heated arrester, was established by previous measurements on the same arrester.

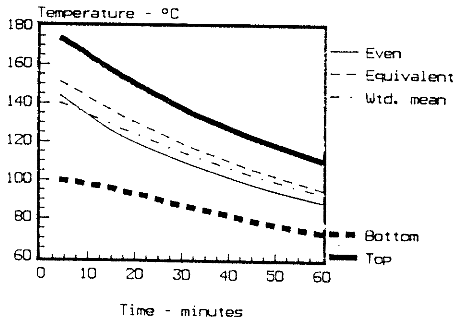

Figure 9. Measured and calculated temperatures in test no. 1.

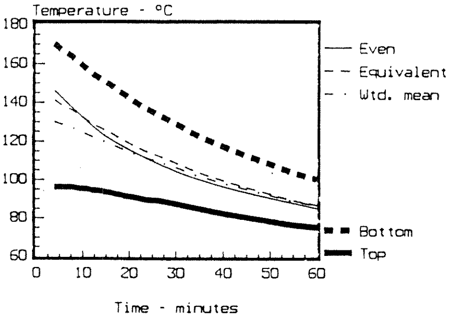

Figure 10. Measured and calculated temperatures in test no. 2.

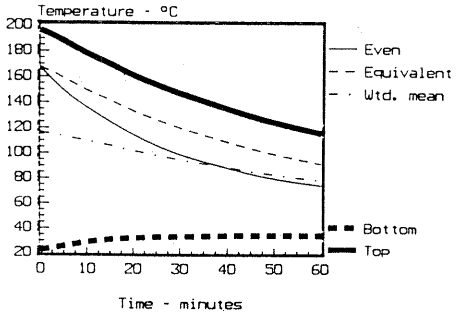

Figure 11. Measured and calculated temperatures in test no. 3.

The efficiency of the equivalent and weighted mean temperatures in estimating the even temperature, i.e. the true thermal performance of the arrester, can be judged from Figures 9 - 11. As seen from Figures 9 and 10, the equivalent temperature is a good, although somewhat conservative approximation of the even temperature. The weighted mean is also a fairly good estimate of the even temperature, except for extremely large temperature differences, as in Figure 11. The equivalent temperature, on the other hand, gives a rather conservative estimate of the cooling performance in this case.

The ability of the arrester to cool down when unevenly heated in polluted conditions was determined by comparing the results from test no. 1 (heated top unit) with results from another test where the arrester was evenly heated (test no. 4). In Figure 12, the even temperature from test no. 1 is compared with the even temperature from test no. 4. The arrester was energized at a COV of 0.80 p.u. of rated voltage while cooling down. It can be clearly seen that the unevenly heated arrester is cooled down somewhat quicker than the evenly heated one. This means that the final part of the operating duty cycle test, i.e. the cooling-down period under continuous operating voltage, will also cover the case of an unevenly heated arrester.

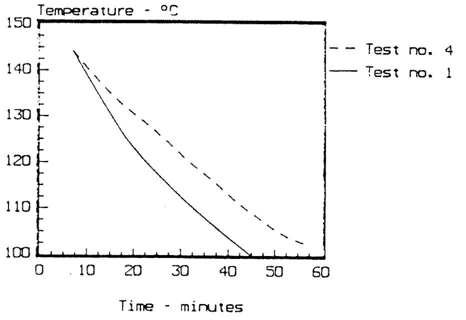

Figure 12. Cooling-down of evenly and unevenly heated arrester.

6. CONCLUSIONS

Extensive fields tests on surge arresters have been carried out in Norway and in France. The most characteristic properties associated with the thermal stress on surge arresters during natural pollution tests have been identified. Based on these properties, the basic requirements on a laboratory test method have been determined in order to obtain thermal stresses similar to those observed under natural pollution conditions.

Among the four laboratory test methods investigated, only two comply with these basic requirements: the slurry test method and the salt fog test method. On the contrary, the solid layer test method and the partial wetting method do not comply with the basic requirements. The solid layer method is characterized by a limited duration of the pollution activity during the test, and, as a consequence, by a limited severity of the test. The partial wetting method is too sensitive to the design of the arrester and will not cause any heating in the lower part of the surge arrester.

The determination of a representative thermal stress to be applied during laboratory tests is based on external charge measurements on a surge arrester under natural pollution conditions. Test results have also shown that it is possible to use an insulator with a similar shape as the surge arrester for these measurements. The use of an insulator with a different profile is not to be recommended.

Extensive laboratory tests have shown that it is possible to choose the test parameters so that the test conditions are similar to those existing in the field, in terms of the external charge accumulation. It is important that the same current threshold is used for both laboratory and field measurements. Based on experience from the various tests reported here, a threshold of 2 mA_{peak} is recommended for the external current.

When using the slurry method, the number of test cycles and the resistivity of the slurry must be properly chosen. During salt fog tests, the severity is not determined by the test salinity, but by other parameters such as the flow of the saline solution and the pressure of the air used in the spraying system. To avoid flashovers, the test salinity must not be too high, however, it must be high enough to avoid an extreme sensitivity of the tests results to possible slight changes in salinity during the tests. A value of 10 kg/m^3 has been used for some tests, and may be recommended.

In order to integrate the effect of uneven heating due to pollution into the standardized type test on surge arresters, the concept of an equivalent temperature was introduced. The equivalent temperature may be used to determine the starting temperature in the operating duty cycle test.

7. REFERENCES

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