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Regular paper

Performance improvement of Insulator string in polluted conditions

Insulator is one the most vital component of power Transmission and Distribution network. It holds carrier of electrical energy and isolates it from earth. Suspend insulators are used variously in power networks because of less expensive price as well as capability to work at different voltage levels. The common problem of this type of insulator is non-homogenous voltage distribution on its units. This dilemma results in electrical discharge of insulator, insulator damage and finally forced outage especially in polluted areas. In this paper, it is offered to change the insulators units' dimensions to make voltage distribution more uniform in the string. Also, the simulations showed significant increment in insulator string efficiency factor by varying units' dimensions.

Keywords: insulator string, pollution, voltage distribution, capacity ratio, reliability

1. INTRODUCTION

H.V insulation provides isolation paths in T&D networks. The first aerial transmission line was designed in 1880 with 50 and 66 kV maximum operation voltage. Population growth as well as daily development of industry necessitates power transmission reliability. In the other hand, strategic situation of power industry and necessity of reliable networks with minimum outage as vital demand of today's societies, stimulate extended activities in design, develop and operation of H.V insulators. Insulators hold conductors in transmission lines. As well, they isolate high voltage lines from pole body (i.e. ground). Forced outages by insulation fault form high percentage of whole network outages. Operation under excessive voltages, more than insulator breaking voltage, is cause of most outages. This situation can be result of network design deficiency, insulator manufacturing process problems, inappropriate insulator choice considering regional climatic conditions, insulator damage by human or natural accidents and unscheduled maintenance application [1].

High voltage insulators are exposed to various climates. Severe environmental conditions and pollution degree have a strong influence on insulator performance and affect the reliability of T&D networks. Flashovers on high voltage insulators due to natural pollution cause problems in the performance and reliability of overhead lines in polluted areas. Deposited Pollution on insulator surface combined with humidity provides a conductive electrolyte and a conductive layer for leakage current. Daily development of T&D networks and necessity of power systems reliability to provide minimum outage in addition to pollution effects made pollution determination important. Types and degree specification of pollution seems to be vital for efficient operation and proper choice of insulation.

Based on the dc artificial pollution tests of various types of porcelain, glass, and composite insulators, the following conclusions have been obtained in [2].

- There is a nearly linear relation between the dc pollution flashover voltage and the disc-
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type insulator string length.

- Compared with the porcelain disc insulators, the glass disc insulators with the same profiles have better antipollution performances.
- The pollution flashover performances of the composite long-rod insulators are affected by their materials and shed shapes [2].

A self-consistent dynamic model for application to ac voltage was established in [3] in order to simulate arc behavior on the surface of ice accumulated on insulator surface. The model considers the arc as time-dependent impedance constituted of a resistance in series with an inductance. The arc resistance throughout the period of arc propagation is determined by using Mayr's equation. The unbridged ice layer is replaced with an equivalent resistance, where the surface conductivity is calculated by taking the effect of melting water into account [3].

Conditions of slight wetting (drizzle, fog, high humidity) are probably most favorable for building up concentrated stable zones. Their temperature is higher than the ambient, and leakage current is in the range of 1 mA.

Concentrated stable discharges cause the degradation of polymer insulation. The related very non uniform voltage distribution along the leakage path can initiate the ignition of internal partial discharges inside surge arresters or other high-voltage apparatus and can also decrease the flashover voltage of external insulation [4].

An experiment to study the form of the discharge during its evolution at the electrolyte surface and to determine the difference between the real dynamic features of flashover and the theoretical dynamic ones has been done in [5].

In some recent investigations, it is shown that with the use of an alternating diameter shed design with small shed spacing, or selective protection to the regions that are prone to dry band activity by cup shaped sheds, the insulators perform significantly better than the commonly used straight shed designs [6].

Climates play significant role in pollution procedure and resulted electrical breakage. The followings are affected by climate:

- Pollution deposition on insulation
- Pollution distribution on insulator's surface
- Durability of Pollution condition
- Pollution dispersion amount from resource

Humidity is the most effective factor on pollution, pollution layer formation, self-cleaning and natural cleaning of insulation. Humidity includes different variables like relative and absolute humidity, fog, breeze and fallings.

Precipitation affect on insulators self-cleaning and result in insulation faults if less than 20 mm annually. Basically dry pollution layer is ineffective on insulation strength and only in moistening periods particles solvent provide conductive layer on insulation surface. Other environmental parameters like temperature, precipitation, wind speed and direction, numbers of dusty and stormy days are effective on degree and intensity of pollution accumulation.

Assessment of wind influence on superficial electrical discharge and pollution deposit process is very complicated. Wind, depends on speed and direction, can be cleaner or polluter; it can transfer particles from near or far pollution resources to insulation or clean them on their surface.

Contamination monitoring is required in order to determine the proper design and choice of insulation type and level. This monitoring is also important for addressing an effective solution against pollution flashover. Meteorological conditions vary

considerably from the coastal areas to the inland areas and play an important role in the deposition rate of pollutants and electrical behavior of insulators. The survey proved that the insulator contamination problem is strongly environment-dependent and no generalized anti-pollution criteria can be offered. The determination of outdoor insulation level and design, in a new location is a difficult matter without having some information on the severity of prevailing pollution.

The problem becomes more serious at higher levels of transmission voltage. It is, therefore, imperative to have a reasonable and accurate assessment of site severity. Works in [7-12] have found considerable relationships between the contamination severity in terms of Equivalent Salt Deposit Density (ESDD) and flashover with respect to the meteorological parameters. An attempt has been done in [13] and [14] to relate most of the meteorological parameters respectively with ESDD and leakage current to develop a new mathematical model using multiple regression analysis technique.

So far, the researchers have studied the effect of the meteorological parameters on ESDD or flashover in piecemeal manner. Reference [7, 8] described that the contamination layer and leakage current depends upon the wind speed and the distance between the seashore and insulator; a mathematical relationship has been developed between these factors. Sometime non-uniform contamination due to wind direction can be found on the surfaces of high voltage insulators as described in [9].

High temperature is responsible for lower humidity which leads to lower flashover voltages; the relationship is described in [10, 11]. As regards the air pressure it has been found that the flashover voltages of polluted insulators decrease as the pressure decreases [12, 13].

Insulation design in transmission lines and substations depend to over voltage and regional pollution. Each factor is critical for insulation design. Two kind of pollution can result in insulation electrical breakage in power frequency voltage:

- a) Pre-deposit pollution
- b) Instant pollution.

Pre-deposit pollution can be one of the followings: high dissolvable salts (NaSO_4 , MgCl_2 and NaCl) those define as ESDD. Low dissolvable salts (gypsum, suspension ash) or non solvable materials (clay, Kaolin, soot and oil) those define as NSDD and acids (NO_x , SO_3 and SO_2). Instant pollution includes conductive fog and birds' pollution (residue).

Although composite insulators with polymeric housings have been used around the world in outdoor high voltage applications for over 30 years, there still exists a lack of adequate pollution testing procedures that would allow for evaluation and comparison of their properties. This is mainly caused by a fact that the majority of composite insulators, because of the variable hydrophobicity of their external surfaces, represent dynamic (time variable) properties [7].

Suspension insulators are very popular due to their less expensive price, flexibility to work in various voltage levels and low maintenance cost.

Insulator string can be applied in various voltage levels by changing insulators units. Non-homogenous voltage distribution on these insulators is considered as a defect; therefore, various tests are defined and performed to determine stability voltage of the insulators. Test approaches are very important cases to determine insulation level adequacy. Also, insulator must have suitable mechanical strength in load conditions.

The Electrical strength must be high enough to resist in normal and excessive voltages, but should break at excessive harmful voltage for the equipments [8], [9].

In this paper, it is offered to change the insulators unit's dimensions to make voltage

distribution more uniform in the string. This paper managed in 5 sections. Section 2, describes pollution and its effect on insulators. In part 3 we talk about inhomogeneous voltage across an insulator string and explain a simple method, using KVL, KCL equations to calculate exposed voltage at each unit of string. At next section we introduced our novel design. Part 5 shows simulation result by using two different dimension insulators. Simulations showed increment in insulator string efficiency factor by varying units' dimensions.

2. POLLUTION

Climate is the most effective factor in pollution formation on insulators and the flashover mechanism. Accumulation and distribution of pollution on insulation surface, pollution conditions durability and its penetration depth from resources to power networks is dependent to regional climate. The main environmental parameters that take part in conductive layer formation on insulation surface and natural self-cleaning of insulators are regional moistening situations such as humidity, dew, fog and precipitation [10].

Pollution reduces electrical strength of insulators; it combines with moisture and lessens superficial resistance up to 20 percent. Polluters such as steam, industrial mist, cement, and plaster in industrial regions as well as salt in coastal region are transferred by fog or wind and form a film on insulator surface that convert to a conductive layer to pass leakage current. This phenomenon makes the insulator instable, increase electrical breakage probability and finally reduces T&D system reliability significantly. Various methods such as ESDD and NSDD are used to determine insulators pollution. In these approaches, insulator surface is washed with specific amount of water and salt concentration (soluble and non- soluble) is calculated [11].

Also, various methods are applied to overcome pollution problems as follows: insulator profile modification to avoid pollution accumulation or wipe easily by rain (i.e. self cleaning increment), preventing insulator moistening by special equipments, increasing stability and arcing voltage by creepage distance increment or adding insulation units to insulator strings, voltage distribution improvements by parallel voltage balancer and equalizing relative voltage distribution in polluted and wet conditions. Insulation design in transmission lines and substations depend to over voltage and regional pollution. Each factor is critical for insulation design. Over voltage satisfies design limit low pollution regions but in high pollution regions this parameter influenced by pollution degree as well.

Nowadays, the operators apply empirical methods to overcome pollution effects which increase insulation stability in some cases. These methods are not scientific or documental, so they losses or malfunctions are inevitable. In high pollution regions, insulation design encounter problems and network stability lose and over design as well as initial investment increment required. Therefore determination of environmental pollution effects on insulation seems to be necessary [12].

Recently, coating of insulators using water repellent silicone type, have attracted considerable interest RTV silicon rubber coating may increase the surface hydrophobicity due to low surface energy, reduce the leakage current and prevent arcing. A lot of long term properties of silicon materials can be summed in the general term, weatherability including resistance to Ozone, water and UV radiation, resistance to low and high temperature, and high dielectric Strength [13].

In all approaches, an excessive cost will be imposed to electrical utility as a tradeoff of system reliability increment in polluted conditions.

A. Pollution effect

Electrical systems insulation usually must have low surface conductance and proper

performance. During insulators operation, pollution films are formed on insulation surface and depend on regional climate, the combined film with moisture, rain, fog or dew result in electrolyte layer as suitable substrate to conduct current in undesired paths. This process increases leakage currents increment, which decreases the withstand voltage of the insulator, that finally result in flashovers and undesirable outages. Flashovers on high voltage insulators due to natural and industrial pollution resources adversely affect performance and reliability of overhead lines in polluted areas [14]. To calculate pollution effect on insulation considering superficial resistance reduction by pollution, a parallel resistance is considered between each insulator. The equivalent circuit is as follows:



Fig. 1: Polluted insulator equivalent circuit

Since there is a leakage current across insulator string in polluted insulators, instead of an open circuit parallel with capacitance of insulator we insert a resistor to show how pollution can reduce the surface resistance of an insulator.

Voltage distribution across insulator is not equal due to capacitance between units of insulator string and ground and cause to more applied voltage and stress on the final unit of insulator string which is next to overhead line. This problem has been shown in the next section. The pollution film on the insulator's surface create a path for leakage current which reduce this inequality of voltage distribution. This would increase string's efficiency; however it reduces string's strength against applied high voltage. So there is a tradeoff between them.

3. VOLTAGE DISTRIBUTION ON INSULATOR STRING

Voltage distribution calculation over insulators in a suspension string is done by considering an equivalent circuit which has same characteristics of the string. In this approximation only circuit behavior of insulator such as voltage and leakage current on its surface are important. Most of electrical programs have some elements which help user to model behavior of power systems. But some components have not represented yet. Insulator is one of these elements. By using proposed equivalent circuit suspension insulators can be modeled and simulated in most of current power electrical softwares such as MATLAB, ATP-EMTP, PSCAD, etc and more investigations would be possible for future studies.

Applied voltage on insulator string is distributed on the string. To determine each unit voltage, electrical capacity between insulator and earth should be considered as well as electrical capacitance between insulator unit and conductive carrier; the former is cause of non-uniform voltage distribution on insulator string. To calculate the distributed voltage on each unit, insulator string is considered as figure 2; where C is the capacitance between each insulator unit and line conductor, C' is the capacitance between each unit and ground. Considering low distance of insulator units as well as small amount of C and C' , the capacitance can be assumed equal for all the units [8].

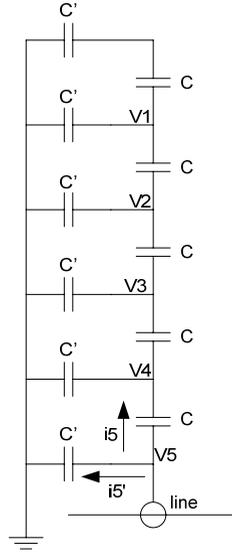


Fig. 2: equivalent circuit of an insulator string with five units in a 63kV line

Solving KVL and KCL equations for equivalent circuit of insulator string, each unit voltage can be calculated.

$$I_{n+1} = \frac{\Delta V_{n+1}}{X_C} = C \cdot \omega \Delta V_{n+1} \quad (1)$$

$$I'_n = \frac{V_{n+1}}{X'_C} = C' \cdot \omega V_{n+1} \quad (2)$$

$$I_n = C \cdot \omega \Delta V_n \quad (3)$$

$$I_{n+1} = I_n + I'_n \quad (4)$$

$$m = \frac{C}{C'} \quad (5)$$

According to above equations:

$$C \cdot \omega \Delta V_{n+1} = C \cdot \omega \Delta V_n + \frac{C}{m} \omega V_{n+1} \quad (6)$$

$$\Delta V_{n+1} = \Delta V_n + \frac{V_{n+1}}{m} \quad (7)$$

Then:

$$V_{n+1} = V_n + \Delta V_n \quad (8)$$

$$\Delta V_0 = V_1 \quad (9)$$

$$\Delta V_1 = \left(1 + \frac{1}{m}\right) \Delta V_0 \quad (10)$$

$$\Delta V_2 = \left(1 + \frac{3}{m} + \frac{1}{m^2}\right) \Delta V_0 \quad (11)$$

And so on.

A. Capacitance ratio modification to balance voltage distribution

According to the obtained equations which mentioned in section 3, if the capacitance ratio (m) becomes larger, voltage distribution on various units of insulator become more

homogenous. There are some methods to increase this capacitance ratio but most of them are expensive and ineffective. For example, the length of cross arm can be increased, but it increases the applied torque, stress and finally excessive cost. Considering feasibility restrictions, this amount limited to 20 and 10 respect to calculated and practical considerations, respectively [7].

4. CHANGING UNITS DIMENSIONS IN INSULATOR STRING

One of the problems in the distribution network is the environmental pollution of its electrical insulation. This problem can be controlled by a suitable design of the insulation level of the distribution line, applying different guides and procedures made for the design of outdoor insulation operating under polluted zones [15].

In this paper, it is offered to use two units with different dimensions to increase capacitance ratio. Therefore, this ratio can be increased by changing the insulator units' dimensions.

One possible configuration is shown in figure 3 which lower unit has more radiuses. This combination can be varied in order to achieve desirable performance of string.

First advantage of this proposed combination can be increasing in falling distance of rain by comparing two arrows in figure 6. The above insulator operates as an umbrella which can cover next insulator and protect it from dust, pollution, rain and so on.

Controlling capacitance ratio of string is the most important advantage of this configuration. As mentioned before capacitance ratio can be controlled by changing dimension and sequence of insulators' units. Considering different areas of insulator units, the capacitance of the two units would be different. Capacity of an insulator is calculated by (12).

$$C = \epsilon \frac{A}{d} \quad (12)$$

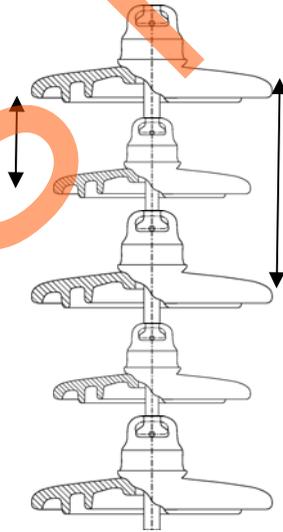


Fig. 3: The proposed insulator string arrangement

Since different insulator units' distances are equal, d almost is constant and insulator area due to approximate its spatial shape by cone, would be related to square of insulator radius. So its capacitance varies with area change corresponding to different radius. The superficial resistance due to deposited pollution on insulator is obtained by (13).

$$R = \rho \frac{l}{A} \quad (13)$$

Where ρ is pollution conductivity which varies in different humidity l is arc length on insulator's surface which can be considered equal to creepage distance and A is cross section of pollution on insulator surface. Since pollution type and its amount (layer thickness) are equal in various units, only pollution length on insulator affects on resistance [9].

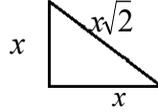


Fig. 4: Insulator area approximation by triangle to calculate the resistance

In figure 4, x is the radius of insulator and we approximate insulator spacing with half of the diameter. Now considering the above assumptions, each resistance value will be depended on insulator's diameter and in different levels of pollution its value would decrease from several $M\Omega$ to tenth's of $K\Omega$. This will change capacitance ratio. In proposed configuration there are two resistances and 3 capacitances due to different radiuses of insulators and capacitance between units of suspension insulators and the tower.

The equivalent circuit of insulator string become as figure 5. KVL and KCL equations are calculated for the equivalent circuit in figure 5.

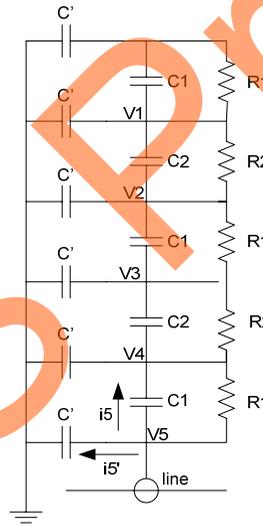


Fig. 5: the proposed equivalent circuit of polluted insulator string

After simplifications, each unit voltage presented as follows:

$$V_4 = x \left(\frac{1 + C_1 \cdot R_1 \cdot \omega + C \cdot R_1 \cdot \omega}{1 + x^3 \cdot C_1 \cdot R_1 \cdot \omega} \right) V_5 \quad (14)$$

$$V_3 = \frac{1}{x} \left(\frac{1 + x^3 \cdot C_1 \cdot R_1 \cdot \omega + x \cdot C \cdot R_1 \cdot \omega}{1 + C \cdot R_1 \cdot \omega} \right) V_4 + \left(\frac{C \cdot R_1 \cdot \omega}{1 + C \cdot R_1 \cdot \omega} \right) V_5 \quad (15)$$

$$V_2 = x \left(\frac{1 + (C + C_1) \cdot R_1 \cdot \omega}{1 + x^3 \cdot C_1 \cdot R_1 \cdot \omega} \right) \cdot V_3 + \quad (16)$$

$$\left(\frac{x \cdot C \cdot R_1 \cdot \omega}{1 + x^3 \cdot C_1 \cdot R_1 \cdot \omega} \right) \cdot (V_4 + V_5) \quad (17)$$

$$V_1 = \frac{1}{x} \left(\frac{1 + x \cdot C \cdot R_1 \cdot \omega + x^3 \cdot C_1 \cdot R_1 \cdot \omega}{1 + C_1 \cdot R_1 \cdot \omega} \right) \cdot V_2$$

$$+ \left(\frac{C \cdot R_1 \cdot \omega}{1 + C_1 \cdot R_1 \cdot \omega} \right) (V_3 + V_4 + V_5)$$

$$\sum_{i=1}^5 V_i = 1 \text{ P.U.} \quad x = \frac{r_1}{r_2}$$

Voltage distribution across any units of insulator can be calculated from above equations and some simplified similar relations. These equations can be developed for using in higher level of voltage and insulators' units e.g. 9 or 16 units to insulate 132 or 230 kV transmission system respectively.

Efficiency of insulator is a critical parameter of insulation system which can determine reliability of system. This factor has been defined as (18).

$$\eta = \frac{n \cdot V_{Max}}{V_{Tot}} \quad (18)$$

Where V_{Max} is the maximum voltage on a unit, n is the number of units and V_{Tot} is the total applied voltage on insulator string.

5. SIMULATION RESULTS

Simulations of the proposed insulator string are performed by MATLAB software. The obtained equations were written in a symbolic mathematic calculation program (m-file) and insulators' voltages are presented in percent of total per unit voltage. The voltage distribution across a clean insulator string has been shown in figure 6. Values of resistances and capacitances in clean environment have been assumed 1 MΩ and 35 pF respectively. As depicted in figure 6 voltage distributes non-uniformly on different units of strings and lower unit suffer from about 31% of applied voltage(63 kV) which excess from its electrical insulation strength (about 14-15 kV). This problem will cause insulation failure in power transmission towers and lines.

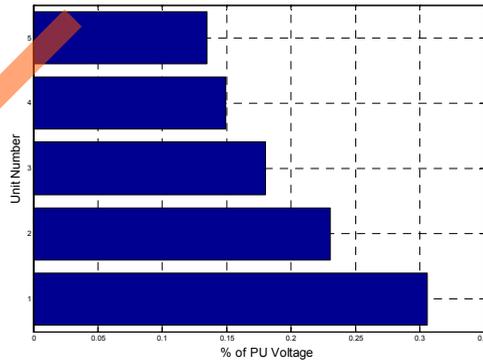


Fig. 6: voltage distribution on various units of insulator string with $x=1$ in clean condition

Voltage distribution across polluted insulator string has been shown in figures 7, 8 and 9. It can be seen in these figures; voltage distribution on each unit is proportional with insulator dimension. Therefore, according to the proposed strategy, voltage distribution on

insulator units is related to insulator dimensions. In this research, $x=0.8, 1$ and 1.2 are considered to choose the best choice in various climactic and pollution conditions. In figure 8, voltage distribution on various components of insulator string with $x = 0.8$ is shown.

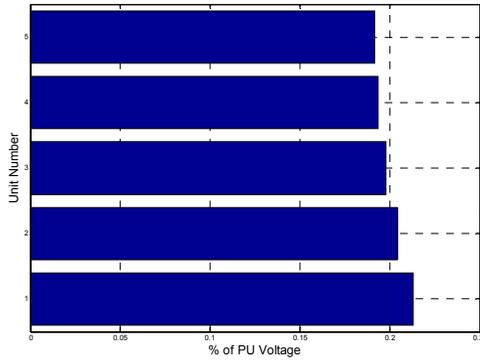


Fig. 7: voltage distribution on various units of polluted insulator string with $x=1$

Voltage distribution across different units of insulator string in figure 7 show more uniform behavior due to decrease in insulator resistance and creating a low resistance path for leakage current. As shown in figures 8 and 9 maximum voltages on insulators' units do not exceed from 22 percent of total applied voltage which is equal to 13.86 kV and insulator can tolerate with this voltage.

Lower unit in figure 9 has less potential comparing with above insulator so to decrease probability of string failure selecting larger radius for insulators which are beside the overhead line is a good option. By limiting voltage distribution in first and second insulators next to line, smaller radiuses could be considered for above insulator can increase weight and cost of string.

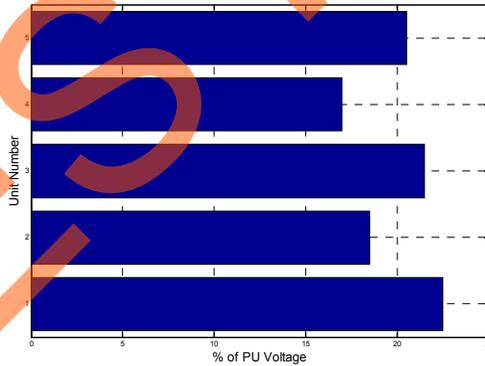


Fig. 8: voltage distribution on various units of polluted insulator string with $x=0.8$

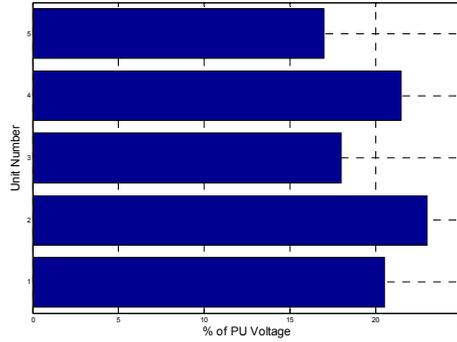


Fig. 9: voltage distribution on various units of insulator polluted string with $x = 1.2$

In other hand for increasing insulator string's efficiency some investigations have been done. The following plot is obtained by varying equivalent capacitor ratio of adjacent insulators the (see figure 3). It can be seen that in areas with normal pollutions if the ratio considered being 1.05, the maximum efficiency of insulator string, 95%, is achieved.

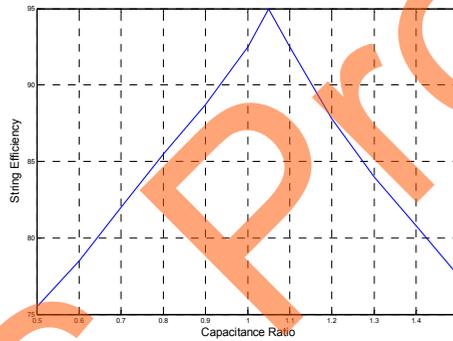


Fig. 10: insulator string efficiency variations due to capacitance ratio

By varying superficial resistance equal to low to heavy pollution classes, various voltage amounts of different units of insulator string and the efficiency are shown in terms of different ratios in tables 1, 2, 3.

Table 1: voltage value of insulator string units and its efficiency for $X=0.8$

	10e4	10e5	10e6	10e7
R1				
V5	21.74	21.73	21.63	20.68
V4	17.39	17.39	17.33	16.81
V3	21.74	21.73	21.69	21.29
V2	17.39	17.41	17.43	17.78
V1	21.74	21.76	21.91	23.41
H	91.99	91.93	91.27	85.41

Table 2: voltage value of insulator string units and its efficiency for $X=1$

	10e4	10e5	10e6	10e7
R1				
V5	19.99	19.94	19.46	15.57
V4	19.99	19.96	19.62	16.79
V3	20.00	19.98	19.78	18.04
V2	20.01	20.02	20.25	21.97
V1	20.01	20.08	20.87	27.61
H	99.99	99.93	95.82	72.43

Table 3: voltage value of insulator string units and its efficiency for X=1.2

R1	10e4	10e5	10e6	10e7
V5	18.51	18.51	18.41	17.5
V4	22.22	22.21	22.12	21.30
V3	18.51	18.51	18.47	18.12
V2	22.22	22.23	22.28	22.79
V1	18.52	18.53	18.71	20.26
η	89.99	89.97	89.75	87.72

As it can be seen from tables 1, 2, 3, in normal pollution condition, insulator with various dimensions contains higher efficiency and smoother voltage distribution compare to normal insulator string. But in heavy pollution condition, in spite of more uniform voltage distribution in insulator units, flashover occurrence probability is higher because of high leakage current on insulator surface. In 63 kV lines, voltage of each insulator unit is equal to 15 kV, and considering the results, the proposed insulator string can perform normally in wide range of pollution.

Also, using various units dimensions reduce insulators exposition to the pollution and precipitation. As well, in rainy conditions, flashover probability reduced because of creepage distance increment between two large units. Note that, using smaller insulators reduce insulator string weight and the applied force to the pole as well. However, various dimensions increase maintenance cost. Therefore, an economic assessment is required to compare these costs with others those are applied by electrical utilities to increase network reliability. This procedure provides economic justification and makes decision making simpler.

6. CONCLUSIONS

It is observed that capacitance ratio (i.e. insulator capacitance to the conductor divided to insulator capacity to the earth) modification can adjust voltage distribution on insulator string units. In this paper, it is offered to use various radiuses as well as various capacitance-superficial resistances for adjacent units. The simulation results showed that 1.05 ratio for five unit insulator string in 63 kV line provide maximum efficiency, uniform voltage distribution and higher reliability in different pollution conditions.

It is recommended to perform an economic assessment in associated with statistical researches to apply the most economic-efficient approach.

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