Proceedings of The 6th International Conference on
Properties and Applications of Dielectric Materials
June 21-26, 2000, Xi'an Jiaotong University, Xi'an, China

Effect of Equivalent Salt Deposit Density on Flashover voltage of Contaminated Insulator Energized by HVDC

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Abstract: In Malaysia, the demand for electric power is increasing day by day due to more consumption of power in the industrial sector. Recently, the high voltage DC transmission lines are under construction near the coastal environments for transmitting the power to the all states of Malaysia. Therefore, there is a concern about the reliability of these systems especially under adverse environmental conditions due to sea salt spray contamination. This reliability of this contaminated insulator can be improved through its performance studies. For this performance study, an analytical expression between flashover voltage and ESDD of the contaminated insulator has been proposed using Dimensional Analysis technique. The results obtained from the analytical expression are compared with the experimental results and in close agreement are found.

Keywords: Contaminated insulator, flashover voltage, ESDD, Dimensional Analysis technique, regression analysis.

I. INTRODUCTION

In the whole world, there are much large-scale high voltage DC transmission systems have been constructed, some still under construction and other still on the drawing boards. Recently, in Malaysia, a large power generating station is under construction. The name of the generating station is Bakun Hydro Power Station. The generating capacity of that plant is 2400 MW. Most of this power will transmit through a DC link from Peninsular Malaysia to Sarawak, other state of Malaysia. The DC link between the two states is shown in Figure 1.Therefore, there is a concern about the reliability of these systems especially under adverse environmental conditions due to sea salt spray contamination. The sea salt contamination adversely affects the dielectric strength and performance of insulators of transmission lines and also converter stations. Many outages of transmission lines due to insulator surface contamination have been experienced, especially in converter stations [1]. Surface contamination will cause tracking on the insulator surface providing a permanent-conducting path along it. The conducting path is due to the present of conduction film along the surface of the insulator. This conduction film will provide means for leakage current leaving black-track on the insulator. Braking of the leakage current will cause sparking on the insulator and further reducing the tracking voltage. This will eventually cause a flashover across the insulator. Therefore, contamination monitoring on the insulator surface is important for the proper design of the insulator, for establishing adequate maintenance systems and defining effective countermeasures against contamination induced flashover. Several studies of insulator contamination performance under natural and artificial conditions have been carried out [2-4]. Still, there is limited amount of data and theory related to the performance of the contaminated insulator. Therefore, an analytical expression is required to study the performance of the contaminated insulator properly. In this paper, a theoretical relationship between the flashover voltage and ESDD of contaminated insulator has been proposed using Dimensional Analysis technique [5]. The results obtained from the analytical expression are verified by the experimental results.

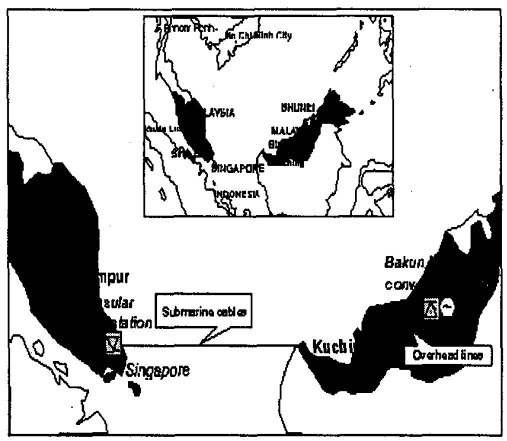

Figure 1. DC link between Peninsular Malaysia and Sarawak

II. THEORETICAL DEVELOPMENT

Four fundamental dimensions; length, mass, time and current are used to develop the relationship between the DC flashover voltage and ESDD of the contaminated insulator. In the outdoor environment, the main factors influencing the direct flashover voltage of the insulator are the ESDD, leakage distance l, charging time T' and the static arc constant N. It is of the form $N = E I^{n}$. Therefore, the relation among them can be written as:

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$$V = V\left(ESDD,\ l,\ N,\ T^{'}\right) \tag{1}$$

In order to utilize the algebraic approach to dimensional analysis, it is convenient to display the dimensions of the respective variables by a tabular arrangement. Therefore, the dimensional matrix of the respective variables can be written as:

	V	$ESDD$	l	N	$T^{'}$
L	2	-2	1	1	0
M	1	1	0	1	0
T	-3	0	0	-3	1
A	-1	0	0	$n-1$	0

The rank of the above dimensional matrix is 4 and it furnishes only one dimensionless product in a complete set. The dimensional matrix with exponents of the respective variables can be re-written as:

	k_1	k_2	k_3	k_4	k_5
	V	$ESDD$	l	N	$T^{'}$
L	2	-2	1	1	0
M	1	1	0	1	0
T	-3	0	0	-3	1
A	-1	0	0	$n-1$	0

The homogeneous linear algebraic equations from the above dimensional matrix can be written as:

$$2k_1 - 2k_2 + k_3 + k_4 = 0 \tag{2}$$

$$k_1 + k_2 + k_4 = 0 \tag{3}$$

$$-3k_1 - 3k_4 + k_5 = 0 \tag{4}$$

$$-k_1 + (n-1)k_4 = 0 \tag{5}$$

Any value may be assigned to k_1 and the equation (2), (3), (4) and (5) may then be solved for k_2, k_3, k_4, k_5 in terms of k_1. Hence, these values are:

$$k_5 = \frac{3n}{n-1}k_1, k_4 = \frac{1}{n-1}k_1, k_3 = -\frac{4n-1}{n-1}k_1,$$
$$k_2 = -\frac{n}{n-1}k_1 \tag{6}$$

By assigning the value $k_1 = 1$, the complete set of dimensionless products consists of the single product, which is related by the following equation:

$$\pi = V(ESDD)^{-\frac{n}{n-1}}\ l^{-\frac{4n-1}{n-1}}\ N^{\frac{n}{n-1}}\ T^{'\frac{3n}{n-1}} \tag{7}$$

By applying the Buckingham's π theorem, the above equation can be written as:

$$V(ESDD)^{-\frac{n}{n-1}}\ l^{-\frac{4n-1}{n-1}}\ N^{\frac{n}{n-1}}\ T^{'\frac{3n}{n-1}} = d_c$$

$$V = d_c\,(ESDD)^{\frac{n}{n-1}}\ l^{\frac{4n-1}{n-1}}\ N^{-\frac{n}{n-1}}\ T^{'-\frac{3n}{n-1}} \tag{8}$$

Where d_c is the dimensional constant. Equation (8) shows the relationship between DC flashover voltage and ESDD of a contaminated insulator. The above equation can be modified by putting the value of n is 0.3[6] and T, N are considered as constant [7]. Therefore, the final expression of DC flashover voltage can be written as:

$$V = d_c\,(ESDD)^{-0.4}\ l^{-0.3} \tag{9}$$

III. EXPERIMENTAL METHOD

Flashover test on cap-and-pin glass (type M92) insulator energized by HVDC supply is carried out in the high voltage laboratory at the Universiti Teknologi Malaysia. The schematic diagram of the experimental setup is shown in Fig. 2. To measure the flashover voltage, cap of the insulator is connected to the ground and the other terminal i. e. pin stud is connected to the high voltage DC source. The artificial contaminated solution is prepared by mixing NaCl with distilled water. In the experiment six different percentage, i. e., 0.2 %, 0.4 %, 0.6 %, 0.8 %, 1.0 % and 1.2 % salt solution is prepared. For a 1.2 % salt solution, 1.2 gm of NaCl is dissolved in a 100 ml distilled water. In the testing setup, the clean and dry insulator is hung on to a steel support. Afterwards, the insulator is contaminated properly by applying 0.2 % salt solution, using spray gun. Once this is done, the voltage from the high voltage transformer (5 KVA, 100 kV) is applied to the insulator. The high voltage DC is applied slowly from zero until complete flashover occurs on the insulator surface. This is achieved by means of a variac connected to the input of the testing transformer. At flashover, the voltage is recorded. For each sample of salt solution, two or three shots of flashover voltage are taken to find out the maximum and minimum flashover voltage (FOV). Similar experimental procedures are repeated for other sample of salt solutions and FOV's are also recorded.

IV. MEASUREMENT OF ESDD

The artificially contaminated insulator is dried under the bright sunlight. After which, dry granules of NaCl sticking to the insulator surface is collected by brushing it off by mean of a small paint-brush.

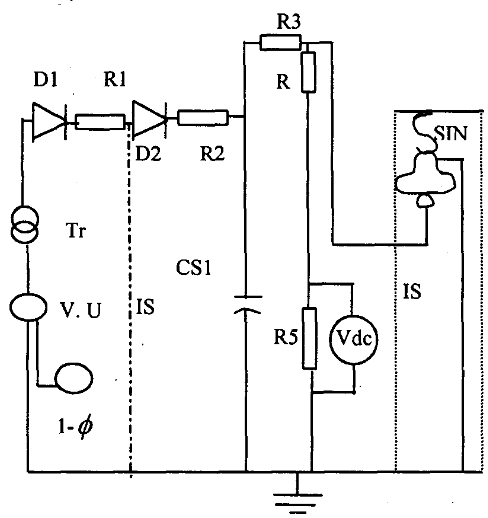

Fig. 2. HVDC experimental setup for flashover voltage measurement

Legend:
Tr. = High voltage transformer, 5 KVA, 100 kV
IS = Insulator support
D1, D2 = Diodes, 140 kV, 5 mA
R 1, R2 = Diode resistance, 500 KΩ, 8 W
R3 = Protection resistance, 416 Ω, 60 W
R4 = Divider high side resistance, 10 MΩ, 60 W
R5 = Divider low side resistance, 1 KΩ, 60 W
CS1 = Charging capacitor, 140 kV, 200 pf.
V. U = Variable unit.
SIN = Insulator string.

The collected salt deposits are then dissolved in 100-ml distilled water. The test cell of this experiment is filled with the test solution and energized with a 120 V DC tests supply. The magnitude of energized current flowing through the test cell is recorded. This test is repeated for three times of each different solution and corresponding solution conductive currents of the cell are recorded. The measurement setup is shown in Fig. 3. The resistivity of the salt solution can be determined by the following formula:

$$\rho = \frac{R.A}{l} = \frac{V.A}{I.l} \quad \Omega\text{-cm} \qquad (10)$$

where

I -Current flowing through the test cell, amp;

V - Supply voltage across the test cell, Volts;

l - Length of the test cell, cm;

A -Area of the test cell, cm^2.

The standard curve [8] represents the relation between the resistivity and salt concentration. From this curve, the relation between the ESDD and solution resistivity is derived and can be written as:

$$ESDD = \frac{\rho^{-1.0143}}{A_1} 65650 \quad \text{mg/sq.cm} \qquad (11)$$

where:

A_1 - the area of the testing insulator, sq.-cm.

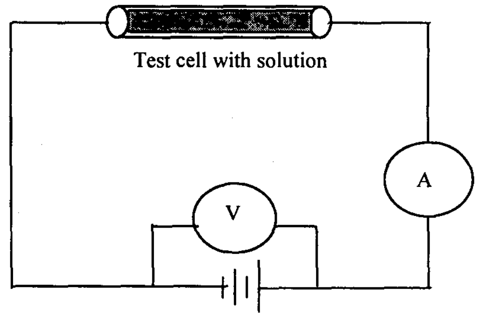

Fig. 3. Test circuit for measuring ESDD

V. RESULTS

The field measurements of ESDD at the vicinity of YTL Power Station, Terrenganu have been accomplished. It is found that the values of ESDD vary between the range of 0.02 to 1.0 mg/ cm^2. Currently, due to salt contamination, the insulators at the YTL Power Station are washed on a weekly basis.

The proposed analytical expressions for calculating flashover voltage are verified by the laboratory experimental test using one unit insulator energized by high voltage DC. The FOV's calculated from the analytical expression and obtained from the experiment are plotted together for comparison. The empirical relation between flashover voltage and ESDD is developed by experiment [9]. In this works, two stations were chosen from which large number of pollution severity data through monthly ESDD measurements were collected. The results of works findings are also plotted in the same figure for comparison as shown in Figure 4. It shows that the calculated FOV's matching quite closely with the measured FOV's. Interestingly, FOV's obtained from model [9] are closely related from the calculated and measured flashover voltages. The only different here, the effect of leakage distance of the insulator is not considered in the literature model [9]. The deviation between analytical and experimental results is negligible. The mean values of flashover voltages for the test along with 97.5 % confidence limits are plotted in Figure 5, which depicts the similarity of the analytical with the experimental results. Here, the proposed analytical expression of flashover voltages is within the 97.5 % limits of confidence of the experimental results.

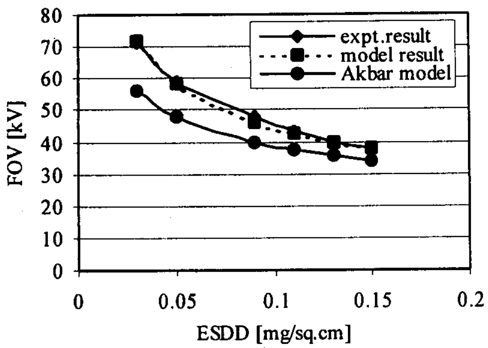

Fig. 4. Variation of DC flashover voltages with ESDD

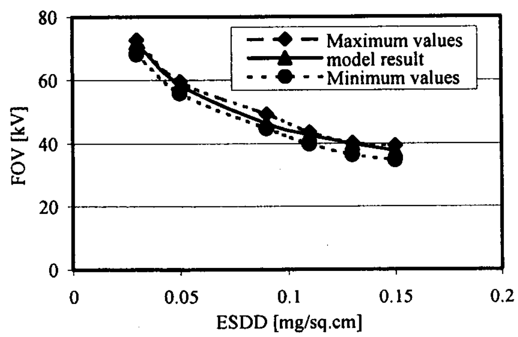

Fig. 5. Comparison of model results with min. and max. values of experimental results

VI. CONCLUSIONS

A mathematical relationship between flashover voltage and ESDD for DC system has been established. In this paper, the flashover voltages are measured using one unit glass insulator energized by high voltage DC. The maximum and minimum values of the measured voltages are calculated using regression analysis. These values are compared with the calculated values. It is found that the analytical results are within the range of the measured results. The results obtained from the analytical expression are compared with the results of other researcher and in close agreement are found.

Therefore, it is concluded that the Dimensional Analysis technique is quite fruitful and attractive for performance study of the contaminated insulator. It may be recommended that the proposed analytical expression will be more helpful for the engineers who are studying the performance of the contaminated insulator

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