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STATE-OF-THE-ART CONCEPTS OF INSULATOR STRINGS FOR HVDC LINES

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1. INTRODUCTION.

HVDC insulators have to support specific electric stresses when compared with HVAC insulators. This is due mainly to a unidirectional flow of electric current and to a non-homogeneous electric field distribution along insulator strings leading to an uneven deposit of pollution. If these stresses are not properly taken into consideration in DC insulator design, they can lead to electric and thermal stress conditions which can cause rapid dielectric material degradation, failure by thermal puncture of cap and pin insulators, overly frequent contamination flashover and severe corrosion damage to metal parts.

Since they have the same basic conception, HVDC insulators must comply in general with the main standards used for AC High Voltage suspension insulators, such as IEC 383, BS 137, ANSI C29-1 and C29-2 ... They must undergo successfully different tests and inspections which check their ability to withstand electrical, mechanical and thermal stresses. Most of these tests can apply both to HVAC and HVDC insulators as they check mechanical reliability and insulator string performance under impulses. In addition to these standard tests, extra tests can be useful to evaluate the behaviour of suspension insulators : thermal-mechanical tests as described in IEC 575 (and which will be introduced in the revision of IEC 383), steep front impulse tests and residual mechanical strength tests allow the selection of high quality materials.

This paper presents the state-of-the-art concepts introduced by SEDIVER in their up-to-date cap and pin toughened glass HVDC insulators.

2. IMPROVEMENT OF THE PERFORMANCE OF DC INSULATOR STRINGS.

2.1. Improvement of the dielectric material.

Insulator dielectric shells, whether made of glass or porcelain, exhibit a form of ionic conductivity. Under DC stress, which is inherently unidirectional, alkali ions within these materials migrate through the silica network which forms the "frame" of glassy materials. The glassy phase represents about 50 % in volume of the currently used porcelain for AC and DC applications. Ionic conductivity depends mainly on temperature, but is also a function of the amount of alkali ions and the nature of the alkalis present. Research work has linked ionic conductivity under DC stress to several possible insulator failure mechanisms, of which two are particularly important : thermal runaway and ionic migration [1].

* Thermal runaway mechanism.

When the resistivity of an insulating material decreases as the temperature increases, this material can, under certain conditions, undergo thermal runaway.

The first condition is that the electrical power dissipated inside the dielectric material by Joule effect has to be greater than the thermal power that the dielectric material can exchange with its environment. The other condition is that the object must be sumitted to a constant voltage so that the electrical power can increase as the temperature rises :

$$P = \frac{U^2}{R(T)} \quad (1)$$

P : Electrical power (Watt)

U : Voltage (volt)

R(T) : Ohmic resistance of the insulator at temperature T with

$$R(T) = \rho(T) \frac{L}{S} \quad (2)$$

S : Dielectric surface under electric stress

L : Dielectric thickness

$\rho(T)$: Resistivity of the material at temperature T with :

$$\rho(T) = \rho_0 . e^{K/T} \quad (3)$$ (example in fig. 1)

K : Coefficient expressing the variation of the resistivity with temperature (Kelvin)

$$\text{and } P = \frac{U^2}{\rho(T)} \times \frac{S}{L} \quad (4)$$

The severity of this mechanism can be greatly reduced by using high resistivity material as shown in equation (4). In glass, partial replacement of soda by potash can increase the resistivity by several order of magnitude (bi-alkali effect). Laboratory thermal runaway tests have been performed on F 16 P insulators (mechanical rating 160 kN, anti-fog type) made with a previous type standard DC glass and with a new high resistivity DC glass, which is 100 times more resistive in service conditions.

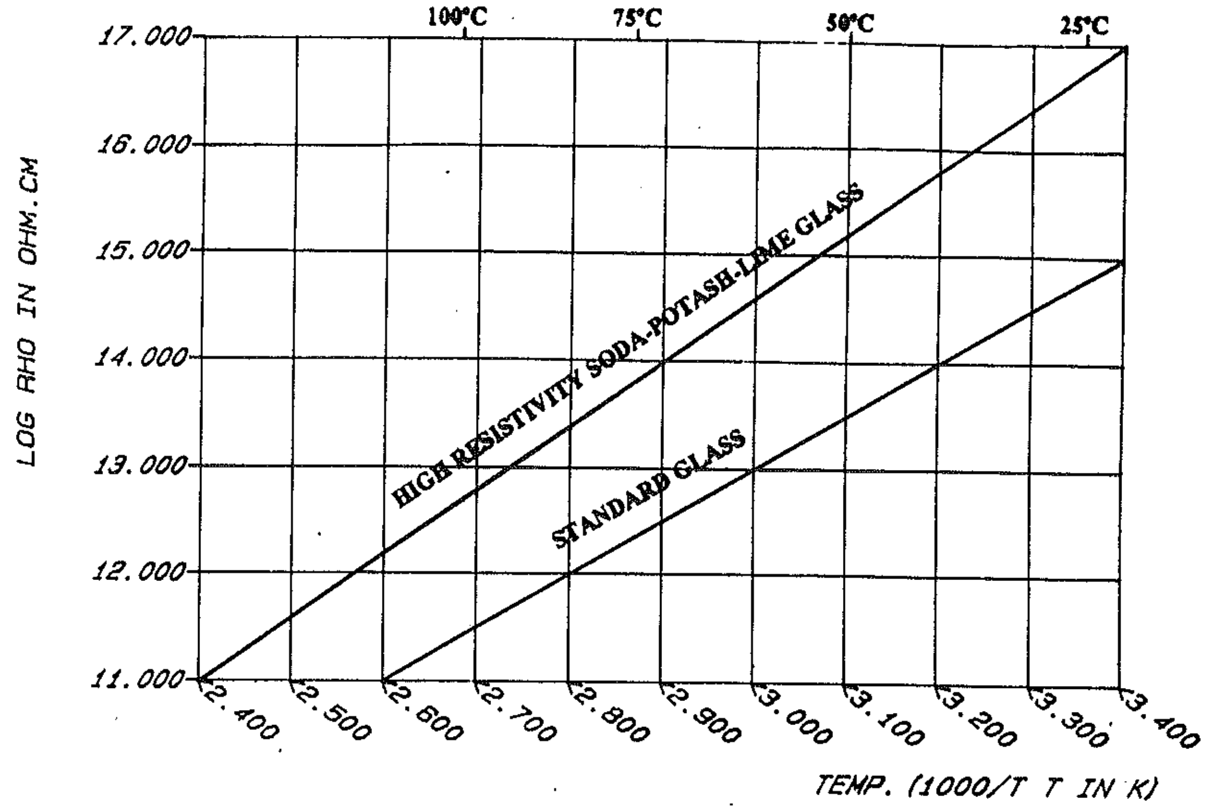


Figure 1. DC resistivity of glasses as a function of temperature.

In this thermal runaway test, the insulators were placed in an oven ; the temperature was raised by steps of 10° C and maintained at each level during 3 hours for a good homogenization, then for 3 more hours 80 kV were applied. The temperature was raised until puncture occured. The previous standard HVDC glass failed with an oven temperature of 100° C and the new high resistivity glass with an oven temperature of 150° C.

This failure mechanism is obtained in laboratory tests with a constant applied voltage. In an insulator string, the mechanism is different. If an insulator begins to run away, the internal temperature rises, leading to a reduction of its resistance. The current is limited by the ohmic resistance of the other units of the string and is almost constant. Thus the voltage accross the insulator decreases, which implies a reduction of the electrical power in the dielectric. A thermal equilibrium is therefore attained without puncture of the dielectric. However high thermal stresses can develop locally.

Examination of failed insulators from operating lines and various laboratory studies have shown that interaction of the unidirectional current flow with discontinuities in dielectric material structure can lead to shell failure, explained by a rapid temperature increase leading to increased current flow in the flawed region of the dielectric shell and to high thermal stresses.

* <u>Ionic migration mechanism</u>.

Due to the structure of glass and to the nature of alkali ions, an ionic migration under DC stress is an unavoidable phenomenon which may create a modification of the glass structure as described in various papers : formation of a depletion layer where all the Na^+ cations have moved out under the effect of the electric field [2] or accumulation of ions at heterogeneities [3]. In the laboratory, it is possible to verify the capability of the insulators to withstand the ionic migration.

Before testing, the quantity of electric current passing through the dielectric body of an insulator is calculated. The calculation is performed on an insulator, designed to withstand the charge passing through the insulator body for a designed life-time of 50 years. This charge is calculated from information about the temperature of the insulator and its environment, the insulator's resistance and their variations with time and the amount of voltage which is likely to occur. according to the following equation :

$$Q = U \int_0^{\tau} \frac{1}{R\ (t)}\, d\tau$$

Q : Charge (Coulomb)

U : Average value of the line to ground voltage (volt)

R (t) : Resistance of the insulating body as a function of temperature (ohm)

τ : time

An insulator manufactured with a high resistivity glass for example 100 times more resistive, would be submitted to a flow of current 100 times lower. Therefore the electrical ageing due to ionic migration would be reduced by a factor of 100. Laboratory test have confirmed the improvement of the behavior of high resistivity toughened glass insulators.

In January 1989 the IEC Technical Board set up a Working Group of the Sub-Committee 36B whose task is to define the characteristics of ceramic material or glass insulators for HVDC overhead lines and to prescribe testing conditions. Three meetings have been held in WINNIPEG (Oct. 89), FRANKFURT (May 90) and PARIS (Sept. 90). This group of experts (including SEDIVER and NGK specialists) is paying peculiar attention to specific DC tests to be performed on various types of cap and pin insulators to check their behaviour versus thermal runaway and ionic migration. Complementary tests to check their reliability are also under discussion :

- Steep front of wave impulse test
- Residual mechanical strength test
- Thermal mechanical test
- SF6 puncture test

2.2. Improvement of the dielectric shape.

The unidirectional electric field associated with direct current has another adverse effect on suspension insulator performance : an accumulation of contaminants considerably heavier than with alternative current is observed. The molding process used for SEDIVER glass shell production permits thin and deep ribs on the lower surface of the shell ; a superior leakage efficiency of this design increases the contamination withstand voltage.

Artificial pollution tests have been performed on various strings according to the two main techniques used world wide.

- The salt fog test : at the time of the preparation of the technical specifications for the HYDRO QUEBEC ± 500 kV DC James's Bay Line, salt fog tests were performed at IREQ on vertical strings of 24 insulators (type F 16 P 13/170 DC), at negative polarity (which is the more severe) with a salinity of 5 kg/m^3. The withstand voltage according to the rapid flashover method or to the IEC 507 method was 22.9 kV/insulator or 135 kV/meter of string. This result was superior to the results obtained on equivalent porcelain insulators.

- The cLean fog test : this test was a part of the type tests requested by NTPC in the RIHAND-DELHI ± 500 kV DC line technical specifications [4] . It was performed at the EPRI High Voltage Transmission Research Center in LENOX (USA), with an average ESDD of 0.045 mg/cm^2 at negative polarity on a complete Vee string and a quadruple dead-end string made of insulators F 16 P / 170 DC.

The withstand voltage of the Vee strings with various fittings was in the range of 720 to 740 kV or 19 to 19.5 kV/insulator or 111.5 to 114.5 kV/meter of string. In the case of the quadruple dead end string, the withstand voltage was lower, 630 kV or 16.6 kV/insulator or 97.5 kV/meter of string, but still with a large safety factor versus the nominal 500 kV voltage.

2.3. Improvement of the metal fittings.

DC leakage current on the surface of a wet and contaminated insulator shell causes electrolytic action involving the pin surface close to the cement line ; a severe erosion of the pin material occurs : by-products of the corrosive attack cause pin expansion and the resultant mechanical stress can cause shell cracking in the head area [5]. The high tensile strength of toughened glass resists much higher stress than porcelain without shell cracking. A thick section of cast-on zinc sleeve on steel pins acts as "sacrificial anode" and completely protects the pin against erosion. In addition, "cement growth" is prevented because the predominant compound in SEDIVER aluminous cement is chemically inert.

The result of electrolytic activity involving the cap is a removal of the zinc plating and a consequent corrosion of the iron material of the cap body. Due to the washing action of rain-falls, rust from the cap is deposited on the shell ; this condition is linked to the high rates of shell failures on operating lines. A cast-on zinc collar on insulator caps becomes a "sacrificial anode" and prevents erosion of the material (fig.2)

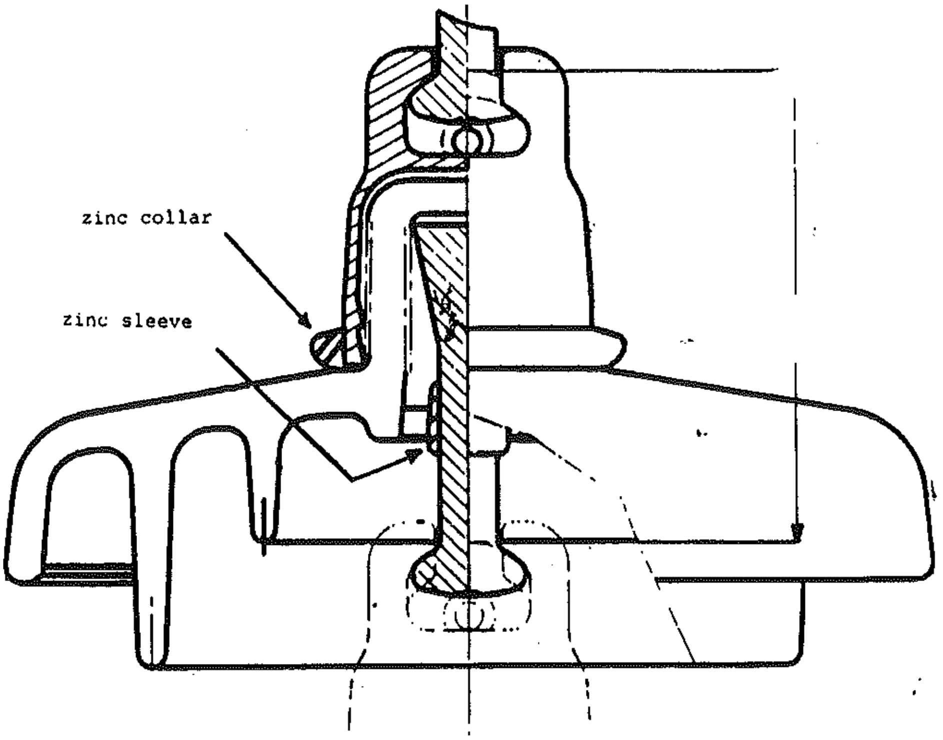


Figure 2. High Resistivity Toughened Glass insulator type F 16 P/170 DC.

2.4. SEDIVER DC test station.

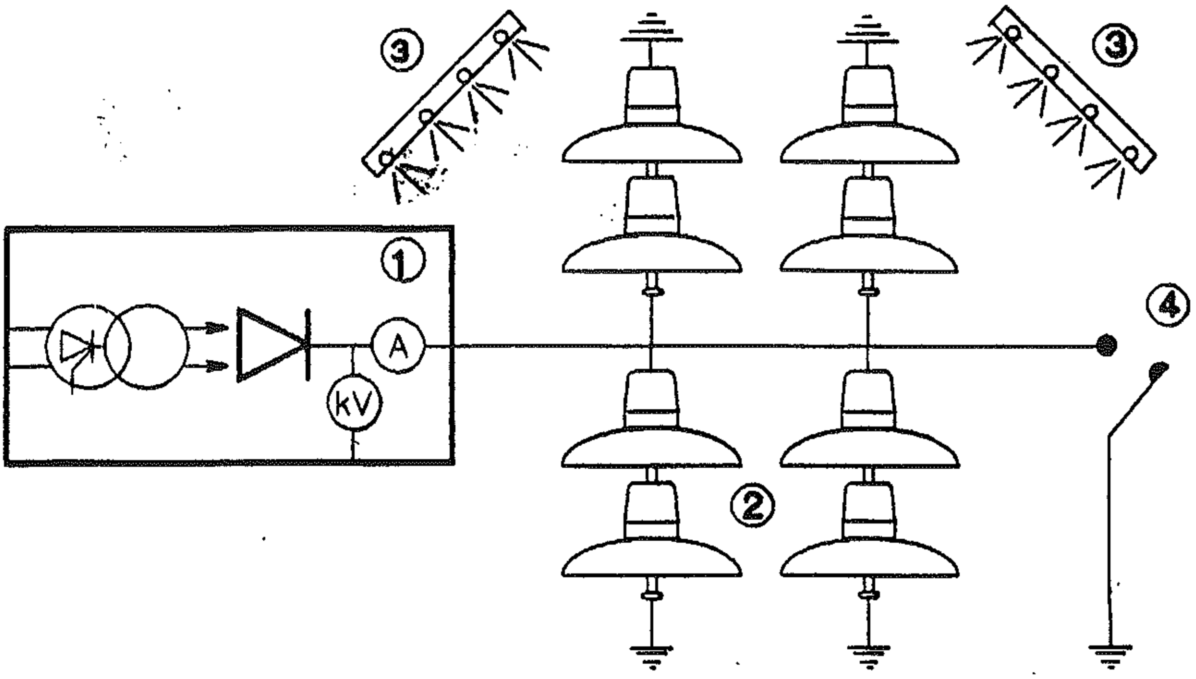
Hundreds of High Resistivity Toughened Glass insulators have been installed in the SEDIVER DC long duration test station (figure 3). This open air test station of 220 m^2 surface is located in a fenced-off part of the factory ; one thousand insulators can be energized through a DC supply (50 kV-5A). An intermittent salt spray is applied with automatic cycles ; the salinity can be adjusted (usually 2.5 kg/m^3 is used). The average permanent electric stress is about 10 kV/insulator. Thanks to the improvement of the fittings, there is no trace of corrosion of the metal parts in spite of 3 years of cycles of salt spray while ordinary metal fittings are corroded in one month in such conditions.

UP TO DATE FIELD EXPERIENCE WITH HIGH RESISTIVITY TOUGHENED GLASS INSULATORS ON HVDC LINES.

After a large period of testing High Resistivity Toughened Glass (HRTG) insulators in the Laboratory and test stations, industrial manufacturing of these insulators began in 1985.

Today about 630.000 HTRG insulators are installed on 6 DC projects. The recorded failure statistics at the end of 1990 of these insulators are reported in table I.

AIRE EXTERIEURE D'ESSAIS COURANT CONTINU - CIRCUIT D'ESSAIS
OUTDOOR DC TEST STATION - TEST CIRCUIT



① Générateur à courant continu Universal Voltronics, Modèle:BAL-50-5000
0 - 50kV - 5A - Polarité positive
Universal Voltronics direct current supply, Model:BAL-50-5000
0 - 50kV - 5A - Positive polarity

② Objets en essai en parallèle
Test objects in parallel

③ Arrosage automatique règlable (cycle - conductivité)
Automatic adjustable spray system (cycle - conductivity)
2 min/h - 230 ohm.cm

④ Mise à la terre extérieure de sécurité
Exterior safety earthing switch

Figure 3.

Table I

Country Utility	Line terminals or project name	Voltage (kV)	Line Length (km)	Total units installed	Period of survey	Annual failure rate per 10.000	Date of commis-sioning	Comments
BRASIL (FURNAS)	ITAIPU II (North route)	± 600	816	190.000	88 89	3.5 3.2	1987	Initial annual failure rate on standard DC glass insulators supplied in 1983 : 17.9
CANADA (HYDRO QUEBEC)	Radisson-Nicolet des Cantons	± 450	1100 (40%Sed.HRTG)	226.400			early 1991	
INDIA (NTPC)	Rihand-Delhi	± 500	850 (40%Sed.HRTG) (60% Porc.)	183.300		N.A	end 1990	
DENMARK (ELSAM)	Skagerrak	± 250	85	19.200	88 89 90	0 0 1	1988	Initial annual failure rate on standard DC glass insulators supplied in 1976 : 56
FINLAND (IMATRAN VOYMA OY)	Rihtniemi-Rauna	± 400	33	9.500		N.A	1989	
NEW ZELAND (TRANSPOWER)		± 250		1.000	88 89	0 0	1987	Heavy polluted area (South Island)

HRTG . High Resistivity Toughened Glass
NA . Not Available

The average yearly rate of failure is very low and almost identical with the failure rate observed on HVAC lines and notably lower than the failure rate observed with previous DC glass supplied before 1985. The results can be explained not only by the use of a high resistivity material, but also by an improvement of the elimination of inhomogeneities or inclusions in the glass manufacturing process.

4. CONCLUSION.

DC line insulators operate in an environment completly different from AC insulators. Experience in service, starting with railways in the 1930's, and continuing with various DC lines in the 60's and 70's have shown that this environment is much more severe : more pollution leading to corrosion of the metal fittings, failure of shells, ...

A study of the mechanisms leading to failure of shell has shown that the interaction of the unidirectional current with heterogeneities in the structure of the dielectric material and the corrosion of metal fittings explain most of the problems.

A new generation of insulators with high resistivity material to reduce the unidirectional current, improved protection of the metal fittings and high quality material to eliminate harmful heterogeneities, has been developed and thoroughly tested. Experience in service, starting in 1987 has demonstrated a complete success : the failure rate has been reduced to a negligible level.

The standards and specifications for HVDC suspension insulators must require these improvements to guarantee a trouble-free operation of HVDC lines.

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UP TO DATE DATA (August 1991)

COUNTRY UTILITY PROJECT	VOLTAGE (kV)	LINE LENGTH (km)	TOTAL UNITS INSTALLED	PERIOD OF SURVEY	ANNUAL FAILURE RATE PER 10 000	DATE OF COMMISSIONING
BRASIL (FURNAS) ITAIPU II	± 600	816	190.000	87 88 89 90 91]	0.6 3.5 2.8 NA NA	1987
CANADA (HYDRO QUEBEC) RADISSON-NICOLET DES CANTONS	± 450	1100 (40% sed. HRTG)	226.400	(6 months) 91	0	early 1991
INDIA (NTPC) RIHAND-DEHLI	± 500	850 (40% sed. HRTG) (60% Porc)	183.300	(6 months) 91	0	end 1990
DENMARK (ELSAM) SKAGERRAK	± 250	85	19.200	88 89 90 91	0 0.5 2.6 0	1988
FINLAND (IMATRAN VOYMA OY) RIHTNIEMI-RAUNA	± 400	33	9.500	90 91	4.2 2.1	1989
NEW ZELAND (TRANSPOWER)	± 250		1.000	88 89 90 91	0 0 0 0	1987

Note : From August 91 to December 92, the failure rate level has been reported as negligible by the various utilities.