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Prediction of pollution flashover voltages of ceramic string insulators under uniform and non-uniform pollution conditions

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Abstract

Present paper emphasizes on the development of a new mathematical model to estimate the contamination flashover voltages of ceramic string insulators under varying uniform and non-uniform pollution conditions subjected to AC voltages. The proposed model is developed based on dimensional analysis of the factors which commonly influence the process of contamination flashover of insulators. The new model for string insulators has been validated using previous authors both experimental and analytical results for total of fifteen string insulators including porcelain, glass string insulators and one porcelain log rod insulator. The validation of the new model indicated that results of proposed model for string insulators are in good agreement with published experimental and model results.

Keywords: Ceramic insulators; Flashover; Mathematical modeling; Pollution; String insulators

1. Introduction

The pollution flashover of insulators had been identified (Burnham, 1995) way back in the early 20th century. To overcome this problem, there have been many investigations carried out. In spite of many past investigations, the recent incidents of outages (Dust, 2016; Indian Blackout, 2010; Enquiry Committee, 2008) due to pollution induced flashover of insulators which have lead to huge generation and load loss, clearly indicate that still the problem is persisting and is continued to be a serious threat in the safe and successful operation of the transmission network. This also shows that the pollution flashover of insulators is still a critical guiding factor in deciding the requirement of insulation in the

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transmission network in the polluted atmospheric conditions. The past investigations carried out to address this problem may be grouped as natural testing, laboratory testing of polluted insulators, prediction of contamination flashover of insulators using intelligent systems and mathematical models. It is observed from the literature that to predict the pollution flashover voltages, a triangular and π-type glass/porcelain models (Li et al., 2014) have been used instead of practical insulators, these models does not exhibit the pollution induced discharge as is exhibited by the practical insulators because the wetting and pollution distribution in such models may not represent the same on an practical insulator. The intelligent systems such as artificial neural network (ANN) (Zegnini et al., 2009), support vector machines (Gencoglu and Uyar, 2009) have been used in predicting the contamination flashover voltages. But the accuracy of such predictions may be limited only to the insulators which have been involved in the prediction process. There are some models (Zhang et al., 2013) which have been developed based on experimental results of practical string insulators and the results of such study have been used to establish separate fitted mathematical expressions for individual insulators to estimate the pollution induced flashover voltages of string insulators. From the above discussions and to the best of authors' knowledge there is no generalized mathematical model based on practical insulator to predict the pollution flashover voltages of ceramic string insulators.

The present work emphasis on the development of a fairly generalized mathematical model to predict the pollution induced flashover voltages of uniform and non-uniformly polluted ceramic string insulators.

2. Development of model

From the literature, it has been observed that the common parameters which influence the pollution flashover are pollution severity in terms of pollution resistance per unit length (R_p), applied voltage (V_s), arc length (L_{arc}) and Ayrton's arc constants. A relation is established between these parameters in terms of their fundamental units mass (M), length (L), time (T) and current (I) using dimensional analysis. The relation between the parameters is expressed in the form of unknown function shown below.

$$V_s = f(A, R_p, (L_{arc})) \tag{1}$$

A matrix is written in terms of fundamental dimensional units of the above said parameters as below:

	Vs	**A**	**(L_{arc})**	**R_p**
M	1	1	0	1
L	2	1	1	1
T	-3	-3	0	-3
I	-1	n-1	0	-2

Rank of the above matrix is found as 3, the total number of variables is 4. As per Buckingham-π theorem (Langhaar, 1951), number of dependent and dimensional less products is one. Its dimensions are represented as [M^o L^o T^o I^o]. Among above variables A, L_{arc} and R_p are considered as independent and V_s as dependent variable. The dimensional less product can be written as:

$$\pi = (A)^a (L_{arc})^b \left(R_p\right)^c \tag{2}$$

where 'a' is exponent of arc constant A, 'b' is exponent of arc length (L_{arc}) and 'c' is exponent of pollution resistance per unit length (R_p). The dimension less product π is written in the form of basic dimensional units of the repetitive variables as:

$$\pi = \left[M^1 L^1 T^{-3} I^{n-1}\right]^a [L]^b \left[M^1 L^1 T^{-3} I^{-2}\right]^c \tag{3}$$

The dependent variable considered is applied voltage and is written as:

$$\left[M^1 L^2 T^{-3} I^{-1}\right] = \left[M^o L^o T^o I^o\right] \tag{4}$$

Now the dimensionless product applied voltage in terms of fundamental dimensions of repetitive variables is,

$$\left[M^1L^2T^{-3}I^{-1}\right] = \left[M^1L^1T^{-3}I^{n-1}\right]^a [L]^b \left[M^1L^1T^{-3}I^{-2}\right]^c \tag{5}$$

The power indices 'a', 'b' and 'c' are determined by equating the powers of fundamental dimensional units MLTI on both sides of the homogeneous linear algebraic Eq. (5):

$$1 = a + c \tag{6}$$

$$2 = a + b + c \tag{7}$$

$$-3 = -3a - 3c \tag{8}$$

$$-1 = (n-1)\,a - 2c \tag{9}$$

The solution obtained is:

$$a = \frac{1}{(n+1)} \quad b = 1 \quad c = \frac{n}{(n+1)}$$

The obtained values of power indices substituted and the equation for V_s can be written as:

$$V_s = K_2(A)^{\frac{1}{(n+1)}}(L_{arc})^1\left(R_p\right)^{\frac{n}{n+1}} \tag{10}$$

Now in Eq. (10), the term (L_{arc}) is replaced by critical arc length $(L_{arc})_c$ to obtain model for flashover then Eq. (10) becomes:

$$V_{fo} = K_2(A)^{\frac{1}{(n+1)}}(L_{arc})_c\left(R_p\right)^{\frac{n}{n+1}} \tag{11}$$

where V_{fo} is the contamination flashover voltage in kV, 'K_2' is the dimensional constant determined from the experimental flashover voltages, 'A' (V/cm) and 'n' are Ayrton's arc constants, who's values have been estimated as $A = 66$ V/cm and $n = 0.7$ mathematically using published experimental data in the authors previous work (Badachi and Dixit, 2015). '$(L_{arc})_c$' critical arc length in cm and 'R_p' pollution resistance/unit length in kΩ/cm.

Pollution resistance/unit length (R_p) can be calculated in terms of form factor (FF), layer conductivity (K_s), creepage length (L) and arc length (L_{arc}) as below:

$$R_P = \frac{\text{FF}}{K_s\,(L - L_{arc})}\,\Omega/\text{cm} \tag{12}$$

Substituting Eq. (12) in Eq. (11) as shown below:

$$V_{fo} = K_2A^{\frac{1}{n+1}}\left(\frac{\text{FF}}{K_s\,(L-(L_{arc})_c)}\right)^{\frac{n}{n+1}}\left((L_{arc})_c\right)\ \text{kV} \tag{13}$$

The above Eq. (13) can be used to estimate the contamination flashover voltages with pollution severity defined in terms of layer conductivity 'K_s' (μS).

If the degree of pollution is defined in terms of Equivalent salt deposit density (ESDD) in mg/cm^2, then layer conductivity 'K_s' may be replaced with ESDD in mg/cm^2, by establishing a relation with the help of curve fit between the layer conductivity and ESDD using IEC60507 (IEC60507, 1991). The obtained relation is as mentioned below:

$$K_s = 86 \times \text{ESDD}^{0.9} \tag{14}$$

Using Eq. (14) in Eq. (13) and the resulted equation is as below:

$$V_{fo} = K_2A^{\frac{1}{n+1}}\left(\frac{\text{FF}}{(86\times\text{ESDD})^{0.9}\,(L-(L_{arc})_c)}\right)^{\frac{n}{n+1}}((L_{arc})_c)\ \text{kV} \tag{15}$$

As pollution distribution on the surface of the insulators in the field is non-uniform and to represent the similar arrangement in laboratory is difficult. But to introduce the non-uniform pollution distribution in the above equation,

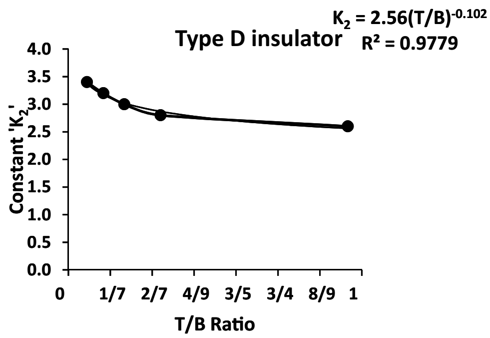

Fig. 1. Relation between average of constants 'K_2' and T/B ratio of Type D string insulator.

Table 1
Dimensional details of Type D insulator.

Insulator named as [Ref.]	No. of units	D (cm)	H (cm)	L (cm)	FF	A_T (cm^2)	A_B (cm^2)
Type D (Porcelain) (Zhang et al., 2013)	7	40	19.5	63.5	1	19.89	33.09

top and bottom side of the insulator surface are assigned different pollution levels. In the above equation, term ESDD is replaced by,

$$\left(\frac{(\mathrm{ESDD_T} \times A_\mathrm{T}) + (\mathrm{ESDD_B} \times A_\mathrm{B})}{(A_\mathrm{T} + A_\mathrm{B})}\right) \tag{16}$$

where $\mathrm{ESDD_T}$ and $\mathrm{ESDD_B}$ are the pollution level of top and bottom surface of the insulators respectively. A_T and A_B are the area of top and bottom surface of the insulator respectively.

Substituting Eq. (16) into Eq. (15) and resulted equation is shown as below:

$$V_{\mathrm{fo}} = K_2 \times A^{\frac{1}{n+1}} \left(\frac{\mathrm{FF}}{\left(86 \times \left(\frac{(\mathrm{ESDD_T} \times A_\mathrm{T}) + (\mathrm{ESDD_B} \times A_\mathrm{B})}{(A_\mathrm{T} + A_\mathrm{B})}\right)^{0.9}\right) (L - (L_{\mathrm{arc}})_\mathrm{c})} \right)^{\frac{n}{n+1}} ((L_{\mathrm{arc}})_\mathrm{c})\ \mathrm{kV} \tag{17}$$

In the above Eq. (17), only unknown is constant K_2 and rest all parameters are known for a given pollution severity and insulator. In order to estimate K_2, experimental results published in the literature (Zhang et al., 2013) are considered due to limited laboratory facility. Here authors' have carried out experiments on 6 different types of string insulators including 3 glass and 3 porcelain string insulators with 7 units in each string. The string insulators are designated as Type A to Type F insulators. Among these, flashover voltages of first porcelain string insulator designated as Type D are considered in the estimation of constant 'K_2'. Eq. (2) and experimental (Zhang et al., 2013) flashover voltages are used to estimate constant 'K_2' for different T/B (ESDD at top to the ESDD at bottom) ratios such as 1/1, 1/3, 1/5, 1/8 and 1/15. Fig. 1 shows the variation of average 'K_2' as a function of (T/B) ratios for the three equivalent ESDDs viz., 0.03, 0.08 and 0.2 mg/cm^2.

Using regression technique, a power fit has been done as shown in Fig. 1. The fitted equation given in Eq. (18) shows a considerably good fit indicated by R^2. Now, the constant 'K_2' is represented as:

$$K_2 = 2.56 \times \left(\frac{\mathrm{T}}{\mathrm{B}}\right)^{-0.102} \tag{18}$$

Further, the detailed study of dimensions of Type D insulator given in Table 1 is carried out and as a result of it, constants 2.56 and 0.102 in Eq. (18) are replaced with $[(r + \mathrm{Hs})/L]$ and $[r/(\mathrm{Hs} + L)]$ respectively.

Constant 'K_2' is written as:

$$K_2 = \left(\frac{r + H_\mathrm{s}}{L}\right) \times \left(\frac{\mathrm{T}}{\mathrm{B}}\right)^{\left(-\frac{r}{H_\mathrm{s} + L}\right)} \tag{19}$$

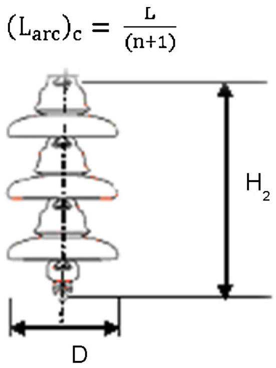

Fig. 2. Sketch of a string insulator.

Substituting Eq. (19) in Eq. (17), the model for V_{fo} becomes:

$$V_{fo} = \left(\frac{r+H_s}{L}\right) \times \left(\frac{T}{B}\right)^{\left(-\frac{r}{H_s+L}\right)} A^{\frac{1}{n+1}} \left[\frac{FF}{\left\{86 \times \left(\frac{(ESDD_T \times A_T)+(ESDD_B \times A_B)}{(A_T+A_B)}\right)^{0.9}\right\}(L-(L_{arc})_c)}\right]^{\frac{n}{n+1}} ((L_{arc})_c)\text{kV} \quad (20)$$

Now Eq. (20) can be used to predict the pollution flashover voltages of ceramic string insulators for non-uniform pollution distribution. In the above equation r represents the radius of insulator shed (cm), L is the creepage length of single disc insulator (cm), Hs is the height of the string (cm) as shown in Fig. 2. (T/B) is the ratio of the ESDD of top to bottom side of the insulator, FF is the form factor of a single disc, (Larc) c is the critical arc length and can be determined from Rizk (1981) as:

$$(L_{arc})_c = \frac{L}{(n+1)} \quad (21)$$

Eq. (20) can be modified for uniform pollution distribution conditions, by polluting the top and bottom side of the insulator uniformly with $ESDD_T = ESDD_B$, hence T/B = 1 and further Eq. (20) is simplified as:

$$V_{fo} = \left(\frac{(r+H_s)}{L}\right) \times A^{\frac{1}{n+1}} \left(\frac{FF}{\left(86 \times (ESDD)^{0.9}\right)(L-(L_{arc})_c)}\right)^{\frac{n}{n+1}} ((L_{arc})_c) \text{ kV} \quad (22)$$

If the pollution severity is defined in terms of layer conductivity 'K_s', Eq. (22) takes the form given in Eq. (23) to compute the pollution flashover voltages.

$$V_{fo} = \left(\frac{(r+H_s)}{L}\right) \times A^{\frac{1}{n+1}} \left(\frac{FF}{(K_s)(L-(L_{arc})_c)}\right)^{\frac{n}{n+1}} ((L_{arc})_c) \text{ kV} \quad (23)$$

To check the correctness of the proposed model (20), flashover voltages are computed for given ESDD with different ratios of top to bottom ESDDs (T/B) for Type D insulator.

The estimated flashover voltages for Type D insulator is shown in Fig. 3.

From Fig. 3, it is observed that between experimental (Zhang et al., 2013) and proposed model results a maximum deviation of 6.82% and a minimum of 0.52%. It is quite obvious that there will be no much deviation between proposed model and experimental (Zhang et al., 2013) results as the flashover voltages of the same string insulator are used in the development of the model. However it would be interesting to verify the model for other types of string insulators. Consequently the next section discusses the validation of the model.

3. Validation of the Proposed Model

The proposed model is verified for its validity by comparing the model results with other researchers experimental and model results. Section 3.1 discusses the validation of the model for non-uniform pollution distribution and Section 3.2 for uniform pollution distribution.

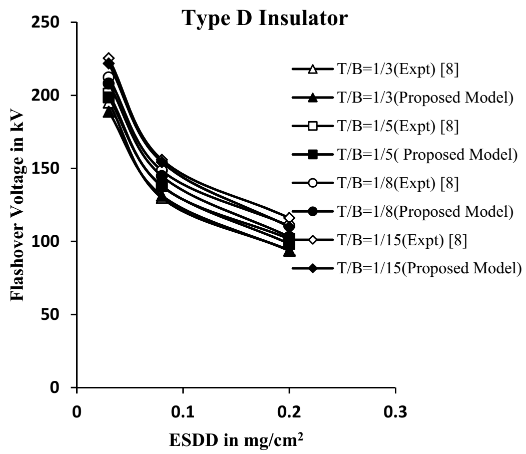

Fig. 3. Comparison of flashover voltages of experimental (Zhang et al., 2013) and proposed model for Type D Insulator.

Table 2
Dimensional details of insulators considered in the study of non-uniform pollution distribution.

Sl. no	Designated insulator [Ref.]	No. of units in String	*D* (cm)	*H* (cm)	*L* (cm)	FF	A_T (cm^2)	A_B (cm^2)
1	Type A(Glass) (Zhang et al., 2013)	7	32	15.5	50	0.845	11.24	20.50
2	Type B(Glass) (Zhang et al., 2013)	7	40	19.5	63.5	1.070	18.20	29.96
3	Type C(Glass) (Zhang et al., 2013)	7	36	20.5	55	0.760	14.99	27.66
4	Type E(Porcelain) (Zhang et al., 2013)	7	33	19.5	48	0.827	18.10	17.10
5	Type F(Porcelain) (Zhang et al., 2013)	7	40	19.5	63.5	1.386	28.60	27.50
6	Type G(Porcelain) (Sima et al., 2010)	14	25.4	14.6	32	0.82	Top area/Bottom area = 0.937	

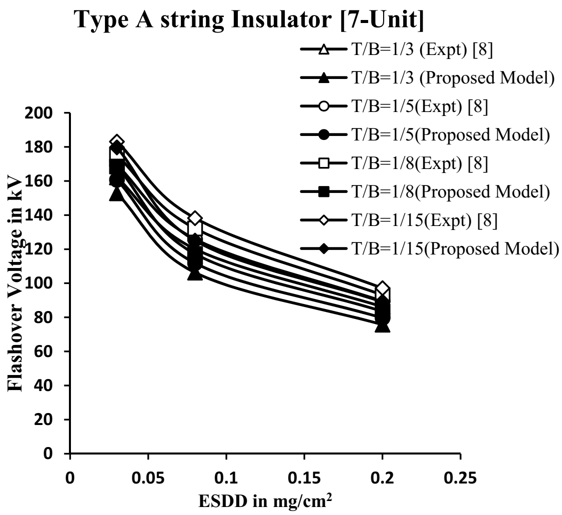

Fig. 4. Comparison of flashover voltages of experimental (Zhang et al., 2013) and proposed model for Type A string Insulator.

3.1. Validation of the model for non-uniform pollution distribution

To validate the model for non-uniform pollution distribution, the proposed model results are verified with other researcher's experimental results (Zhang et al., 2013; Sima et al., 2010) of 6 different types of string insulators. The dimensional details of the insulators considered for the validation are shown in Table 2. The glass string insulators are designated as Type A, B and C and porcelain string insulator as Type E, F and G.

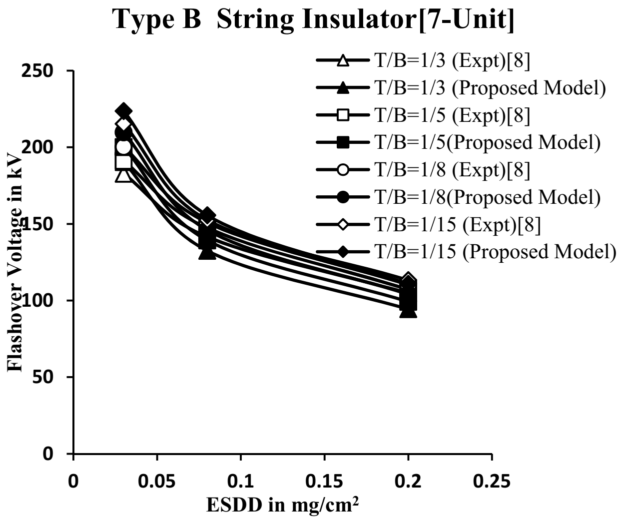

Fig. 5. Comparison of flashover voltages of experimental (Zhang et al., 2013) and proposed model for Type B string Insulator.

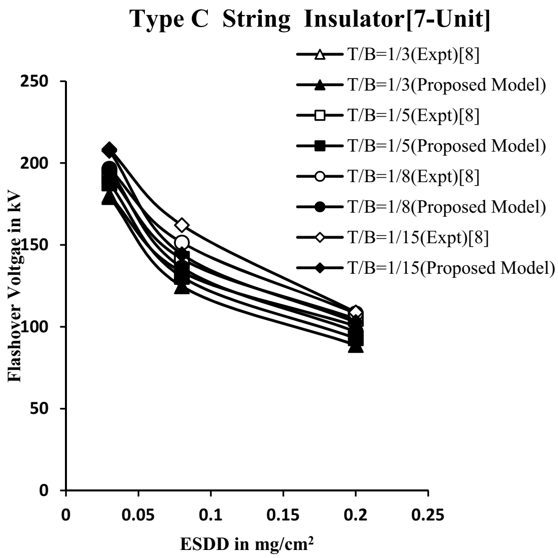

Fig. 6. Comparison of flashover voltages of experimental (Zhang et al., 2013) and proposed model for Type C string Insulator.

Fig. 4 shows the comparison of experimental flashover voltages (Zhang et al., 2013) with proposed model results for Type A string insulator. The model predicts the flashover voltages for different T/B ratios with a maximum deviation of 12.14% and minimum deviation of 1.84%.

Fig. 5 represents the relation between the flashover voltages and pollution severity in terms of ESDD (mg/cm^2) for different T/B ratios for Type B String insulator. The relation clearly indicates that model has predicted the flashover voltages, which are having highest deviation of +9.94% and − 4.74% with reference to experimental flashover voltages (Zhang et al., 2013).

Fig. 6 illustrates the comparison between experimental flashover voltages (Zhang et al., 2013) and model results for Type C string insulator at different T/B ratios. The predicted results of the model are having a variation of maximum of 11.58% and minimum of 0.43% in comparison with experimentally determined flashover voltages (Zhang et al., 2013).

Fig. 7 depicts the comparison between experimentally determined (Zhang et al., 2013) and model computed flashover voltages of Type E string insulator at different T/B ratios. The comparison indicates that, the model is able to estimate

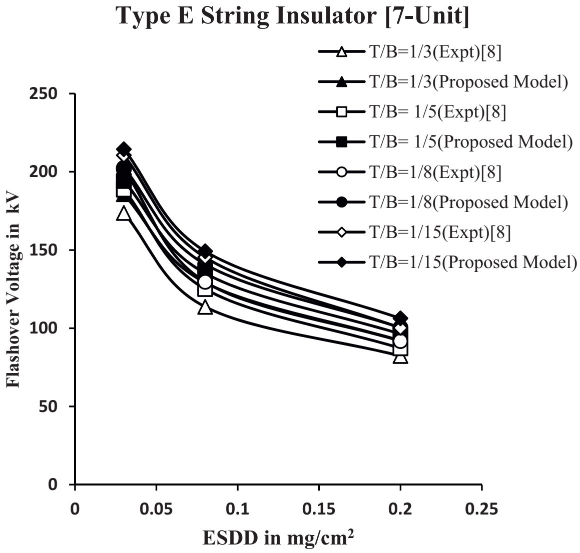

Fig. 7. Comparison of flashover voltages of experimental (Zhang et al., 2013) and proposed model of Type E string insulator.

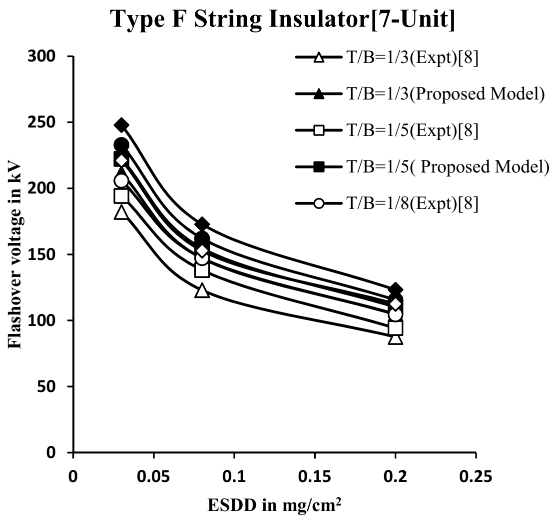

Fig. 8. Comparison of flashover voltages of experimental (Zhang et al., 2013) and proposed model for Type F string insulator.

the flashover voltages in comparison with experimental results with a maximum deviation of −13.62% and minimum deviation of −0.51%.

Fig. 8 shows the comparison of experimental (Zhang et al., 2013) and model computed flashover voltages at different T/B ratios for Type F string insulator. It is seen from the comparison that model results are having a maximum of −19.7% and a minimum of −9.51% disparity from the experimental results (Zhang et al., 2013).

Fig. 9 represents the relation between experimentally determined flashover voltages and model computed flashover voltages for different T/B ratios for Type G string insulator. The relation clearly indicates that model is able to predict the flashover voltages with a maximum of −16.21% and a minimum of −1.42% variations in comparison with experimentally found results (Sima et al., 2010).

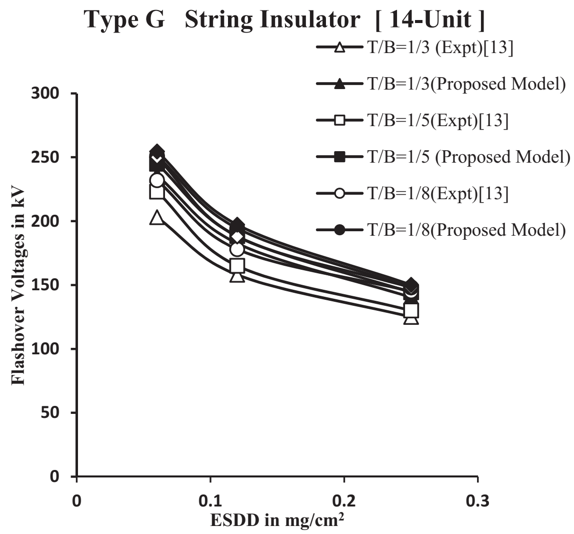

Fig. 9. Comparison of flashover voltages of experimental (Sima et al., 2010) and proposed model for Type G string insulator.

Table 3
Dimensional details of insulators considered in the present study for uniform pollution condition.

Sl. No.	Designated Insulator	No. of Units in String	Diameter in cm	Height in cm	Creepage Length in cm	Form factor
1	Type H (Porcelain) (Dixit, 2009)	3	26.0	14.3	36.0	0.67
2	Type I (Porcelain) (Gencoglu and Cebeci, 2009)	9	29.0	14.0	41.8	0.9
3	Type J (Porcelain) (Gencoglu and Cebeci, 2009)	9	28.0	14.6	43.2	0.99
4	Type K (Porcelain) (Rumeli, 1973)	7	28.8	18.5	30.4	0.68
5	Type L (Porcelain) (Hongwei et al., 2010)	8	25.5	14.6	40.8	1.104
6	Type M (Porcelain) (Hongwei et al., 2010)	8	25.5	14.3	29.0	0.736
7	Type N(Glass) (Hongwei et al., 2010)	8	25.5	14.0	31.0	0.894
8	Type O (Porcelain-long rod VKL 75/14) (Ozbek, 2002)	–	15.7	127.0	187.6	6.22

3.2. Validation of the proposed model for uniform pollution distribution

The proposed model can also be used for predicting the pollution flashover voltages under uniform pollution distribution by maintaining same ESDD on both top and bottom sides of the insulator. To validate it, the proposed model results are compared with other researchers experimental (Dixit, 2009; Hongwei et al., 2010) and model results (Gencoglu and Cebeci, 2009; Rumeli, 1973; Ozbek, 2002). There are 7 different types of string insulators designated as Type H, I, J, K, L, M, N string insulators and a long rod porcelain insulator designated as Type O are considered for validation and their dimensional details are given in Table 3.

Fig. 10 illustrates the comparison of experimental (Dixit, 2009), model (Gencoglu and Cebeci, 2009; Rumeli, 1973) results with the proposed model under uniform pollution distribution for Type H, I, J and K String insulators. This graph is plotted against both ESDD and layer conductivity, as proposed model has degree of pollution in terms of ESDD but the other researchers (Dixit, 2009; Gencoglu and Cebeci, 2009; Rumeli, 1973) have in terms of layer conductivity. The relation clearly indicates that proposed model predicts the flashover voltages of the strings with different no. of units with a maximum deviation of −9.7% and minimum of −1.7% in correlation with experimental (Dixit, 2009) and other model results (Gencoglu and Cebeci, 2009; Rumeli, 1973). Overall for the above said insulators the model is able to predict the flashover voltages with a deviation of less than 10%.

Fig. 11 depicts the relation between flashover voltages and pollution severity in terms of ESDD (mg/cm^2) of experimentally results (Hongwei et al., 2010) and proposed model computed results of Type L and M insulator. The relation clearly indicates that a deviation of −16.6% and +9.37%.

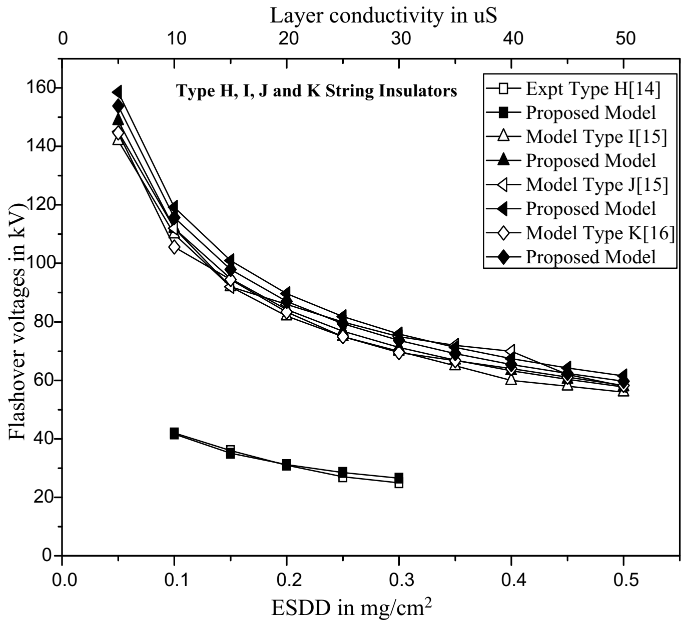

Fig. 10. Comparison of flashover voltages of experimental (Dixit, 2009), model (Gencoglu and Cebeci, 2009; Rumeli, 1973), with proposed model results of Type H[3-unit], Type I & Type J[9-unit] and Type K[7-unit] String insulators.

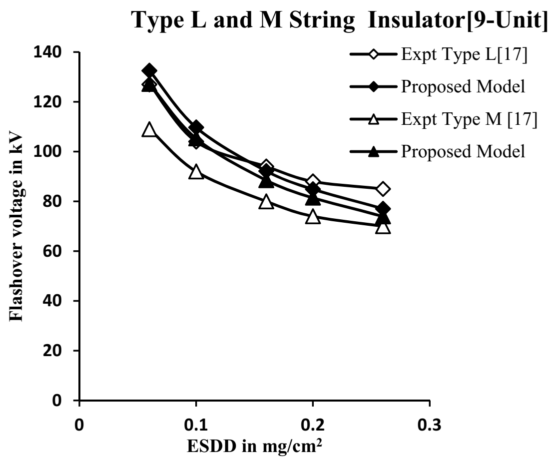

Fig. 11. Comparison of flashover voltages of Expt. (Hongwei et al., 2010) and proposed model results of Type L and M string insulator.

Fig. 12 shows the variation of flashover voltages with variation of pollution condition in terms of ESDD (mg/cm^2) of Type N string insulator. During the comparison of experimental (Hongwei et al., 2010) and model results, it is observed that model results are with a maximum deviation of −10% and minimum of −1.56%.

It is interesting to verify the validity of the proposed model for uniform pollution distribution of a long rod porcelain insulator designated as Type O insulator. Fig. 13 shows the comparison of model results (Ozbek, 2002) obtained from (Gencoglu and Cebeci, 2009) and proposed model results of a long rod porcelain insulator. From the comparison, it is clear that proposed model results are having a deviation of +9% and −8.84% in accordance with other model (Ozbek, 2002) results. This indicates that the proposed model can also predict the flashover voltages of long rod porcelain insulator with a deviation within ±10%.

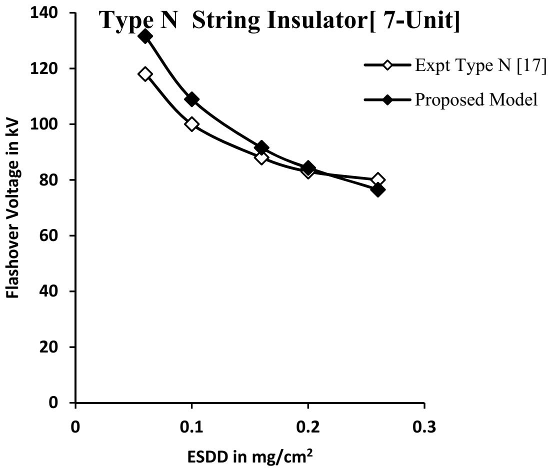

Fig. 12. Comparison of flashover voltages of Expt. (Hongwei et al., 2010) and proposed model results for Type N string insulator.

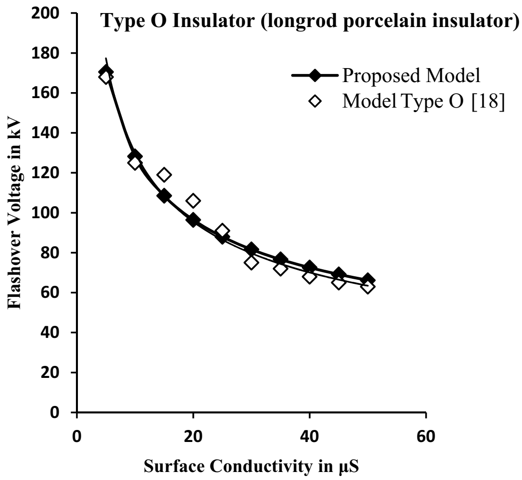

Fig. 13. Comparison of flashover voltages of the model (Ozbek, 2002) and proposed model results for Type O long rod porcelain insulator (VKL 75/14).

4. Conclusions

Present paper discusses the development of a new mathematical model for predicting the contamination flashover voltages of ceramic string insulators under varying pollution conditions. The versatility of the proposed model is that it can be applied for both non-uniform and uniform pollution conditions. The new model has been validated for non-uniform pollution distributions with published experimental flashover voltages for six different types of ceramic string insulators. It has been observed that, the new model has been able to estimate the flashover voltages with maximum deviations between −19% and +10%.

The proposed model has been also validated for uniform pollution distribution with both experimental and model results of other researchers for eight types of ceramic string insulators. The validation clearly indicated that model has been able to estimate the pollution flashover voltages with maximum deviation of ±10%.

From the above discussions, it is clear that the accuracy of the proposed model is comparatively better for uniform pollution distribution conditions. However, the above deviations may seems to be acceptable due to slight variations in the parameters such as laboratory dimensions, source characteristics and rate of wetting. To conclude, the proposed model may put insight in the selection of insulators under various pollution conditions.

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