8TH SOUTHERN AFRICA
REGIONAL CONFERENCE

14 - 17 NOVEMBER 2017

"**Electricity Supply to Africa and Developing Economies …. Challenges and opportunities."**

Technology Solutions and Innovations for Developing Economies

Air Breakdown Voltage Decreases as Altitude Increases- A Review of HV Insulator Test Results from Chinese Experiments

P NAIDOO, C NYAMUPANGEDENGU, I R JANDRELL

The University of the Witwatersrand

South Africa

Summary: Air is the major insulation in electrical power systems. As an example, in overhead powerlines, the air gap dielectric strength between energised conductors and between the conductors and earth determines both the design specifications and operational performance of the system. The dielectric strength of air is a function of the air density (pressure and temperature) and humidity. The disruptive discharge voltage for a given air gap increases with increase in either air density or humidity. The IEC and IEEE standards have provided guidelines and correction factors for the design of air gaps and external insulation for varying altitudes. However, several studies have shown that the "cookbook" approach in the use of the standards and guidelines has significant limitations. Furthermore at altitudes exceeding 1800m above sea level, the standards are known to be inapplicable.

In Africa and other developing economies, expansion of the electric power transmission infrastructure is imperative. The developments however inevitably entail transferring large power over long distances and through challenging environmental conditions such as high altitude terrains. In that regard it is necessary to build up knowledge through research on the understanding of air breakdown mechanisms at high altitude. Over the last three decades, The People's Republic of China had embarked on longer distance and higher voltage power transmission development for both alternating and direct current voltages. Faced with the inadequate knowledge of the air dielectric strength phenomena at high altitude, the Chinese elected to perform both laboratory and field tests at varying altitudes as additional input to their design and engineering standards for power transmission development.

This paper reviews selected experiments as performed at the various test sites across China. The recommendation is that further work be done in mathematically modeling the air breakdown process as altitude increases; specifically to focus on the very small air gap (mm) between consecutive sheds of the insulator. The hypothesis is that the pre-breakdown corona in the gaps sets in motion a cascading avalanche leading to complete flashover.

Keywords — Altitude, Air Pressure, Air Gaps, Insulators

Introduction China leads and Africa follows in large scale continental high voltage power transmission development. Africa has an abundance of natural mineral and energy resources, mostly renewable. The North African deserts have the capacity to deliver large scale solar electrical energy. The Congo River can deliver large scale hydro electrical energy. The constant challenge is the remoteness of generation to that of the large load centres; South Africa is located 3000 km south of the Inga on the Congo River; similarly, Egypt is located 6000 km to the north of Inga. Extra and ultra-high direct current power transmission voltages of 800 kV and 1100 kV are capable of moving bulk power over long distances. In the Peoples Republic of China, over distances of 3000 km, voltages of 800 kV and 1100 kV bipoles are engineered to deliver 6 and 10 GW, respectively.

Huang et al [1], in their ultra high voltage global review, concluded that China is different from other countries with respect to high altitude and heavy pollution operating environments. This particular challenge promoted extensive studies that involved many scientists and engineers and the establishment of many artificial and field laboratories at different altitudes. Our paper is therefore a small peep into the work done in China. This study is being promoted to help set the research agenda for further computational investigations into the mathematics and physics of air gap discharges with particular reference to varying altitudes. This paper focuses only on the insulator as external insulation.

A first task in research study was to set the boundary conditions for geographical altitude. The working boundary for electrical power systems would be from 0 m as at sea level and up to 5500 m above sea level [2]. The results of hypsography, a study of the distribution of elevation on the surface of the earth, shows that the global high voltage electrical power systems will be located as shown in table 1. The bulk of the power system population will be located in the lower altitude range and only a small percentage of the global power systems will be found in the upper altitude range of 2000 to 5500m.

Table 1: Distribution of elevations on the surface of the earth

Altitude Range (m)	Distribution of Elevation (%)
0 – 1000	72
1000-2000	15,5
2000-3000	6,9
3000-4000	3,9
4000-5500	5,6

Yujian et al [3] notes that the commonly used altitude correction methods of IEC 60060 and IEC 60071-2 are suitable for altitudes of 2000m and below. For higher altitudes, Yujian et al recommended that design specifications be obtained from onsite experiments.

Literature Review: External Insulation as in Insulators

In general, the power line insulation is selected on the basis of the pollutant type, the severity of the pollution level, the weather conditions and known operating experiences. These parameters are all wrapped up into a general guideline; expressed as the specific insulation creepage distance for a given high voltage; mm/kV. For the case of varying altitudes, from a range of low to high levels, there is no general guideline for the design and selection of the power line insulation levels. In the case of composite insulators, the flashover voltage is generally determined by the leakage length; the longer the leakage length, the higher the flashover voltage. The influence of shed design and ratio of shed spacing to shed projection is usually neglected.

Xiang Sheng and Jianqun [4] required external insulation design for power lines to operate in the range 0 to 2500m. A single insulator sample was subjected to high voltages for three cases of varying altitudes. The results obtained showed that the flashover voltage of a polluted insulator will decrease as the air pressure decreases; meaning that one would need to employ insulators of longer creepage at higher altitude application. Having determined the single insulator withstand level by experimentation, one can then use (1) to calculate the number of insulators that will be required for a given altitude application.

N = 1.1 Uı / U□ **(1)**

N = number of insulators; Uı = maximum phase to earth operating voltage; U□ = maximum withstand voltage of a single insulator; 1.1 = factor of safety for the case of a broken insulator.

Shi et al [5] built upon the early work in response to the growing demand for higher voltage power transmission circuits in the high altitude western regions of China. The 750 kV North West Grid pilot transmission voltage was in the development phase and the 110 kV AC traction voltage was being investigated for the Qinghai – Tibet railways, located at 4500m.

The reduction in flashover voltage as a result of a decrease in air density that is caused by an increase in altitude was derived empirically and is given by equation 2.

$$V_f = V_o \left(\frac{P}{P_o}\right)^n \qquad (2)$$

Vf= pollution flashover voltage at reduced pressure P, V_o = pollution flashover voltage at standard pressure Po (101.3 kPa), n = declining exponent that represents the impact that altitude makes on the flashover voltage. The bigger n, the larger is the declining degree of the flashover voltage.

Typical values of ***n*** are given in table 2 [6]. The reasons for the different values could be due to artificial laboratory simulations; thus, promoting the need for actual field measurements at high altitude sites of 3000m and above.

Table 2: Recommended values for the exponent *n* that accounts for the influence of air pressure

Institution	**AC**	**DC(-)**	**DC(+)**
Japan	0.5 – 0.55	0.35	0.40
USSR	0.5 – 0.6	0.5	-
Sweden	0.29	0.50	-
Canada	0.5	0.35	0.40
Chongqing University	0.36 - 0.9	0.14 - 0.3	0.23 - 0.63
Tsinghua University	0.18 - 0.6	0.40 - 0.84	0.6 - 0.72

Shi et al [5] conducted laboratory tests with simulated altitude range of 4000 m to 6000m, in steps of 500m. They used two typical values of ESDD (equivalent salt deposit density) as pollutant. Their observations; flashover voltage decreases as altitude increases; the average exponent ***n*** was found to be 0.47 for each of the two samples.

Zhang et al [8, 9] conducted actual field tests at altitudes of 2820m, 3575m and 4484m. The values of ***n*** for AC testing were as follows; field values obtained were in the range of 0.52 – 0.56; laboratory values were in the range 0.52 – 0.59. They concluded that the influence of air pressure ***n*** is related to insulator type and salt deposit density and the value of ***n*** is in the range of 0.5 to 0.6 for AC voltages. In further studies at the same high altitude sites [7], the team concluded that both temperature and pressure have a role in the breakdown process. Equation 2 was transformed into equation 3 which now includes the effect of temperature [6]. The exponent ***n*** characterizing the influence of air pressure was found to be between 0.51 to 0.59. On average ***n*** = 0.56. The exponent ***w*** characterizing the influence of temperature was found to be between 0.20 and 0.23. On average ***w*** = 0.21.

$$\mathbf{k} = \frac{\square\square}{\square\square} \square \square\frac{\square}{\square\square}\square^{\square} \ \mathbf{x} \quad \square\square \ \square \ \square\square\square\square\square \ \square \ \square\square \ \square \ \square\square^{\square\square} \qquad \textbf{(3)}$$

Table 3 is an extract from Chinese National Standards, GB/T 14597. The statistical atmospheric parameters in various altitude regions show that with an increase in altitude, both air pressure and temperature decreases. However, pressure remains the dominant variable in equation 3.

Table 3: Statistical Atmospheric Parameters in Various Altitude Regions

Parameter	Altitude (m)								
	0	1000	2000	2500	3000	3500	4000	4500	5000
P (kPa)	101.3	89.8	79.4	74.6	70.0	65.7	61.6	57.7	54.0
t (□)	20.0	20.0	15	12.5	10.0	7.5	5.0	2.5	0

In observations at Chongqing University, the test results show that the value of ***n*** is related to the insulator material, insulator configuration, voltage type and the pollution severity [8]. For porcelain and glass suspension insulators, the value of *n* under AC voltages is 0.36 to 0.9 and under negative DC conditions, it is 0.14 to 0.3. For post insulators under negative DC conditions, the value of ***n*** is 0.23 to 0.63. Similar results were obtained at Qinghua University [8]. For porcelain and glass insulators, the value of ***n*** is 0.37 – 0.6 for AC voltages and 0.3 to 0.77 for negative DC voltages. For post insulators, the value of ***n*** was 0.4 – 0.84 for AC voltages and 0.6 to 0.72 for negative DC voltages. For composite insulators, the value of ***n*** was 0.18 – 0.52 for AC voltages. The consistent results from all their work was that the value of ***n*** under AC conditions was greater than ***n*** under negative DC voltages and that ***n*** had some relationship to the insulator type, material and configuration.

In further work done at Chongqing University [9], the team employed high speed photography to study the DC pollution flashover performance of various types of porcelain, glass and composite insulator strings under altitude simulated laboratory conditions. They observed that for varying altitude, the relationship between pollution flashover voltage and string length is linear. The DC flashover voltage decreases with the increase in pollution level; the characteristic exponent ***n*** is related to insulator type. The same observation applied for increasing altitude, where the characteristic exponent ***n*** is related to insulator type. In addition, the team concurred that composite insulators have hydrophobic advantages for heavy pollution areas. The interesting new result that emanated from their work using high speed photography is that the partial arc had two components; one an air-gap component and another, a surface arc component. The team suggested a new physical insulator model for high altitude insulators to consist of a circuit having a surface arc of length $\square_{\square}$ and air gap arc length of $\square_{\square}$ in series with a resistance representing the wet pollution layer that is supplied by a constant voltage.

Rao [10] et al studied high altitude and heavy pollution design performance of UHV 800 kV bipoles at the high altitude (2100m) Kunming National Engineering Laboratory. The results of their studies showed that for composite insulators, over a range of shed separation and diameters, there is an effective saturation of the flashover voltage with alternating shed diameters and increasing ratio of shed spacing to shed projection. The flashover voltage of the full scale suspension and post insulator decreased with increasing value of equivalent salt deposit density. The atmospheric conditions of the test were recorded as pressure: 78.9 to 79.9 kPa, temperature: 14.0 to 29.2 ºC and humidity: 7.1 to 14.1 g/m^3.

The above presented review has been on flashover along the surface of solid insulators with regard to air gap. China has done extensive air gap breakdown research for the case of AC, DC and switching impulse voltages for altitudes ranging from sea level to 5000m. The literature review and observations will be presented in a separate paper.

Discussion

A first idea is that with increasing altitude the reduced air pressure in the small air gap between sheds plays a key role in the breakdown process of the insulator. A situation could evolve, air gap by air gap as in consecutive sheds, to set in motion a chain of breakdowns across the consecutive air gaps that will ultimately lead to the breakdown of the whole insulator as observed by Zhang et al [9]. Further study emphasis should thus be on understanding of pre-breakdown corona growth, development and behaviour in the small air gap between consecutive sheds. The air gap under review should be a small air gap that is in the order of mm. The difference in performance of AC to DC voltages as observed in experimentation has good correlation with the corona theory of AC and DC voltages.

Corona inception voltage decreases as air pressure lowers with rising altitude. Meng et al [11] found good correlation between computation results of positive inception voltages as compared with experimental results for several kinds of DC conductors. The tests were conducted using classical high voltage corona cage experimentation. The test sites were located at four different altitudes of 23m, 2250m, 2829m and 3800m above sea level. The reduction in corona inception voltage with increasing altitude was established; the tendency of the reduction was found to be linear. Meng et al [11] further reasoned that this was attributed to the enlargement of the ionization zone as a result of the increase in the effective ionisation coefficient.

The ionisation zone is the small volume of space surrounding the energised conductor. It is defined as the region where the electric field strength is so high that the coefficient of ionisation by electron collision, α, is greater than the electron attachment coefficient, η; that is $\alpha>\eta$. If a free electron originates in the ionisation zone from the effect of any source of radiation such as cosmic rays, a primary electron avalanche will be created by electron collision. Photons will be emitted from the primary avalanche in all directions. The photons are absorbed by air leading to photo-ionisation of the air inside the ionisation zone. With the availability of photoelectrons in the air, successor avalanches of the second generation will start at various distances from the primary avalanche. With the accumulation of the positive ions created by the successor avalanches, the inception streamer develops.

The criterion for self propagating inception streamer is that the number of electrons N_1 in the primary avalanche is greater than or equal to the number of electrons N_2 in the secondary avalanches as generated by the photo-ionisation process. Their computation model was developed according to the gas discharge theory. The relevant equations as extracted from their paper [11] as developed for a stranded conductor of radius r that is located in the centre of a corona cage of radius R; refers

N_2 [illegible] N_1 (The criterion for a self propagating inception streamer) **(3)**

Taking the radius of the ionization zone as yi, then N[illegible] is given by:

N[illegible] = exp ([illegible] **(4)**

The head of the primary avalanche is assumed to be spherical; the radius r[illegible] is given by

r_1 = [illegible] **(5)**

[illegible] is the electron diffusion coefficient and [illegible]e is the electron drift velocity)

The number N[illegible] in the secondary avalanches is given by the formula:

N[illegible] [illegible] **dy** **(6)**

(where N[illegible] is the secondary avalanche. f[illegible] is the number of photoelectrons that is released by absorption of one photon, f_2 is the number of excited states produced per ionizing collusion, 5 is the ionisation coefficient for electron collisions, 6 is the coefficient for electron attachment, [illegible] photo absorption coefficient and g is a geometry factor to account for the fact that some of the photons will get lost to the high voltage conductor.)

To determine the inception voltage, they use the charge simulation method starting with a low initial voltage to determine the electric field distribution near the conductor in the absence of space charge. First they calculate [illegible] and then N[illegible] and N[illegible] checking against the condition for N_2 [illegible] N_1; if yes, they obtain the corona inception voltage, if not, then the applied voltage is raised and the calculations are repeated. The charge simulation method was found to be more attractive than the finite element method or the finite difference method due to its simplicity to represent the equipotential surfaces of the electrodes, its application to unbounded arrangements where the boundaries can extend to infinity and its direct determination of the electric field. Recommend we consider applying this understanding to air gap breakdown between insulator sheds.

Air is predominantly composed of oxygen and nitrogen. Swanson and Jandrell [12] investigated the role of singlet oxygen in positive corona in air. A particular state of excited molecular oxygen is singlet oxygen which remains excited for a longer period. Their work concluded that the role of singlet oxygen when excited does not contribute to the production of seed electrons. Its role is not significant as compared to that of space charge. The argument is that ionisation, attachment and photoionisation mechanisms will remain dominant in the breakdown process. The modelling showed that singlet oxygen and negative ions produce high densities close to the anode. The influence of space charge on the collapse of the electric field for positive corona is the key component for pulse formation and duration. Their work concurs with that as promoted by Meng et al [11], thus equations 3 to 6 has relevance and requires further review and investigation.

Maruvada [13] in his analysis notes that the concentration of charged particulates in air is generally low as compared with that of the gas molecules. He assumes that the charged particles suffer collisions only with the gas molecules and that the gas molecules remain unaffected by the collisions with the charged particles. The gas molecules act as a fixed scattering centre for the charged particles. The mass motion of charged particles is then governed by diffusion and drift; diffusion emanates from the existence of a density gradient and drift emanates from the presence of an electric field. These forces affect only the charged particles and not the gas molecules. Maruvada then writes the charged particle current as equation 7.

[illegible] **(7)**

D □ Particle flow vector,
E □ Electric field vector
F □ Diffusion coefficient and μ=particle mobility
GF6 □ Represents diffusion and *HI represents drift

From experimental work, Maruvada records that particle mobility is a function of the applied electric field as a function of gas pressure, to yield equation 8.

B □ □□ □ $\frac{C}{J}$ □ ; p = gas pressure (8)

It is further noted that for ions, the diffusion coefficient and mobility are related to each other by the Einstein relation and is given in equation 9.

$\frac{\&}{B} = \frac{KL}{,} =$ **0.862 x □□□M T** **(9)**

k = Boltzmann Constant (k = 1.3806 x NO□□P Joule/K); e = charge of an electron (e = 1.602 x NO□□Q Coulomb) and T = absolute temperature of the gas (K)

Equations 1 to 9 as applied to the presence of a charge within a defined environment as in the small air gap between consecutive sheds of an insulator requires further investigations.

The literature review guides that the research be directed towards computational analysis. The theory and equations of interest would be those as provided by Faraday, Gauss, Maxwell, Poisson, Laplace, Townsend, et al. To support the computational analysis on small air gap breakdown, repeatable laboratory experiments under varying simulated altitudes conditions are recommended. The classic corona cage experimentation methodology using existing laboratory voltages, possibly only positive direct voltage, with corona current and high speed photography measurements will deliver confidence to the computational analysis.

Conclusion

An insulator is just one example of high voltage external insulation. In a separate paper under preparation, a similar conclusion is sought for the case of small and long air gaps that were experimentally studied under alternating, direct and switching impulse voltages. Based on the theory and mathematics of corona and gap discharges, the recommendation is that computational modeling and analysis be investigated for the case of small air gaps. The hypothesis is that corona initiated gas discharge leads to the complete external insulation breakdown of the air between consecutive sheds of insulators. Inter-shed, air gap by air gap breakdown, sets in motion a cascading avalanche of consecutive air gap breakdown that eventually leads to the full length insulation breakdown.

The literature review presented is a small peep into the extensive field and laboratory investigations as promoted by China. Emanating from the published work, we can confidently conclude that for external insulation insulators, the breakdown voltage decreases with increasing altitude. Equipment designers can select a factor of safety in addition to the IEC recommended standards for altitude correction. Transmission expansion into extra and ultra high voltages for higher bulk power transfers having lower electrical power losses over longer distances and traversing varying altitudes, from sea level to 5500m, is practically possible. Africa can grow and develop the continental grid from Cape to Cairo with full confidence in performance excellence. There is no technical constraint.

References

[1] D Huang, Y Shu, J Ruan, Y Hu. *Ultra High Voltage Transmission Development in China: Developments, Current Status and Future Prospects.* Proceedings of the IEEE, Vol.97, No. 3, March 2009.

[2] P Naidoo. *Understanding Altitude in the Study of Air Gap Breakdown under High Voltages.* Proceedings of SAUPEC 2016, Vaal University of Technology, South Africa

[3] D Yujian, L Weiming, F Jianbin, L Qingfeng, Z Jun, S Zhiyi. *Altitude Correction of Switching Impulse Flashover Voltage of Rod Plane Air Gaps.* 18th ISH, Seoul, Korea, August 25-30, 2013.

[4] L Xiang Sheng, B Jianqun. *Selection of Insulation Level of HVAC Power Lines Operating in High Altitude Polluted Area.* Internal report, Wuhan High Voltage Research Institute, China.

[5] W D Shi, Z C Guan, L M Wang, J Zhou. *A study on the selection of outdoor insulators used in high altitude areas.* 2003 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, IEEE, 2003.

[6] Z Zhijin, H Haizhou, J Xingliang, H Jianlin, S Caixin. *Comparison of AC Pollution Flashover Performance of Insulators in Chamber with High Altitude Spots.* Proceedings of the 2010 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, IEEE, 2010

[7] X Jiang, Z Zhang, J Yuan, Q Hu, L Luo. *Study of AC Pollution Flashover Performance of Porcelain Insulators at High Altitude Sites of 2800 – 4500 m.* IEEE Transactions on Power Delivery, Vol. 24, No. 3, July 2009.

[8] Z Zhang, X Jiang, Y Chao, L Chen, C Sun, J Hu. *Influence of Low Atmospheric Pressure on AC Pollution Flashover Performance of Various Types of Insulators.* IEEE Transactions on Dielectrics and Electrical Insulation Vol. 17, No. 2, April 2010.

[9] Z Zhang, X Jiang, Y Chao, L Chen, C Sun, J Hu. *Study on DC Pollution Flashover Performance of Various Types of Long String Insulators under Low Atmospheric Pressure Conditions.* IEEE Transactions on Power Delivery, Vol.25, No. 4, October 2010.

[10] H Rao, L Li, R Li, G Wang, Y Liao, F Zhang. *Study on the External Insulation Performance of +/- 800 kV DC Transmission Lines at High Altitudes.* Proceedings of 2012 International Conference on High Voltage Engineering and Application, Shanghai, China, September 17-20, 2012.

[11] X Meng, X Bian, F Chen, Y Yang, L Wang, Z Guan. *Influence of Air Pressure on Positive DC Corona Inception Voltage of Stranded Conductors in the Corona Cage.* Proceedings of the 2010 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, IEEE, 2010.

[12] A G Swanson, I R Jandrell. *Investigation into the Role of Singlet Oxygen in Positive Corona in Air.* SAIEE Research Journal, Vol. 106 (4), December 2015.

[13] P S Maruvada. *Corona in Transmission Systems*. Crown Publications, SA, 2011.