EVALUATION OF LIFETIME OF AIR INSULATED SWITCHGEAR VERSUS SERVICE CONDITIONS IN MV SUBSTATIONS

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ABSTRACT

Air insulated switchgears (AIS) are particularly sensitive to environmental conditions of the substation where they are installed. In order to establish the relationship between the state of switchgears and service conditions in substations, it is important to assess the actual service conditions. The three most important parameters influencing the lifetime of switchgears are relative humidity, condensation generated by the temperature instability as well as the pollution level.
The aim of this paper is to give some indication based on a return of 30 years of field in typical Utility environment, in order to assess the expected and remaining lifetime of switchgear installed in DSO's substations.

INTRODUCTION

The degradation mechanisms of an electrically insulating material or system subjected to electrical stresses are very complex phenomena. As a result, there is currently no clear and unambiguous relationship between the results of accelerated aging tests and the actual service life of equipment operating under normal operating conditions. Different methods of accelerated aging on assemblies or components are nevertheless available but only allow a comparison between the solutions designed by the manufacturers.
However, the empirical knowledge of the DSOs and the laboratories working in direct partnership makes it possible to evaluate the aging of the equipment installed in the network under real conditions of service and to compare it with the results obtained by accelerated aging tests on the assemblies and their components.
The basic parameter that influences the aging of electrical equipment is the local electric field present in the most critical places. This one is influenced by several factors related to both the design and the conditions of use of the switchgear: the ratio between the operating voltage and the rated voltage of the equipment, the shape (radius of curvature) of the metal parts between which this electric field is applied, the quality of the insulation and in particular the insulation surface resistance subjected to local tangential fields and the resistance to tracking. Those 2 parameters are influenced by the quality of the insulating materials and by the degradation of their surfaces under the influence of the electric field as well as the pollutants present on the surface. These may be due to external pollution but also to internal pollution of the switchgear produced by partial discharges where the electric field is close to or above the limit of the dielectric strength of the air, taking into account its relative humidity. It should be noted that this limit can be reached for temperatures remaining above the ambient air's dew point (i.e. without condensation). The degradation of the insulation surfaces itself increases the occurrence of tracking currents which amplify the degradation. This phenomenon induces a snowball effect.

Evaluating the aging conditions of switchgear requires first of all a very good understanding of the substation service conditions in which it is installed.

One can observe that the normal conditions defined in the international standard IEC 62271-1, giving the common specifications for switchgears, are very wide.
Indeed, the first parameters influencing the degradation of a switchgear is humidity and moisture. The standard allows an average value of the relative humidity, measured over a period of 24 h, up to 95 %, and over a period of one month, up to 90 %, and considers that condensation can be expected where sudden temperature changes occur during high humidity periods, and therefore does not exclude this phenomenon.

For DSOs, this statement is quite important because it does not require temperature regulation in the thousands of secondary substations. This would be unpayable, would increase substantially the price of energy for the end customer and would go in the opposite direction to the rational use of energy prescribed by the European directive.

On the other hand, primary substations have an essential function in the network and are much less numerous than secondary substations. This is why temperature control is generally used in these substations.

MEASURING CAMPAIGNS

Temperature and Humidity monitoring

In order to evaluate the actual conditions in substations connected to the grid, it is necessary to carry out measurement campaigns. This has been done for a whole year in several primary and secondary substations.

The first type of measurement campaign is based on continuous monitoring of temperature and relative humidity, as well as monitoring of the ultrasonic signal generated by partial discharges in the most critical inspected substations. This campaign is fairly representative of the installed base and comprises about 25 primary substations and 25 secondary substations. Some of the equipment installed in these substations was inspected to assess their aging condition.

This campaign during one year gave the following results for the primary substations:

Value ≤ Limit of the standard - 5 units

Limit - 5 units < Value ≤ Limit of the standard

Value above limit

Elia substations	T_{mean} (°C)	T (°C)	Max(T24h)	Max(Rh24h)	Max(Rh1m)
	---	≤ 40 °C	≤ 35 °C	≤ 95 %	≤ 90 %
Aalter Terlaken	23,2	30,0	29,4	75,6	68,0
Bascoup	21,5	31,5	30,8	66,2	59,1
Bévercé	18,4	27,5	26,2	74,8	64,9
Blankenberge	21,9	31,5	29,8	75,0	64,7
Burcht	19,6	29,5	28,9	78,5	74,4
Héliport	27,4	34,5	33,9	63,6	55,5
Knokke	19,3	33,5	26,9	77,0	65,3
Marche-lez-Écaussines	20,5	27,0	26,4	83,2	74,8
Menen West	18,7	30,0	28,8	82,2	77,6
Merelbeke 1 oud	17,6	26,5	26,4	79,9	74,3
Merelbeke 2 nieuw	24,3	31,5	31,0	65,3	60,3
Midi	21,2	33,5	32,8	69,4	60,1
Putte	20,1	40,5	38,9	83,6	72,7
Rijkevorsel 1	21,9	34,5	30,5	75,5	64,3
Rijkevorsel 2	18,3	34,5	29,2	81,7	74,8
Schaarbeek	20,7	29,0	28,5	72,5	57,6
Sclessin	17,4	27,5	26,5	84,9	81,3
Trois Ponts	16,0	28,0	26,3	82,2	76,6
Wiertz	19,6	24,5	23,9	77,1	65,5
Bilzen	20,5	25,5	25,5	86,5	84,8
Borgloon	20,5	30,5	29,3	82,3	78,5
Sint-Truiden	21,8	29,5	29,1	70,7	66,6

Table 1 Mean temperature for one year, maximum temperature on this year and maximum mean temperature per 24 h, maximum value over one year of the mean value of the relative humidity for 24h and for 1 month.

Furthermore, a simulation of the risk of condensation on components of the switchgear based on a real time monitoring of the temperature and the relative humidity shows that no condensation occurs during the entire year for most of those substations, except for 2 of them, Menen West and only once a year for Rijkevorsel 2.

For secondary substations, the relative humidity is generally somewhat higher, but remains within the range of normal service conditions. They may be out of normal service conditions when the equipment is installed in metal substations or in a compact substation where no transformer is present.

Value ≤ Limit of the standard - 5 units

Limit of the standard - 5 units < Value ≤ Limit of the standard

Value above limit of the standard for normal service conditions

Type of construction **with tranformer without heating**	Quantity of this type	Range of max instantaneous T (°C)	Range of Max(T_{mean} 24h)	Range of Max(Rh_{mean} on 24h)	Range of Max(Rh_{mean} on1month)
		≤ 40 °C	≤ 35 °C	≤ 95 %	≤ 90 %
Brick	4	28,0 - 34,5	26,8 - 31,8	81,8 - 88,8	63,5 - 75,5
Brick	1	32,5	30,7	91,5	81,6
Underground	2	27,0	25,4 - 26,5	82,1 - 82,3	61,6 - 74,6
Underground	1	27,5	27,0	91,1	89,4
In building	3	30,0 - 33,5	29,4 - 32,5	49,6 - 59,6	43,3 - 52,2
In building	2	27,8 - 29,5	25,0 - 29,4	61,2 - 69,7	51,3 - 66,5
In building	2	23,5 - 25,0	22,8 - 24,3	88,9 - 89,6	75,1 - 85,0
Concrete prefabricated not enterable	1	38	25,1	92,8	90,0
Concrete prefabricated enterable	1	35,0	29,5	90,9	81,1
Type of construction **without tranformer without heating**	Number of this type	Range of max instantaneous T (°C)	Range of Max(T_{mean} 24h)	Range of Max(Rh_{mean} on 24h)	Range of Max(Rh_{mean} on1month)
Brick	1	30	28,8	100	97,3
Underground	1	30,5	30,2	98,5	95,0
Concrete prefabricated enterable	6	9,5 - 24,5	8,7 - 15,3	95,7 - 100	90,6 - 99

Table 2 Ranges of maximum relative humidity and temperature values in secondary substations in function of the type of substation

All of these measured secondary substations equipped with transformer but without heating were in the normal service conditions of the standard for the temperature and humidity level. When the mean value on 24h of the relative humidity level were close to the limit, (in orange in the table 2), condensation occurred a few times a year, or often for the substation without transformer and without heating, with this humidity level above the limit of the standard (in red in the table 2).

Pollution measuring campaign

Standard IEC 62271-1 defines the pollution level permitted under normal operating conditions as being "very light" in accordance with IEC 60815-1. This standard on high voltage isolators for use in polluted conditions provides methods for measuring pollution levels and can be used for indoor measurement.

For this purpose, to have a view of these levels in the primary substations, a measurement campaign is carried out. Measurements will continue during 2017.

In this standard, the level of pollution is given by the combination of deposition of non-soluble dust (NSDD) and deposition of equivalent soluble dust (ESDD) over one year. The values for NSDD and ESDD are the maximum values of regular measurements over a time period of a minimum of one year.
The method is well described in the standard in order to have reproducible measurements.
Samples of dust deposits were taken and examined for a number of primary substations on the Belgian network to

be representative of the service conditions that may be encountered.

As can be seen on the map below, some of them are on the coastal zone, others in the city and in the industrial environment, and others in the countryside.

Figure 1 geographic situation of the substations in which the pollution was measured

The following table gives the measurement results for those substations.

Sample Nr	Substation	ESDD [mg/cm² year]	NSDD [mg/cm² year]	SPS normalised per year
1	Heid de Goreux -1	0,0053	0,00490	Very light
2	Heid de Goreux - 2	0,0043	0,00644	Very light
1	Heid de Goreux -1	0,0185	0,00490	Light
2	Heid de Goreux - 2	0,0161	0,00644	Light
3	TS Sint denijs westrem	0,0026	0,00622	Very light
4	TS Sint denijs westrem	0,0054	0,02156	Very light
5	Chiny	0,0183	0,01499	Light
6	Chiny	0,0094	0,04693	Very light/light
7	Chiny	0,0078	0,01760	Very light
8	Trois pont 24/08/2016 ech. 1	0,0015	0,01496	Very light
9	Trois pont 24/08/2016 ech. 2	0,0020	0,01067	Very light
10	Trois pont 24/08/2016 ech. 3	0,0017	0,01356	Very light
11	Recogne 26/08/2016 ech. 1	0,0011	0,01022	Very light
12	Recogne 26/08/2016 ech. 2	0,0012	0,00695	Very light
13	Beverce 29/08/2016 ech. 1	0,0017	0,01684	Very light
14	Beverce 29/08/2016 ech. 2	0,0009	0,01541	Very light
15	Beverce 29/08/2016 ech. 3	0,0011	0,01253	Very light
16	Ville s/ haine 30/08/2016 ech 1	0,0025	0,00232	Very light
17	Ville s/ haine 30/08/2016 ech 2	0,0017	0,00405	Very light
18	Burcht ech 1	0,0020	0,01278	Very light
19	Burcht ech 2	0,0017	0,00627	Very light
20	Petrol ech 1	0,0006	0,00085	Very light
21	Petrol ech 2	0,0008	0,00137	Very light
22	Petrol ech 3	0,0020	0,00644	Very light
23	Merksem-Staal ech 1	0,0023	0,00598	Very light
24	Merksem-Staal ech 2	0,0010	0,00308	Very light
25	Merksem-Staal ech 3	0,0063	0,01625	Very light
26	Sclessin Cel 1.07	0,0010	0,01483	Very light
27	Sclessin Cel 1.10	0,0024	0,00787	Very light
32	Blankenberg 1	0,0034	0,00747	Very light
33	De Haan 1	0,0026	0,00706	Very light
34	de Haan 2	0,0014	0,00312	Very light
35	Knokke 1	0,0061	0,01756	Very light
36	Knokke 2	0,0032	0,01597	Very light
37	Knokke 3	0,0031	0,01550	Very light
38	Aalter 1	0,0021	0,03234	Very light
39	Aalter 2	0,0021	0,01084	Very light
40	Meneen west 1	0,0046	0,01782	Very light
41	Meneen west 2	0,0024	0,00428	Very light
42	Meneen west 3	0,0018	0,00478	Very light

Table 3 Measurement of pollution level in a sample of substations giving the value of ESDD and NSDD and the result in pollution level following IEC 60815-1

The values of ESDD and NSDD are corrected for a duration of one year in function of the duration before the first sample collection or between sample collections.

As can be seen, most of the samples taken from these substations, even in the coastal area, show a "very light" pollution level. Only two substations have a "light" pollution and these are new substations for which the samples were taken a few months after the installation, without having cleaned the cells after the installation, thus with the presence of dust brought by the workers during the installation work. Additional samples will be taken in 2017. The installation is normally cleaned inside the cubicles by the manufacturer or its subcontractor prior to commissioning.

The low levels of pollution observed are probably due to the good protection of the installation by the substation building. There is relatively little energy loss and the ventilation required for such large rooms is really limited, just to ensure air renewal and to avoid moisture.

No similar campaign has yet been carried out for secondary substations, but the risk of achieving higher pollution levels in a polluted environment should be taken into consideration as the ventilation openings are much larger in proportion to the volume of rooms. In secondary substations with small ventilations, the risk of humidity is higher because unheated or exclusively heated by losses of transformer.

OBSERVATION OF THE STATE OF SWITCHGEAR

Some primary switchgear types presented by manufacturers as being compatible with normal service conditions as described in the standard IEC 62271-1 show significant degradation of their insulation and their metal parts already before reaching ten years of service in substations where the measurement campaigns described above have assessed that the ambient conditions are normal according to IEC 62271-1.

Figure 2 Tracking currents on insulating surfaces where high tangential electrical-fields are present.

Premature degradation of equipment is due to excessively high local electric fields. It is always the most critical location that limits the life of the entire equipment. As already explained above, this most critical electric field is a function of the chosen design (shape of the conductive parts, phase-to-ground and phase-to-phase distances) as well as a function of the rated voltage of the apparatus. The actual local electric field can also be increased by a lower quality and degradation of the insulating components as well as by the actual operating voltage. The influence of this local electric field is increased by the relative humidity of the fluid (ambient air for AIS) around these parts, and by pollution by dust deposits.

The ratio between the rated voltage and the actual service voltage has a significant influence on the local electric field. A handicap for the Belgian network is the operating voltage often between 15 kV and 16 kV, leading to the use of devices with a rated voltage of 17.5 kV. Most manufacturers do not develop a special design for this rated voltage but, especially for AIS, improve a 12 kV design by adding insulating components, increasing phase-to-ground and phase-to-phase electrical distances to pass the lightning impulse withstand voltage test. This policy has the advantage of reducing the costs and dimensions of the equipment but the big disadvantage of introducing additional insulating elements on the surface of which tangential electric fields are present.

The combination of poor design causing a high local electric field such as 2.5 kV / mm (calculated for new equipment) and a relative humidity above 60% for new equipment, or even greater than 40 % for an already degraded installation, leads to the generation of partial discharges.

An example is given below by monitoring ambient relative humidity, temperature and several measurements of ultrasonic signals generated by partial discharges, for different locations of local fields that are too high. The relationship between partial discharges and the relative humidity of the ambient air can be seen for a relatively degraded primary switchgear.

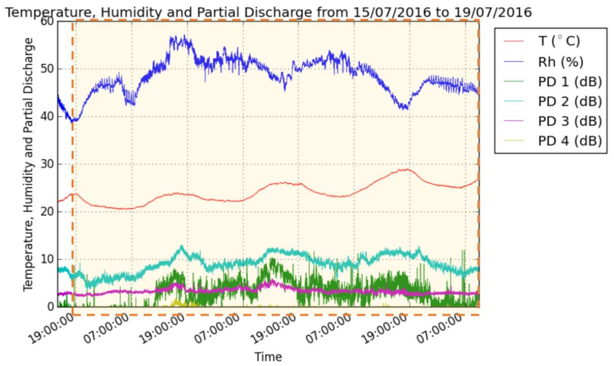

Figure 3 Monitoring of ultrasonic signals generated by partial discharges (PD1to PD4) from busbar compartments of a switchgear, temperature (red curve) and relative humidity (blue curve).

In the figure below, we can see on an AIS equipped with switches and a busbar in the ambient air, the Corona effect due to the poor quality of the insulating plates between the cubicles for a relative humidity around 80%. This material has a very low resistance to tracking current and this rapidly leads to a high local electric field on the air gap around the busbar. This Corona effect produces ozone that combines with the nitrogen in the air to produce nitric acid. This acid also attacks in a second step the weakest components of the switch.

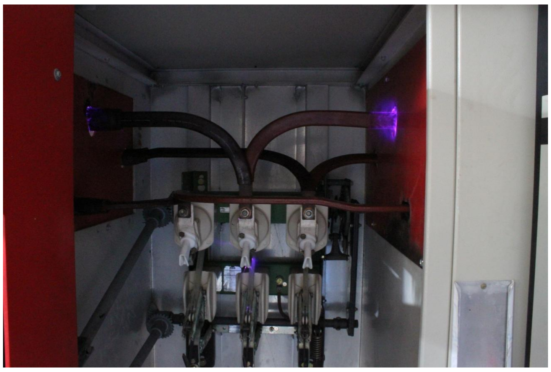

Figure 4 AIS equipped with switches and a busbar in ambient air – Corona effect around the busbar going through the insulating plate and on the insulating rod of the switch.

For this apparatus, a test was carried out to demonstrate the influence of the relative humidity rate on the activity of the partial discharges. This influence is illustrated in the figure below. One can see on this graph the 25 dB difference between wet and dry conditions. The breakdown occurred at 20kV for a level of 50 dB.

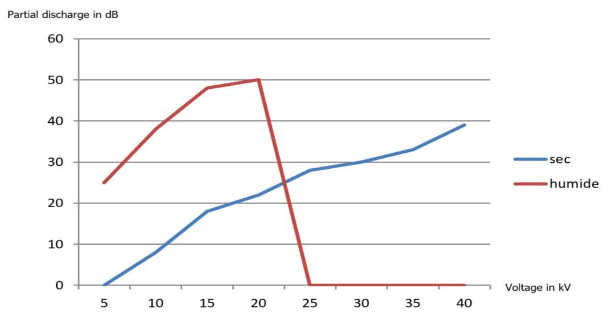

Figure 5 The red curve shows the influence of the service voltage on the level of partial discharges (ultrasonic measurement) in humid air (85%) and the blue curve for rather dry air (50%), for a 12 kV switchgear.

In a secondary substation in bricks without ventilation and equipped with small transformer, the relative humidity was mostly between 60% and 80%. Partial discharges appeared after about 12 years.

Figure 6 Trace of tracking currents on the insulators in the vicinity of the active parts.

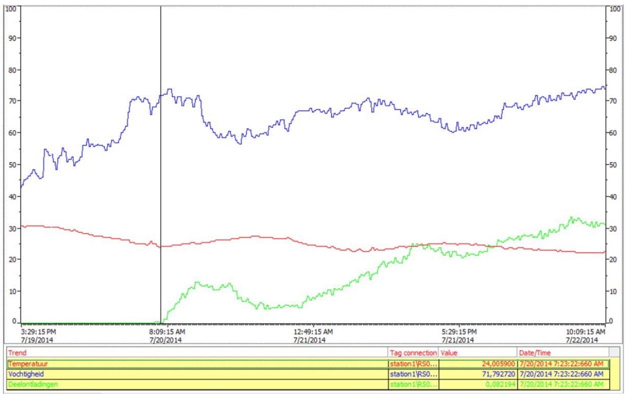

Figure 7 PD, temperature and relative humidity monitoring in a secondary substation – AIS after 12 years

It can be seen from the graph above that PDs appear when the relative humidity exceeds about 60%. The tracking current withstand of the above insulator material (tested in accordance with IEC 60587) is much lower than that of the example shown in the figure below, of a cycloaliphatic vessel epoxy material of a load break switch.

Figure 8 Very poor service conditions in an underground substation and very high quality of insulation – no tracking current unless rather short creapage distances (confirmed by tracking test)

We made a lot of comparisons between the switchgear states in real service conditions on the grid after a certain lifetime and the same switchgear after a test at severe climate conditions for the level 2 according to technical specification IEC 62271-304, and this mainly for switchgear installed in secondary substations. This comparison led us to the conclusion that it is rather difficult to give a single value of expected lifetime for the whole range of service conditions which respect the normal conditions of services as defined by the standard.
Nevertheless, based on the results of this severe conditions test, and on tests of the most critical insulating components of a switchgear, it is possible to foresee an expected lifetime for a switchgear placed in well-defined service conditions.

CONCLUSION

The definition of normal service conditions is quite broad and covers a large number of actual situations. The behaviour of a switchgear in a room with a relative humidity of less than 50% is quite different from that observed in an environment of more than 80% relative humidity.
We observed on a large sample of situations that the condition of a switchgear after 7 weeks aging test (level 2 in accordance with IEC 62271-304) was not far from its condition after seven years under normal service conditions in not heated substations with transformer with an average relative humidity value between 70% and 80%, which is most often the case in the secondary substations in Belgium.
This technical specification IEC 62271-304 does not claim to guarantee a lifetime of the tested switchgear. The level 2 test under severe conditions described in this technical specification does not provide a lifetime of 30 years under all normal service conditions, but this may be the case for operating conditions with a relative humidity rate of less than 60%, with a level of pollution "very light". Failure of this level 2 test however shows that a switchgear design is not suitable for 30 years lifetime in normal service conditions according to IEC 62271-1, and certainly not for relative humidity level above 60%. To simulate 30-year aging under actual service conditions, it should be necessary to increase the conductivity of the water measured in the test room and possibly increase the duration of the test for some more weeks.

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