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# ADDED CFO VOLTAGES FROM FIBERGLASS POLES AND ITS ELECTRICAL DEGRADATION

By

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# ADDED CFO VOLTAGES FROM FIBERGLASS POLES AND ITS ELECTRICAL DEGRADATION

By

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The critical flashover (CFO) voltage of an insulation structure is commonly used to describe the insulation structure's lightning impulse strength. The fiberglass distribution pole was recently introduced to power distribution systems. However, very little work has been done on either the lightning impulse characteristics of distribution line structures with fiberglass poles or the electrical degradation of fiberglass.

The work in this thesis represents the results of a laboratory study on lightning impulse characteristics of distribution line structures with fiberglass poles and the electrical degradation of fiberglass. The critical flashover (CFO) voltages of the fiberglass distribution pole as an insulation structure alone and its combination with various insulators were evaluated. The added CFO voltages from fiberglass distribution poles to basic insulation components were calculated based on the test results. The

accelerated aging tests and corresponding electrical evaluation tests were also conducted to investigate the electrical degradation of fiberglass.

# DEDICATION

I would like to thank my parents, Yuhua and Zhijun, and my wife Xiaoying Tan. They have always encouraged and supported me through all my academic years at Mississippi State University.

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## TABLE OF CONTENTS

Page

CHAPTER Page

APPENDIX

# LIST OF TABLES

TABLE Page

TABLE Page

TABLE Page

## LIST OF FIGURES

# Chapter I

# INTRODUCTION

The critical flashover (CFO) voltage of the insulation structure is commonly used to estimate the lightning impulse strength of overhead distribution lines. The fiberglass pole has been used in power distribution systems in recent years to improve the lightning impulse strength of the distribution lines. In this thesis, four points are presented and discussed: the CFO voltages of different distribution line structures, the added CFO voltages from fiberglass poles to basic insulation components, lightning impulse strengths of various distribution line structures, and the accelerated aging tests of fiberglass samples.

## Overvoltage and Insulation Coordination in Power Systems

The insulation structures in an electric power system are subject to different types of overvoltages when they are put into service [14,18]. Therefore, the insulation structures in an electric power system should be designed properly to prevent the electric equipment from being damaged and to avoid the interruption of proper electric energy delivery. It has been well known that the design of an insulation structure is based on the principle that its alternating insulation strength should be higher than the subjected normal voltage stress and most of the alternating overvoltages occurring in power system [26]. Besides the alternating insulation strength, the design and improvement of an insulation structure are mainly decided by the other overvoltages in power system such as lightning impulse overvoltage and switching surge overvoltage.

The switching surge overvoltages are mainly caused by routine switching operations, for example, disconnecting a transformer from a power distribution system. Although the magnitude of the switching surge is affected by many factors, the rated voltage level of the power system plays a decisive role in the resulting magnitude of the switching surge overvoltage. In other words, the magnitude of the switching surge overvoltage is directly proportional to the rated voltage level of a power system [13, 18]. Therefore, the switching surge overvoltage in a power transmission system is much higher than that in a power distribution system. The switching impulse strength of the electric equipment in a power transmission system should be higher than most of the switching surge overvoltages occurring in the system if the insulation structure is designed properly. The risk of insulation failure in a power transmission system can be reduced to the minimum by using the appropriate protective equipment and improving the switching impulse strength of the electric equipment. The lightning impulse overvoltages, either induced lightning surges or direct lightning strokes, have a smaller impact on the power transmission system due to high switching impulse strengths of the electric equipment.

The power distribution systems play a very important role to provide reliable, high quality electrical energy to the customers. Based on a principle of insulation design, the insulation of the electric equipment in a power distribution system can withstand the switching surge overvoltage with a magnitude of three or four times higher than rated voltage [18]. Generally speaking, the routine switching operations occur less frequently in a power distribution system and the magnitudes of these switching surge overvoltages are also significantly less than in a power transmission system. Therefore, the lightning impulse overvoltage is a more important factor than switching impulse overvoltage when designing the insulation structure of electric equipment in a power distribution system. The studies of power companies and field investigations have proven that lightning impulse overvoltages occurring in a power distribution system are much more dangerous for the electrical equipment than in a power transmission system. The effect of lightning impulse overvoltage on the power distribution system can be reduced by using protective equipment, such as the circuit breaker, auto-recloser, and fuses, and by improving the lightning impulse strength of the electrical equipment.

## Lightning Impulse Strengths of Distribution Line Structures

The improvement of the lightning impulse strength of the distribution line structure can be achieved in the following two ways: increasing the lightning impulse strength of the insulator or using the distribution pole as an additional insulation component.

When the distribution pole was not used as an insulation component in a distribution line structure, the insulator serves as the only insulation component in the distribution line structures. This kind of distribution line structure exhibits good insulation strength under rated voltage. But the lightning impulse strength of the insulator is always less than the lightning surge overvoltage occurring in the power distribution system. Therefore, the faults caused by lightning may damage a distribution line much more than a transmission line. Laboratory work and theoretical analysis prove that it is very important to improve the lightning impulse strength of the distribution line structure.

We can achieve this goal by means of redesigning the insulator, but another efficient and viable way is to use distribution pole as an additional insulation component to improve the lightning impulse strength of distribution line structures. Until now, the wood pole has been used in the distribution line structure to serve as a second or third insulation component in a combined distribution line insulation structure. The lightning impulse strength of the distribution line structure was greatly improved through the usage of this type of combined insulation structure.

On the other hand, considerable laboratory work has been done on the lightning impulse strength of wood poles when used as an additional insulation component [1, 2, 3, 4]. From laboratory test results, the CFO voltage of the insulator plus the wood pole is greater than the CFO voltage of the insulator alone. The improvement of lightning impulse strength for a combined insulation structure can be expressed by the added CFO voltage. The added CFO voltage is obtained by subtracting the CFO voltage of the insulator from the total CFO voltage of the insulator plus the pole. The added CFO voltage from a wood pole to a porcelain pin insulator is 80-110 kV/ft under dry conditions. The added CFO voltage from a wood pole to a polymer suspension insulator is 50-100 kV/ft under dry conditions and 20-50 kV/ft under wet conditions [1]. The other test data also support the fact that the lightning impulse strength of the distribution line structure was strengthened if the wood pole was used as an additional insulation component.

The fiberglass pole has been chosen to replace the wood pole by some power companies. In some power distribution systems, the insulation components of the distribution line structures consist of the insulator and the pole. When combined with either a polymer suspension insulator or a porcelain pin insulator, the fiberglass pole is considered to be an additional insulation component.

Little work has been done on the lightning impulse strength of this type of combined insulation structure when a fiberglass pole is used as an additional insulation component. The CFO voltage of the combined insulation structure and the added CFO voltage from a fiberglass pole are still not available for the insulation design engineer to estimate the lightning impulse strength of overhead distribution line structures.

## Electrical Degradation of Fiberglass Poles

The insulation of all electrical equipment is subjected to continuous electrical stress during its period of service. The continuous electrical stress would decrease the insulation strength of the electrical equipment. At the same time, some other stress factors, such as overvoltage, thermal stress, irradiation, cryogenic temperature, and mechanical stress, would also have adverse effect on the material’s insulation strength. These electrical and non-electrical stresses, if combined together, would decrease the material’s insulation strength and shorten its insulation life at a faster rate than a single stress. In power systems, the aging of the insulation materials is usually associated with the multi-stress aging process. Among various aging factors, the electrical stress always plays a dominant role during the process of insulation degradation. For other aging factors, when sometimes combined with the electrical stress, their effect on the insulation material might be more obvious. When the material's insulation strength is less than the applied electrical stress, an insulation failure is expected to appear and a fault might also initiate simultaneously in power systems.

Various insulation materials such as polymer, glass, paper, mineral oil, and fiberglass have been used for different insulation structures. Their aging processes have already been proven to be different from each other. The aging process is controlled by two factors: the nature of single or combined external stresses and the inherent resistance of the various insulation materials to applied stresses [21]. Research has been done on aging processes and mechanisms of different insulation materials [15, 16, 17, 20, 22, 23, 24] and some conclusions have been drawn based on the conducted research. For example, the abilities of organic insulation materials to resist multi-stress aging are apparently weaker than inorganic insulation materials. As a result, they have a much faster degradation rate than inorganic insulation materials.

More research should be conducted on the abilities of the insulation materials to resist aging since insulation failure is always associated with the insufficient insulation strength due to the insulation material's degradation. During the last several decades, engineers and researchers in the insulation community focused on how to design and conduct the aging tests for different insulation materials and how to predict their insulation lives under normal stresses.

Two types of aging methods, the conventional aging test and the accelerated aging test, were used to investigate the insulation degradation in the laboratory [24]. In the conventional aging test, all possible external stresses are applied to the insulation material's samples. The samples are tested under simulated stresses until insulation failure occurs. Since it is very difficult to simulate actual service conditions of the electrical equipment, the precision of test data of conventional aging tests is considered to be poor. As a result, there have been different insulation failure times even for the same set of samples. Furthermore, the conventional aging test is very expensive and time-consuming since the insulation material is designed to operate under normal stress for many years.

Accelerated aging tests are one of the better ways to evaluate insulation degradation, even when the complete details of the aging mechanism are not fully known. In the accelerated aging tests, one or more stresses are applied to the tested sample at a stress level that is greater than that level found during normal operation. As a result, the rate of insulation degradation would be faster at the higher stress level. In general, the greater the stress, the shorter the insulation life would be. The insulation failure can take place in days or weeks instead of many years if proper high stresses are selected in the accelerated aging test. Compared to the conventional aging test, the accelerated aging tests are more accurate and are more cost-effective and time saving.

Many aging models have also been proposed over the past few decades to associate the stress levels with insulation life [20]. Those aging models always extrapolate the test data from an accelerated aging test and predict the insulation life under normal stress. Single stress models and multi-stress models are two basic types of aging models. For the single stress model, only a single stress is considered in the procedure of developing the model; all other stresses or factors that may affect the insulation life are kept constant or ignored. The multi-stress model relates two or more stresses to the insulation life. Based on research, test results, and field study, it is not clear which of the two models is better for predicting the insulation life of specific materials.

## Thesis Presentation

### *Purpose of Thesis*

There are three purposes in the thesis relating to the insulation of fiberglass poles. The first purpose of this thesis is to evaluate the CFO voltages of the fiberglass pole and the total CFO voltages of the insulators plus the fiberglass pole. Different insulators were used in the laboratory work in order to have a clear and comprehensive understanding about lightning impulse strengths of various distribution line structures. The tested insulators were 15 kV, 25 kV, and 35 kV polymer suspension and porcelain pin insulators. Also, two types of fiberglass distribution poles were used in the tests.

The second purpose of the thesis is to calculate the added CFO voltages. The added CFO voltage derives from using a fiberglass pole as an additional insulation component. The CFO and added CFO voltages are discussed under different lightning impulse polarities, test conditions, and pole lengths. The comparison of CFO voltages and added CFO voltages between wood and fiberglass poles is also presented.

The final purpose of the thesis is to investigate the electrical degradation of fiberglass samples under different accelerated aging tests. Four types of accelerated aging tests were conducted for different fiberglass samples. The discussion of the test data is also presented.

### *Goals*

The goals in this thesis include:

1. Evaluating the CFO voltages of different fiberglass poles.
2. Evaluating the CFO voltages of different insulators plus fiberglass poles.
3. Calculating the added CFO voltages.
4. Comparing added CFO voltages of fiberglass poles with wood poles.
5. Conducting accelerated aging tests on fiberglass samples.
6. Conducting electrical tests to evaluate insulation strengths of tested fiberglass samples before and after accelerated aging tests.
7. Analyzing and discussing the test results from the accelerated aging tests.

# Chapter II

## CFO VOLTAGES OF FIBERGLASS POLES

### Calculation of CFO Voltage and BIL Value

The breakdown in the air gap or flashover on the insulation material's surface is caused by a physical phenomenon called electronic avalanche [27]. An effective electronic avalanche possesses a statistical characteristic. As a result, the insulation strengths of different dielectrics such as gas, liquid, or solid dielectric exhibit a statistical nature.

For the purpose of insulation coordination, the voltage-withstand strength of the insulation structure is quite often expressed in terms of BIL, Basic Insulation Level. For self-restoring insulation, such as gas dielectrics, BIL is understood by most utilities as the crest value of a standard impulse for which the insulation exhibits 90% probability of withstand (or 10% probability of failure) [13]. The CFO voltage of an insulation structure is defined as the crest value of a standard impulse for which the insulation exhibits 50% probability of withstand (or 50% probability of failure) [13]. The CFO voltage can be measured through different types of laboratory methods. In this thesis, the up and down method was used to evaluate the CFO voltage of an insulation structure and it is described in IEEE Standard 4-1995 [7]. There are three steps in this method:

1. Apply a lightning impulse with a magnitude less than the expected flashover voltage of an insulation structure.
2. Increase the magnitude of the lightning impulse by a very small amount (approximately 3~5 % of the expected flashover voltage) for subsequent impulses until flashover occurs.
3. Apply a series of 20 impulses. Decrease the prospective voltage by about 3~5% after each flashover and increase the prospective voltage by about 3~5% after each withstand during the series of these 20 impulses.
4. Average the values of the 20 impulses to obtain the CFO voltage.

For self-restoring insulation, normal (Gaussian) distribution is the best model for approximating the probability density function of disruptive surface flashover. Utilizing statistics for Gaussian distribution, the desired level of withstand can be calculated using the integral probability function, which is defined in equation (2-1).

$$Z = \frac{|VFO - CFO|}{s} \tag{2-1}$$

The VFO is the flashover voltage of an insulation structure with a specific probability of withstand. CFO voltage is the value from the up and down method. Sigma, $\sigma$, is the standard deviation; for lightning impulses, $\sigma$ is generally used as 3 % of the CFO voltage. Z is the number of standard deviations for a specific confidence factor (the probability of withstand), and it can be acquired from cumulative normal (Gaussian) distribution tables. According to previous definition, VFO in equation (2.1) is referred to as BIL when the probability of withstand of an insulation structure is equal to 90%. Also, the value of Z is equal to 1.28 in this situation. Therefore, the BIL voltages of an insulation structure can be calculated as:

$$BIL = CFO \times [1 - Z \times \frac{s}{CFO}] \tag{2-2}$$

Since CFO is measured through the experiment, the BIL with 90% probability of withstand for self-restoring air insulation is:

$$BIL=CFO\times[1-1.28\times(0.03)]=0.9616\times CFO \tag{2-3}$$

## Atmospheric Correction for Test Results

The disruptive discharge of self-restoring external insulation greatly depends upon the atmospheric conditions. Usually, the disruptive discharge voltage for a given path in an air gap is increased by an increase in either air density or humidity. A disruptive discharge voltage measured at given test conditions (temperature “t”, pressure “b”, humidity “h”) can be converted to the value that would be obtained under the standard reference atmospheric conditions ($t_0$, $b_0$, $h_0$) by applying correction factors. It is very important to conduct the study on the test data from the same atmospheric conditions.

The air condition correction factors were calculated according to IEEE Std 4-1995 [7]. The air density correction factor $k_1$ can be calculated as

$$k_1 = \delta^{m} \tag{2-4}$$

$$\delta = \left(\frac{b}{b_0}\right)\times\left(\frac{273+t_0}{273+t}\right) \tag{2-5}$$

$$m = 1 \tag{2-6}$$

Delta, $\delta$, is the relative air density and m is a constant equal to 1. The humidity correction factor, $k_2$, is also 1. The measured disruptive voltages, V, are corrected to $V_0$, which are the voltages under standard atmosphere conditions as shown in the following equation:

$$V_0 = \frac{V}{K} \tag{2-7}$$

Where $K = k_1 \times k_2$, $k_1 = \delta$, $k_2 = 1$, then $K = k_1 \times k_2 = \delta$.

## Test Equipment and Setup

All of the tests were performed in the High Voltage Laboratory at Mississippi State University. The 1.2/50 μs standard lightning impulse was generated by a 3000 kV impulse voltage generator and applied to the insulation structures. The measurement system consists of a capacitive impulse voltage divider, shielded coaxial cable, and a TDS-540 Tektronix digital storage oscilloscope. The oscilloscope and other data output equipment were placed in a double-shielded copper screen room to eliminate the strong electromagnetic interference caused by the flashover when the tests were performed.

The tests were conducted for different fiberglass pole lengths. The tests were done to determine the relationship between the tested pole length and the CFO voltage. The minimum tested pole length that was evaluated in the tests is 1 foot and the maximum tested pole length is 8 feet. Two metallic bands, upper and bottom bands, were utilized as electrodes and tightly wrapped around the fiberglass pole. When the CFO voltages of only the fiberglass pole were evaluated, the lightning impulse was applied to the upper band and the bottom band was grounded. The bottom band can be adjusted along the pole to achieve different pole lengths. During the tests of the combined insulation structure, the upper band was removed and the lightning impulse was applied to a conductor attached to the insulator. In order to obtain accurate results, the combined insulation structure was separated from nearby objects to eliminate the interference of electrostatic fields. The room temperature and air pressure were measured before the tests. Both parameters would be used to make atmospheric correction for recorded test data. The test setups for evaluating CFO voltages are shown in Fig. 2.1 and Fig. 2.2.

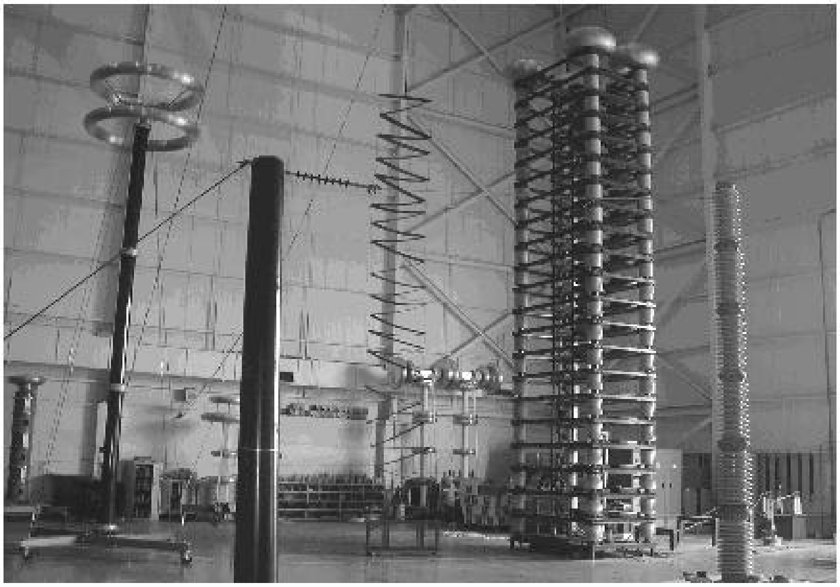

Fig. 2.1 The Test Setup for Evaluating the CFO Voltages of 35 kV Polymer Suspension Insulators Plus Fiberglass Poles.

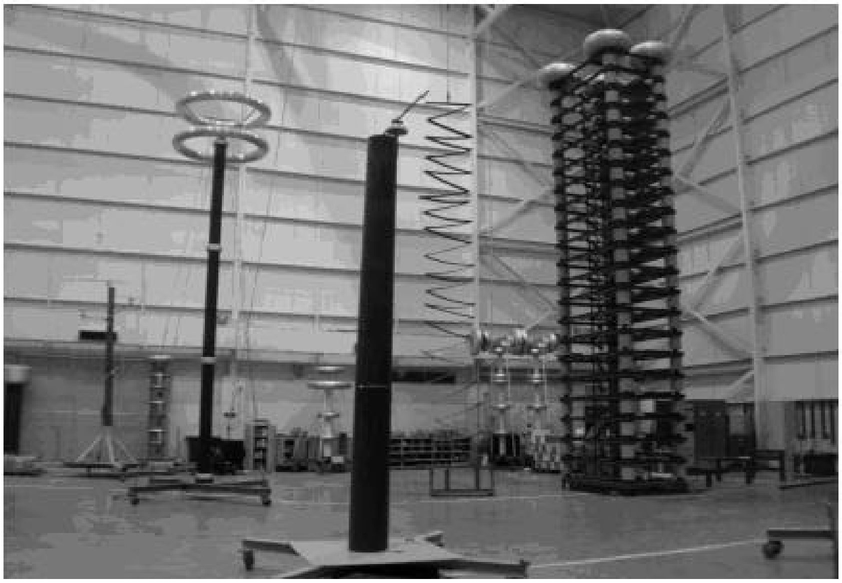

Fig. 2.2 The Test Setup for Evaluating the CFO Voltages of 35 kV Porcelain Pin Insulators Plus Fiberglass Poles.

The rain can be simulated in the tests through the use of a controlled water supply system. A set of adjustable nozzles was used to simulate rain with various precipitation rates. In the wet tests, the vertical and horizontal components of standard rain were used as specified by IEEE Std 4-1995. The water resistivity was 180-200 Ω· m and precipitation rate was 5±0.5 mm/min. In order to make the test data in wet tests more accurate, the fiberglass pole was carefully cleaned with clean water and thoroughly pre-wetted for at least 15 minutes before applying the lightning impulse.

## Test Results and Analysis

Two types of fiberglass poles were used for evaluating the CFO voltages. Tests were conducted under dry and wet conditions and positive and negative lightning impulse polarities. The tested pole lengths are from 1 foot to 8 feet. Table 2.1 presents the CFO voltages of brown and green fiberglass poles.

Table 2.1 The CFO Voltages of Fiberglass Poles (Brown and Green)

| Test Condition & Impulse Polarity<br>Insulation Strength (ft) | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| Brown Pole | 1 | 200 | 198 | 171 | 185 |
| | 2 | 374 | 397 | 313 | 358 |
| | 3 | 547 | 622 | 399 | 492 |
| | 4 | 725 | 791 | 521 | 614 |
| | 5 | 902 | 1022 | 675 | 789 |
| | 6 | 1056 | 1234 | 777 | 907 |
| | 7 | 1252 | 1419 | 835 | 1006 |
| | 8 | 1341 | 1546 | 951 | 1122 |
| Green Pole | 1 | 198 | 199 | 173 | 187 |
| | 2 | 378 | 425 | 308 | 323 |
| | 3 | 537 | 589 | 461 | 468 |
| | 4 | 692 | 739 | 629 | 680 |
| | 5 | 822 | 852 | 782 | 852 |
| | 6 | 947 | 1016 | 897 | 992 |
| | 7 | 1074 | 1150 | 1044 | 1161 |
| | 8 | 1201 | 1303 | 1158 | 1249 |

The previous published test results show that the CFO voltage of the wood pole for positive lightning impulses is approximately 15 % to 20 % less than for negative lightning impulses under dry conditions. For wet conditions, CFO voltage is about 5 % to 15 % less than under dry conditions regardless of the lightning impulse polarity [1].

From the test data in Table 2.1, the CFO voltages of the two types of fiberglass poles are almost directly proportional to the tested pole length. If the tested pole length is the same, the CFO voltage of the fiberglass pole for negative polarity is the greatest under dry conditions and it has the smallest value for positive polarity under wet conditions. The CFO voltage under wet conditions is less than under dry conditions for the same pole length and impulse polarity. The CFO voltage for positive polarity is less than for negative polarity for the same test and pole length.

Comparing the CFO voltages of the fiberglass pole to the CFO voltages of wood pole, it was found that the CFO voltage of the fiberglass pole is greater than that of the wood pole for the same pole length, lightning impulse polarity, and test condition. Also, the CFO voltage strength, the amount of CFO voltage per foot, of the fiberglass pole is approximately 20 kV/ft greater than that of the wood pole under wet conditions and for positive impulse [8]. Furthermore, the CFO voltage strengths of the fiberglass and the wood pole decrease with the increase of the pole length. For example, the CFO voltage strength decreases from 171 kV/ft at 1 foot to 119 kV/ft at 8 feet under wet condition and positive polarity lightning impulse. Under the same conditions, the CFO voltage strength of the wood pole decreases from 150 kV/ft at 1 foot to 97 kV/ft at 8 feet [8].

# Chapter III

## ADDED CFO VOLTAGES FROM FIBERGLASS POLES

### The CFO Voltages of Insulators

The insulation components used in a power distribution system are different and can exhibit different lightning impulse strengths. Furthermore, different lightning impulse strengths are also expected among different combinations of the insulation components. It is necessary for a design engineer to know the CFO voltages and BIL values of available insulation structures when designing a power distribution system. In this chapter, the CFO voltages of insulators and the CFO voltages of the combined insulation structures need to be evaluated at first in order to calculate the added CFO voltages from fiberglass poles in combined insulation structures.

In a power distribution system, the available insulation components include insulators, poles, cross-arms, standoffs, etc. Different types of insulators were commonly used as the basic insulation component in a combined insulation structure. The CFO voltages of the insulators have been studied for a long time. It was found that the CFO voltages of the insulator depend on the insulator's configuration because the configuration of insulator would affect the discharge path when flashover occurs.

In this chapter, the CFO voltages of different types of polymer and porcelain insulators are reported under dry and wet conditions and at positive and negative lightning impulses. The test results are presented in Table 3.1.

Table 3.1. The CFO Voltages of Polymer Suspension Insulators and Porcelain Pin Insulators

| Insulator type and Voltage Level, (kV) \ Test Condition & Impulse Polarity | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| Polymer Suspension Insulators | 15 | 163 | 187 | 159 | 174 |
| | 25 | 241 | 304 | 230 | 281 |
| | 35 | 310 | 384 | 309 | 354 |
| Porcelain Pin Insulators | 15 | 106 | 137 | 103 | 117 |
| | 25 | 119 | 139 | 118 | 127 |
| | 35 | 142 | 164 | 152 | 152 |

From Table 3.1, it can be seen that the CFO voltages of these two types of insulators follow the same discharge principle as a non-uniform electrical field in the air. In other words, the CFO voltages at negative lightning impulse are always higher than at positive lightning impulse and the CFO voltages under wet conditions are less than under dry conditions.

## The CFO Voltages of Polymer Suspension Insulators Plus Fiberglass Poles

### *Test Results*

In power distribution systems, the fiberglass pole can be used as a second or third insulation component in a combined insulation structure in order to improve the lightning impulse strength. Fig. 3.1 shows the typical configuration of a distribution line structure where the pole serves as a second insulation component.

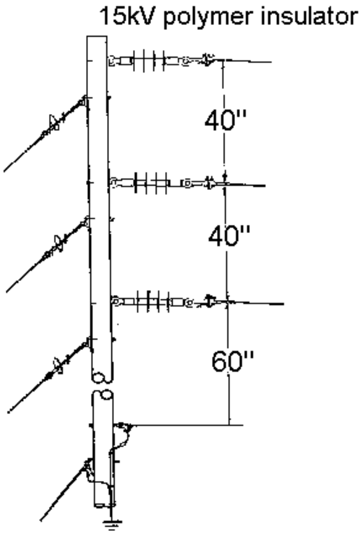

Fig. 3.1 The Typical Configuration of a 15 kV Distribution Line Structure

The CFO voltages of the fiberglass pole were presented in Chapter II. The total CFO voltages of polymer suspension insulators plus the fiberglass pole were evaluated under dry and wet conditions and at positive and negative lightning impulses. The rated voltages of tested insulators are 15 kV, 25 kV, and 35 kV. The tested insulation length of the fiberglass pole is from 1 foot up to 8 feet.

The total CFO voltages of 15 kV, 25 kV, and 35 kV polymer suspension insulators plus fiberglass poles are presented in Table 3.2, Table 3.3, and Table 3.4. The added CFO voltages from the fiberglass poles are also calculated and listed in these tables.

Table 3.2 The CFO Voltages of a 15 kV Polymer Suspension Insulator Plus a Fiberglass Pole and Added CFO Voltages from the Fiberglass Pole.

| Test Condition & Impulse Polarity / Fiberglass Pole length (ft) | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| 15 kV Insulator Plus Fiberglass Pole | 1 | 299 | 337 | 270 | 323 |
| | 2 | 487 | 490 | 443 | 440 |
| | 3 | 641 | 645 | 589 | 609 |
| | 4 | 796 | 812 | 738 | 772 |
| | 5 | 929 | 964 | 841 | 900 |
| | 6 | 1071 | 1125 | 931 | 999 |
| | 7 | 1196 | 1212 | 1069 | 1166 |
| | 8 | 1307 | 1351 | 1172 | 1253 |
| 15 kV Polymer Insulator | | 163 | 187 | 159 | 174 |
| Added CFO by Fiberglass Pole | 1 | 136 | 150 | 111 | 149 |
| | 2 | 324 | 303 | 284 | 266 |
| | 3 | 478 | 458 | 430 | 435 |
| | 4 | 633 | 625 | 579 | 598 |
| | 5 | 766 | 777 | 682 | 726 |
| | 6 | 908 | 938 | 772 | 825 |
| | 7 | 1033 | 1025 | 910 | 992 |
| | 8 | 1144 | 1164 | 1013 | 1079 |

Table 3.3 The CFO Voltages of a 25 kV Polymer Suspension Insulator Plus a Fiberglass Pole and Added CFO Voltages from the Fiberglass Pole.

| Test Condition & Impulse Polarity / Fiberglass Pole Length (ft) | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| 25 kV Insulator Plus Fiberglass Pole | 1 | 336 | 407 | 311 | 396 |
| | 2 | 505 | 546 | 460 | 490 |
| | 3 | 648 | 679 | 608 | 647 |
| | 4 | 828 | 849 | 762 | 815 |
| | 5 | 961 | 991 | 889 | 943 |
| | 6 | 1152 | 1199 | 1000 | 1063 |
| | 7 | 1290 | 1345 | 1160 | 1189 |
| | 8 | 1358 | 1388 | 1264 | 1288 |
| 25 kV Polymer Insulator | | 241 | 304 | 230 | 281 |
| Added CFO by Fiberglass Pole | 1 | 95 | 103 | 81 | 115 |
| | 2 | 264 | 242 | 230 | 209 |
| | 3 | 407 | 375 | 378 | 366 |
| | 4 | 587 | 545 | 532 | 534 |
| | 5 | 720 | 687 | 659 | 662 |
| | 6 | 911 | 895 | 770 | 782 |
| | 7 | 1049 | 1041 | 930 | 908 |
| | 8 | 1117 | 1084 | 1034 | 1007 |

Table 3.4 The CFO Voltages of a 35 kV Polymer Suspension Insulator Plus a Fiberglass Pole and Added CFO Voltages from the Fiberglass Pole.

| Test Condition & Impulse Polarity / Fiberglass Pole length (ft) | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| 35 kV Insulator Plus Fiberglass Pole | 1 | 463 | 531 | 406 | 429 |
| | 2 | 534 | 620 | 475 | 497 |
| | 3 | 675 | 742 | 623 | 659 |
| | 4 | 833 | 879 | 789 | 842 |
| | 5 | 981 | 1077 | 932 | 973 |
| | 6 | 1168 | 1221 | 1021 | 1089 |
| | 7 | 1281 | 1364 | 1191 | 1228 |
| | 8 | 1399 | 1443 | 1335 | 1353 |
| 35 kV Polymer Insulator | | 310 | 384 | 309 | 354 |
| Added CFO by Fiberglass Pole | 1 | 153 | 147 | 97 | 75 |
| | 2 | 224 | 236 | 166 | 143 |
| | 3 | 365 | 358 | 314 | 305 |
| | 4 | 523 | 495 | 480 | 488 |
| | 5 | 671 | 693 | 623 | 619 |
| | 6 | 858 | 837 | 712 | 735 |
| | 7 | 971 | 980 | 882 | 874 |
| | 8 | 1089 | 1059 | 1026 | 999 |

## *Discussion and Analysis*

### The CFO Voltages of Insulators Plus Fiberglass Poles

Fig 3.2 shows the total CFO voltages of 35 kV polymer suspension insulators plus fiberglass poles and the CFO voltages of fiberglass poles under dry and wet conditions and for a positive lightning impulse. Fig 3.3 shows the total CFO voltages of 35 kV polymer suspension insulators plus fiberglass poles and the CFO voltages of fiberglass poles under the dry and wet conditions and for a negative lightning impulse. Similar figures can be drawn from the CFO voltages of 15 kV or 25 kV polymer suspension insulators plus fiberglass poles.

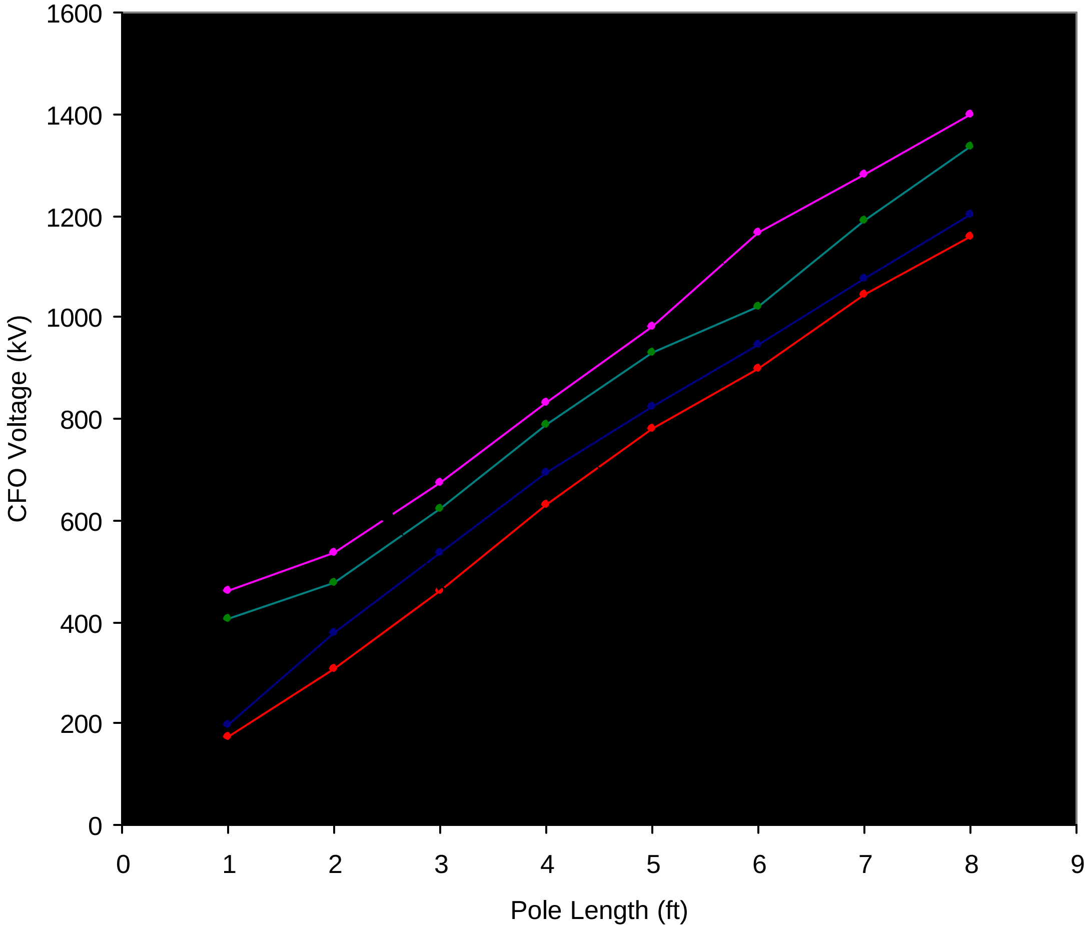

Fig. 3.2 The CFO Voltages of 35 kV Polymer Suspension Insulators Plus Fiberglass Poles and the CFO Voltages of Fiberglass Poles Alone under Dry and Wet Conditions for Positive Lightning Impulse.

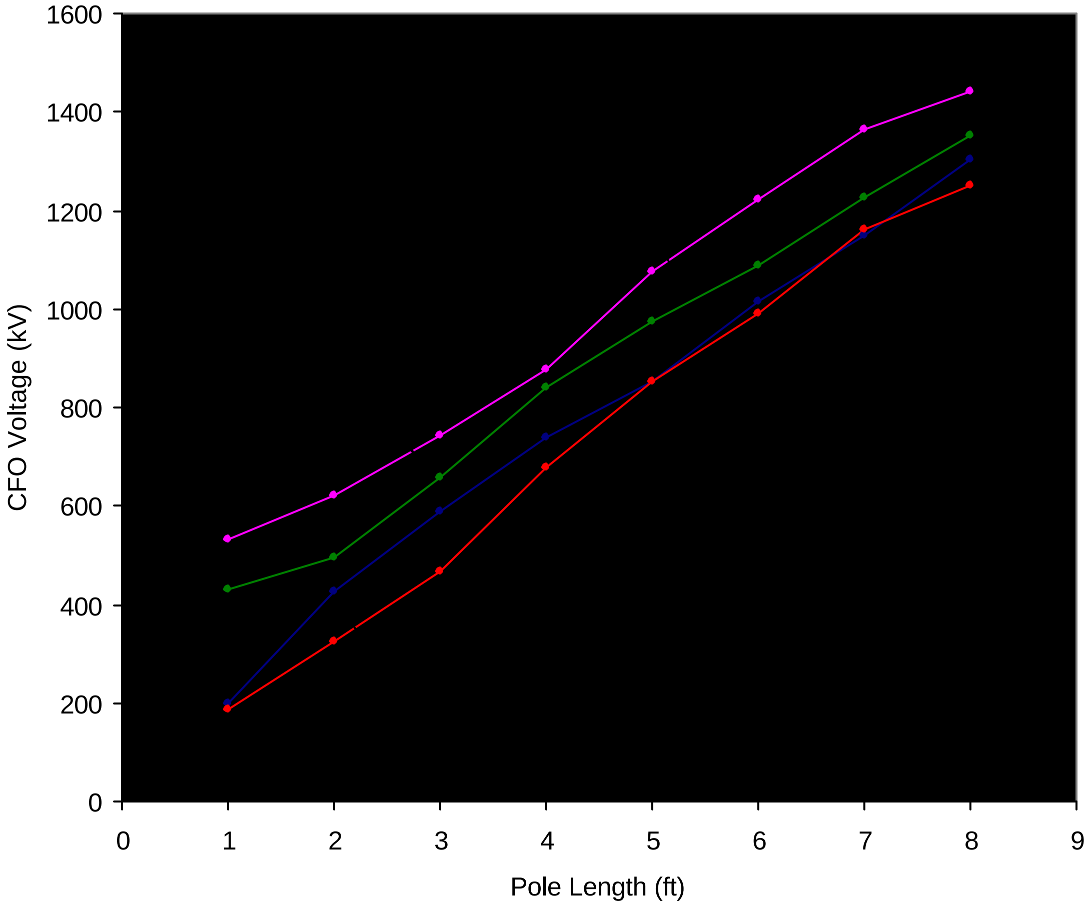

Fig. 3.3 The CFO Voltages of 35 kV Polymer Suspension Insulators Plus Fiberglass Poles and the CFO Voltages of Fiberglass Poles Alone under Dry and Wet Conditions for Negative Lightning Impulses

From Fig. 3.2 and Fig. 3.3, the total CFO voltages of polymer suspension insulators plus fiberglass poles have a linear relationship with the pole length. It is almost directly proportional to the pole length, regardless of the test condition and impulse polarity.

In the tests, the insulation failure of a combined insulation structure was caused by either the surface flashover or breakdown in the air. These two discharge phenomena are associated with the breakdown in the gaseous dielectric. Therefore, the measured CFO voltages should conform to the principle of breakdown of the gaseous dielectric, in spite of the types of discharges occurring in the combined insulation structure. In a gaseous dielectric, the flashover voltage is higher for a negative lightning impulse than for a positive lightning impulse when it is broken down. This principle was validated in the conducted tests for 15 kV, 25 kV, and 35 kV polymer suspension insulators plus fiberglass poles. The total CFO voltages of polymer suspension insulators plus fiberglass poles under dry conditions are much higher than under wet conditions for the same impulse polarity and tested pole length because the insulation strengths of dielectrics are much lower in the wet conditions.

The CFO voltage of a polymer suspension insulator plus a fiberglass pole is higher than that for wood pole under the same test condition, impulse polarity, and pole length. For example, when the tested pole length is 1 foot, the CFO voltage of a 15 kV polymer suspension insulator plus a fiberglass pole is 299 kV under dry conditions for a positive lightning impulse. The CFO voltage of a 15 kV polymer suspension insulator plus a wood pole is 250 kV under dry conditions for a positive lightning impulse [9]. Based on the previous statement, the fiberglass pole can improve the lightning impulse strength of the distribution line structure when used as a second insulation component in the distribution line structure.

When the individual insulation components are used in a combined insulation structure, their lightning impulse strengths would be changed slightly due to different insulation structures. Therefore, the total CFO voltage of a combined insulation structure is not equal to the sum of the CFO voltages of those individual insulation components. The results from the experiments show that the summation of the CFO voltage of the fiberglass pole and the CFO voltage of the insulator is not equal to the measured total CFO voltage of the combined insulation structure with the same insulator and pole length. The total CFO voltages of polymer suspension insulators plus fiberglass poles are presented in Fig. 3.4. The rated voltages of the tested polymer suspension insulators are 15 kV, 25 kV, and 35 kV.

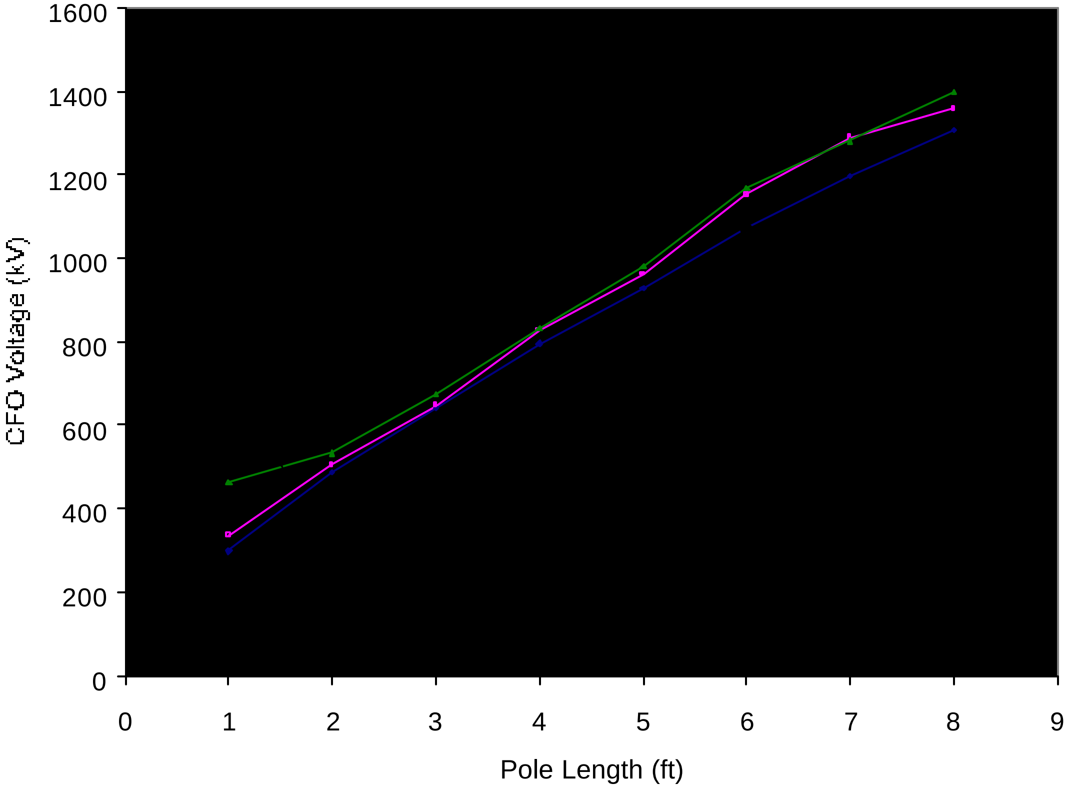

Fig. 3.4 The CFO Voltages of 15 kV, 25 kV, and 35 kV Polymer Suspension Insulators Plus Fiberglass Poles under Dry Conditions for Positive Lightning Impulses

The CFO voltage of a 35 kV polymer suspension insulator plus a fiberglass pole is the highest and the CFO voltage of a 15 kV polymer suspension insulator plus a fiberglass pole is the least among the three combined insulation structures if the test condition, impulse polarity, and tested pole length are the same. From Chapter II, it is known that the CFO voltages of these three types of polymer suspension insulators are different from each other.

## The Added CFO Voltages from Fiberglass Poles

The added CFO voltage from a fiberglass pole can be calculated by subtracting the CFO voltage of an insulator from the total CFO voltage of an insulator plus a fiberglass pole [1, 3, 8]. The added CFO voltage from a fiberglass pole indicates the lightning impulse strengths' difference between two different insulation structures, for example, a combined insulation structure and an insulation structure with a single insulation component. Although the CFO voltages of insulators would be slightly different in different insulation structures, the CFO voltages of individual insulation components are not used to calculate the added CFO voltage. Therefore, the variation of the CFO voltages of individual insulation components should have no impact on the calculation. Fig. 3.5 presents the CFO voltages of fiberglass poles and added CFO voltages from fiberglass poles to 35 kV polymer suspension insulators under dry and wet conditions for positive lightning impulses. The figures for 15 kV and 25 kV polymer suspension insulators are not shown but they are very similar to Fig. 3.5.

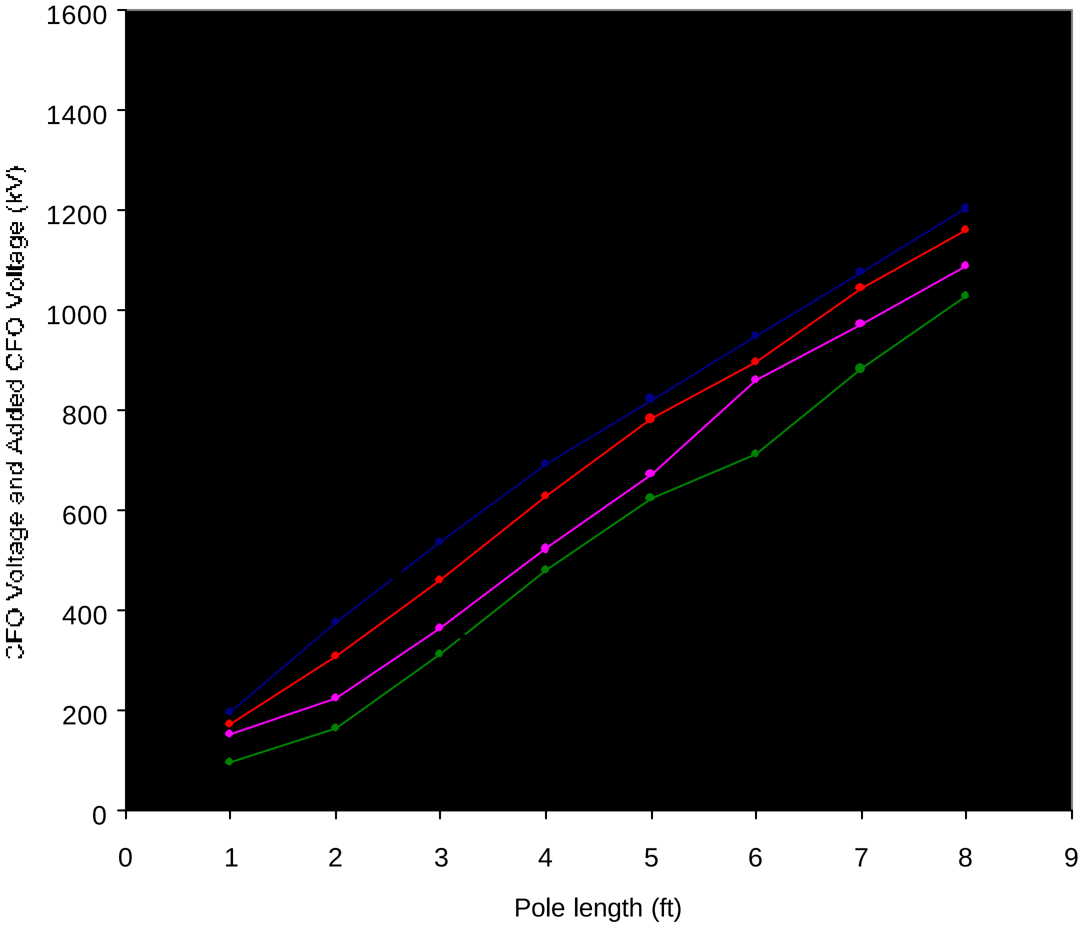

Fig.3.5 The CFO Voltages of Fiberglass Poles and the Added CFO Voltages from Fiberglass Poles to 35 kV Polymer Suspension Insulators under Dry and Wet Conditions for Positive Lightning Impulses

Analyzing Fig. 3.5 and the test results presented in Table 3.2 to Table 3.4, it can be found that the added CFO voltages from fiberglass poles to polymer suspension insulators are less than the CFO voltages of corresponding fiberglass poles when the test condition, impulse polarity, and tested pole length are the same. As mentioned before, the measured total CFO voltage of a combined insulation structure is less than the summation of CFO voltages of its insulation components. Based on the definition of the added CFO voltage, the added CFO voltages from fiberglass poles should be less than the CFO voltages of fiberglass poles alone. It is also known that the added CFO voltages from fiberglass poles to all polymer insulators are higher under dry conditions than under wet conditions from the results in Tables 3.2 to 3.4.

Also, the added CFO voltages to 15 kV polymer suspension insulators are higher than the added CFO voltages to 25 kV or 35 kV polymer insulators. This conclusion is not affected by such factors as test conditions and impulse polarity. The reason for this is that the CFO voltage of 15 kV polymer insulator is much less than for 25 kV and 35 kV polymer insulators. This conclusion suggests that the fiberglass pole, when used as an additional insulation component, can improve the lightning impulse strength of a combined insulation structure, but the amount of added CFO voltage is decided by the basic insulation component.

The added CFO voltage strength, which is defined as the amount of added CFO voltage per foot, is equal to the added CFO voltage divided by the tested pole length. This parameter is always used to indicate the lightning impulse strength of the fiberglass pole when it serves as a second or third insulation component.

Tables 3.5 to 3.7 show the added CFO voltage strengths from fiberglass poles for 15 kV, 25 kV, and 35 kV polymer suspension insulators under different test conditions and lightning impulse polarities. Fig. 3.6 shows the added CFO voltage strengths from fiberglass poles to 35 kV polymer suspension insulators.

Table 3.5 The Added CFO Voltage Strengths from Fiberglass Poles to 15 kV Polymer Suspension Insulators

| Test Condition & Impulse Polarity<br>Added CFO Voltage Strength (kV/ft) | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| 15 kV Insulator Plus Fiberglass Pole | 1 | 136 | 150 | 111 | 149 |
| | 2 | 162 | 152 | 142 | 133 |
| | 3 | 159 | 153 | 143 | 145 |
| | 4 | 158 | 156 | 145 | 150 |
| | 5 | 153 | 155 | 136 | 145 |
| | 6 | 151 | 156 | 129 | 138 |
| | 7 | 148 | 146 | 130 | 142 |
| | 8 | 143 | 146 | 127 | 135 |

Table 3.6 The Added CFO Voltage Strengths from Fiberglass Poles to 25 kV Polymer Suspension Insulators

| Added CFO Voltage Strength (kV/ft) \ Test Condition & Impulse Polarity | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| 25 kV Insulator Plus Fiberglass Pole | 1 | 95 | 103 | 81 | 115 |
| | 2 | 132 | 121 | 115 | 105 |
| | 3 | 136 | 125 | 126 | 122 |
| | 4 | 147 | 136 | 133 | 134 |
| | 5 | 144 | 137 | 132 | 132 |
| | 6 | 152 | 149 | 128 | 130 |
| | 7 | 150 | 149 | 133 | 130 |
| | 8 | 140 | 136 | 129 | 126 |

Table 3.7 The Added CFO Voltage Strengths from Fiberglass Poles to 35 kV Polymer Suspension Insulators

| Test Condition & Impulse Polarity / Added CFO Voltage Strength (kV/ft) | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| 35 kV Insulator Plus Fiberglass Pole | 1 | 153 | 147 | 97 | 75 |
| | 2 | 112 | 118 | 83 | 72 |
| | 3 | 122 | 119 | 105 | 102 |
| | 4 | 131 | 124 | 120 | 122 |
| | 5 | 134 | 139 | 125 | 124 |
| | 6 | 143 | 140 | 119 | 123 |
| | 7 | 139 | 140 | 126 | 125 |
| | 8 | 136 | 132 | 128 | 125 |

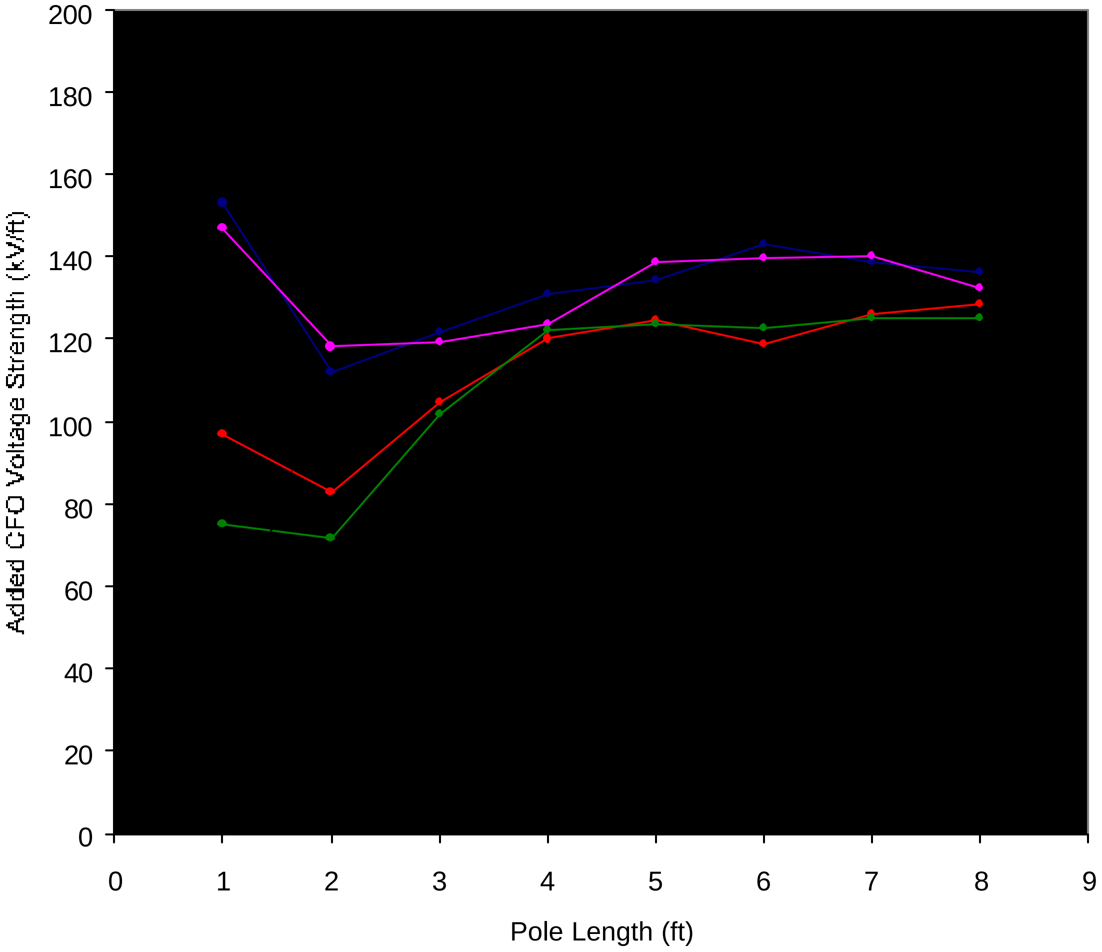

Fig. 3.6 The Added CFO Voltage Strengths from Fiberglass Poles to 35 kV Polymer Suspension Insulators under Dry and Wet Conditions for Positive and Negative Lightning Impulses.

The added CFO voltage strengths from fiberglass poles to polymer suspension insulators vary from 70 kV/ft up to 160 kV/ft when the test condition, impulse polarity, or pole length is changed. In general, the added CFO voltage strengths to polymer suspension insulators are higher under dry conditions than under wet conditions, but the added CFO voltage strengths under the negative lightning impulse are not always higher than for the positive lightning impulse. For most of the tested pole lengths, the added CFO voltage strengths under positive and negative lightning impulses are about the same. It also can be found that added CFO voltage strengths from fiberglass poles to polymer insulators vary within a small range when the tested pole length is longer than 3 feet. However, when the tested pole length is less than 3 feet, the added CFO voltage strengths can have large deviations.

The added CFO voltage strengths from wood poles to the polymer suspension insulator are 50-100 kV/ft under dry conditions and 20-50 kV/ft under wet conditions when the pole serves as a second insulation component [1]. It has been proved that the lightning impulse strength of a polymer suspension insulator plus a fiberglass pole is higher than a polymer suspension insulator plus a wood pole. As a result, the added CFO voltages and added CFO voltage strengths from a fiberglass poles are greater than a wood poles. From the above test results, the added CFO voltage strengths from fiberglass poles to polymer suspension insulators are 95-162 kV/ft under dry conditions and 72-145 kV/ft under wet conditions.

## The Discharge Path and Its Effect on CFO Voltage

For the combined insulation structure, the flashover always occurs on those paths where the tested insulation structure has the weakest impulse strength. Therefore, different discharge paths should be observed in the tests when the combined distribution line structure, the polymer suspension insulator and the fiberglass pole, are evaluated. The different discharge paths have a tremendous impact on the CFO voltages and added CFO voltages since the measured CFO voltages are determined by the lightning impulse strengths.

Several different discharge paths were seen when the fiberglass pole was used as additional insulation component. When the tested pole length is 1 foot, the discharge happened in the air gap between the energized insulator and the grounded electrode on the pole. This indicates that the lightning impulse strength of the combined insulation structure is higher than the air gap. When the tested pole length was 2 feet or above, the discharge always initiated through the air from the energized insulator to the pole surface about 1 foot below the top of the pole. Then the discharge traveled on the surface of the pole until the grounded electrode was reached. In a few cases, the discharge path was only on the insulator’s surface and pole’s surface. Hence, the lightning impulse strength of the air gap between the energized insulator and grounded electrode is higher than the surfaces of the insulator and pole when the tested pole length increased.

It is known that the lightning impulse strength of an insulation structure under wet conditions is much less than under dry conditions. Since the water in the wet tests did not affect the internal surface of the fiberglass pole, the discharge always appeared on the external surface of pole. The following discharge paths were observed in the tests:

1. The path started through the air from the energized polymer insulator to the external surface of the pole somewhere below the top of the pole. Then it traveled on the external surface of the pole and finally ended at the grounded electrode.
2. The path initiated through the air from the energized polymer insulator to the external surface of the pole somewhere below the top of the pole. Then it ended at the grounded electrode but appeared on both sides of the pole’s surfaces.
3. The path initiated from the energized insulator and developed on the surfaces of the insulator and the pole, either external or internal to the pole’s surface. Finally, it ended at the grounded electrode.

The discharge path depends on the test condition and tested insulation structure. Different discharge paths were observed even for the same test condition and insulation structure. For example, in the up and down test, the measured lightning impulse voltages varied in a wide range due to different discharge paths when applying the series of 20 lightning impulses. Therefore, the average value of these 20 lightning impulses, the CFO voltage of the tested combined insulation structure, greatly depends on the discharge path. The discharge path is one of the most important factors that affect the measured CFO voltage. The different discharge paths that were seen in the tests are presented in Appendix A.

## The CFO Voltages of Porcelain Pin Insulators Plus Fiberglass Poles

### *Test Results*

The porcelain pin insulator is commonly used on power distribution systems and their lightning impulse strengths have also been studied for many years. The CFO voltages of 15 kV, 25 kV, and 35 kV porcelain pin insulators were evaluated and the results are presented in Table 3.1. The CFO voltages of porcelain pin insulators plus fiberglass poles were also evaluated to determine the added CFO voltages. The tests were conducted under dry and wet conditions and positive and negative lightning impulses. The evaluated pole lengths were from 1 foot to 8 feet.

The CFO voltages of 15 kV, 25 kV, and 35 kV porcelain pin insulators plus fiberglass poles are presented in Table 3.8, Table 3.9 and Table 3.10. The added CFO voltages from fiberglass poles are also calculated and listed in the tables.

Table 3.8 The CFO Voltages of 15 kV Porcelain Pin Insulators Plus Fiberglass Poles and Added CFO Voltages from Fiberglass Poles.

| Fiberglass Pole length (ft) \ Test Condition & Impulse Polarity | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| 15 kV Insulator Plus Fiberglass Pole | 1 | 291 | 326 | 189 | 229 |
| | 2 | 387 | 486 | 308 | 323 |
| | 3 | 564 | 634 | 470 | 504 |
| | 4 | 714 | 771 | 632 | 696 |
| | 5 | 831 | 890 | 787 | 863 |
| | 6 | 985 | 1027 | 911 | 1005 |
| | 7 | 1082 | 1155 | 1068 | 1168 |
| | 8 | 1211 | 1304 | 1175 | 1246 |
| 15 kV Porcelain Insulator | | 106 | 137 | 103 | 117 |
| Added CFO by Fiberglass Pole | 1 | 185 | 189 | 86 | 112 |
| | 2 | 281 | 349 | 205 | 206 |
| | 3 | 458 | 497 | 367 | 387 |
| | 4 | 608 | 634 | 529 | 579 |
| | 5 | 725 | 753 | 684 | 746 |
| | 6 | 879 | 890 | 808 | 888 |
| | 7 | 976 | 1018 | 965 | 1051 |
| | 8 | 1105 | 1167 | 1072 | 1129 |

Table 3.9 The CFO Voltages of 25 kV Porcelain Pin Insulators Plus Fiberglass Poles and Added CFO Voltages from Fiberglass Poles.

| Test Condition & Impulse Polarity / Fiberglass Pole length (ft) | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| 25 kV Insulator Plus Fiberglass Pole | 1 | 317 | 339 | 295 | 314 |
| | 2 | 489 | 524 | 416 | 441 |
| | 3 | 601 | 674 | 567 | 566 |
| | 4 | 761 | 810 | 707 | 751 |
| | 5 | 883 | 934 | 848 | 903 |
| | 6 | 1004 | 1035 | 979 | 1013 |
| | 7 | 1133 | 1165 | 1104 | 1170 |
| | 8 | 1240 | 1311 | 1228 | 1257 |
| 25 kV Porcelain Insulator | | 119 | 139 | 118 | 127 |
| Added CFO by Fiberglass Pole | 1 | 185 | 189 | 162 | 165 |
| | 2 | 281 | 349 | 274 | 284 |
| | 3 | 458 | 497 | 422 | 417 |
| | 4 | 608 | 634 | 529 | 579 |
| | 5 | 725 | 753 | 684 | 746 |
| | 6 | 879 | 890 | 808 | 888 |
| | 7 | 976 | 1018 | 965 | 1051 |
| | 8 | 1105 | 1167 | 1072 | 1129 |

Table 3.10 The CFO Voltages of 35 kV Porcelain Pin Insulators Plus Fiberglass Poles and Added CFO Voltages from Fiberglass Poles.

| Test Condition & Impulse Polarity / Fiberglass Pole length (ft) | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| 35 kV Insulator Plus Fiberglass Pole | 1 | 325 | 343 | 323 | 340 |
| | 2 | 496 | 556 | 434 | 467 |
| | 3 | 643 | 697 | 575 | 590 |
| | 4 | 775 | 848 | 710 | 777 |
| | 5 | 907 | 950 | 859 | 911 |
| | 6 | 1022 | 1065 | 1000 | 1049 |
| | 7 | 1140 | 1181 | 1112 | 1187 |
| | 8 | 1274 | 1318 | 1237 | 1264 |
| 35 kV Porcelain Insulator | | 142 | 164 | 152 | 152 |
| Added CFO by Fiberglass Pole | 1 | 183 | 179 | 171 | 188 |
| | 2 | 354 | 392 | 282 | 315 |
| | 3 | 501 | 533 | 423 | 438 |
| | 4 | 633 | 684 | 558 | 625 |
| | 5 | 765 | 786 | 707 | 759 |
| | 6 | 880 | 901 | 848 | 897 |
| | 7 | 998 | 1017 | 960 | 1035 |
| | 8 | 1132 | 1154 | 1085 | 1112 |

## *Discussion and Analysis*

### The CFO Voltages of Insulators Plus Fiberglass Poles

The CFO voltages of a porcelain pin insulator plus a fiberglass pole have a relationship with the tested pole lengths that increases linearly. The insulation failure of this type of combined insulation structure is also related to the surface flashover. Therefore, the CFO voltage of a porcelain pin insulator plus a fiberglass pole under a negative lightning impulse is higher than that found under a positive lightning impulse. Also, the CFO voltage is higher under dry conditions than under wet conditions because the lightning impulse strength in the wet test is less than in the dry test. In all cases, the fiberglass pole will improve the lightning impulse strength of the distribution line structure with a porcelain pin insulator according to the previous results shown.

### The Added CFO Voltages from Fiberglass Poles

Based on the calculations and test results, the added CFO voltages are less than the measured CFO voltages of fiberglass pole for the same test conditions. Also, the added CFO voltages are higher under dry conditions than under wet conditions. The conclusions are based on three types of tested porcelain pin insulators. Table 3.11 to Table 3.13 present the added CFO voltage strengths under dry and wet conditions for positive and negative lightning impulses. The added CFO voltage strengths to a 25 kV porcelain pin insulator are presented in Fig. 3. 7.

Table 3.11 The Added CFO Voltage Strengths from Fiberglass Poles to 15 kV Porcelain Pin Insulators

| Test Condition & Impulse Polarity / Added CFO Voltage Strength (kV/ft) | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| 15 kV Insulator Plus Fiberglass Pole | 1 | 185 | 189 | 162 | 165 |
| | 2 | 141 | 175 | 137 | 142 |
| | 3 | 153 | 166 | 141 | 139 |
| | 4 | 152 | 159 | 132 | 145 |
| | 5 | 145 | 151 | 137 | 149 |
| | 6 | 147 | 148 | 135 | 148 |
| | 7 | 139 | 145 | 138 | 150 |
| | 8 | 138 | 146 | 134 | 141 |

Table 3.12 The Added CFO Voltage Strengths from Fiberglass Poles to 25 kV Porcelain Pin Insulators

| Added CFO Voltage Strength (kV/ft) \ Test Condition & Impulse Polarity | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| 25 kV Insulator Plus Fiberglass Pole | 1 | 198 | 200 | 177 | 187 |
| | 2 | 185 | 193 | 149 | 157 |
| | 3 | 161 | 178 | 150 | 146 |
| | 4 | 161 | 168 | 147 | 156 |
| | 5 | 153 | 159 | 146 | 155 |
| | 6 | 148 | 149 | 144 | 148 |
| | 7 | 145 | 147 | 141 | 149 |
| | 8 | 140 | 147 | 139 | 141 |

Table 3.13 The Added CFO Voltage Strengths from Fiberglass Poles to 35 kV Porcelain Pin Insulators

| Test Condition & Impulse Polarity<br>Added CFO Voltage Strength (kV/ft) | | Dry Condition | | Wet Condition | |
|---|---|---|---|---|---|
| | | Positive (kV) | Negative (kV) | Positive (kV) | Negative (kV) |
| 35 kV Insulator Plus Fiberglass Pole | 1 | 183 | 179 | 171 | 188 |
| | 2 | 177 | 196 | 141 | 158 |
| | 3 | 167 | 178 | 141 | 146 |
| | 4 | 158 | 171 | 140 | 156 |
| | 5 | 153 | 157 | 141 | 152 |
| | 6 | 147 | 150 | 141 | 150 |
| | 7 | 143 | 145 | 137 | 148 |
| | 8 | 142 | 144 | 136 | 139 |

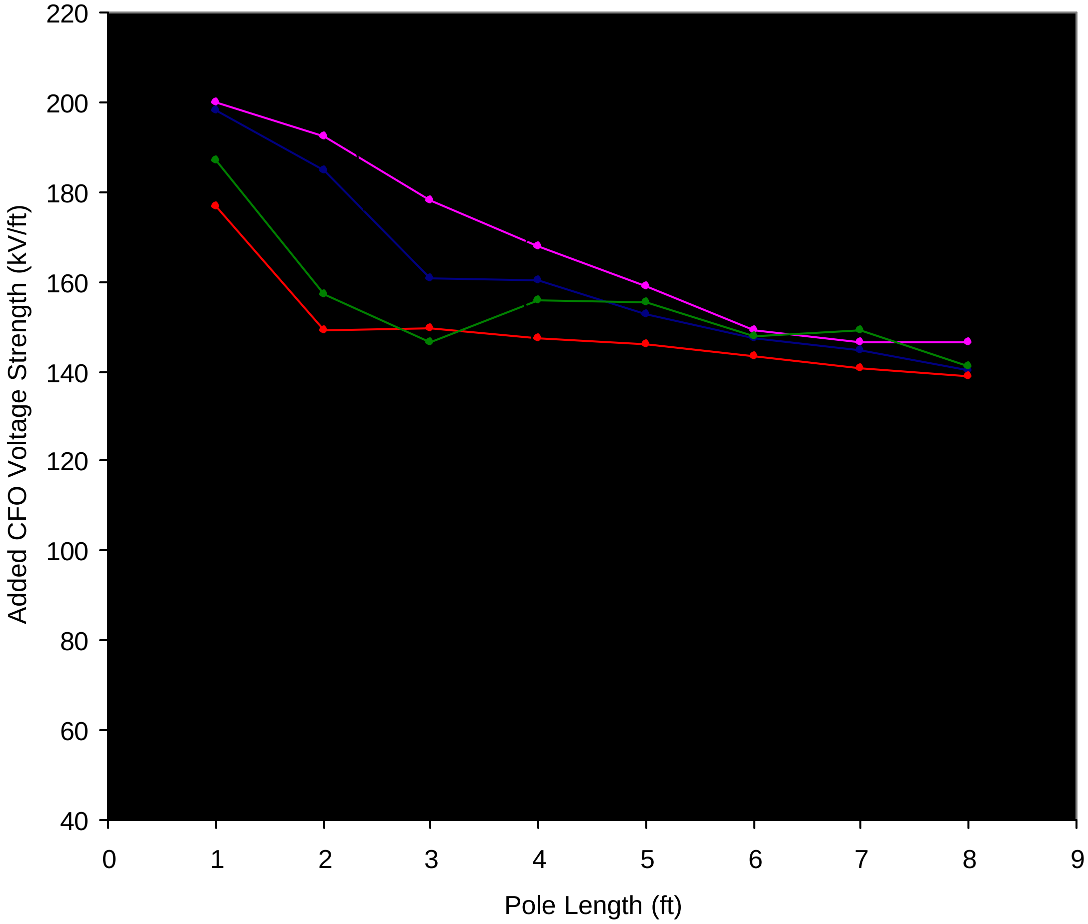

Fig. 3. 7 The Added CFO Voltage Strengths from Fiberglass Poles to 25 kV Porcelain Pin Insulators under Dry and Wet Conditions for Positive and Negative Lightning Impulses.

The added CFO voltage strengths decrease as the tested pole lengths increase based on the calculated results in Table 3.11 to Table 3.13. It also has a higher value in the dry conditions than in the wet conditions. When the wood pole is used as a second insulation component in a distribution line structure, the added CFO voltage strengths to porcelain pin insulators are 80-110 kV/ft under dry conditions and 20-50 kV/ft under wet conditions [1]. According to the results presented in the tables for the fiberglass pole, the added CFO voltage strengths to porcelain pin insulators are 140-200 kV/ft under dry conditions and 130-180 kV/ft under wet conditions. The added CFO voltage strength to porcelain pin insulators is much higher when a fiberglass pole is used as a second insulation component rather than a wood pole. The improvement of added CFO voltage strength is more obvious under wet conditions.

## The Discharge Path and Its Effect on CFO Voltage

Studies show that the interface between two different types of dielectrics always has the weakest insulation strength when the combined insulation structure is subjected to external electrical stress. Usually, the discharge would take place on the interface when external electrical stress exceeds the interface's insulation strength. The tested distribution line structure consists of a porcelain pin insulator and a fiberglass pole; the insulator's surface and the pole's surfaces have smaller lightning impulse strengths than the other discharge paths. If the flashover happened in the tests, the discharges were observed to travel on the surfaces of the insulator and the pole. Since both sides of the surfaces of fiberglass pole are exposed to the air, the discharge might take place on either side of the pole's surface depending on which side of the pole's surface has less lightning impulse strength. The discharges were also observed on both sides of the pole surfaces in cases where the tested pole would breakdown. Because the wet external surface has less lightning impulse strength than the internal surface in the wet tests, the discharges usually appear on the outside surface of the pole.

Unlike the combined insulation structure consisting of polymer suspension insulators and fiberglass poles, it is almost impossible for the discharge to appear in the air for the combined insulation structure with a porcelain pin insulator at the top of a fiberglass pole. When the porcelain pin insulator and the fiberglass pole were tested, different discharge paths were seen for the same combined insulation structure. Therefore, the effect of discharge paths on the CFO voltages of these types of combined insulation structures varies. The different discharge paths observed in the tests are presented in Appendix A.

# Conclusions

When the fiberglass pole is used as an additional insulation component, the measured CFO voltages and calculated added CFO voltages varied. As a result, different lightning impulse strengths are expected for the tested distribution line structures. In addition, the observed discharge paths are different from each other. Some conclusions can be drawn from the conducted tests:

## *The Fiberglass Pole*

- The CFO voltage of a fiberglass pole under positive lightning impulse is less than under negative lightning impulse for the same test conditions.
- The CFO voltage of a fiberglass pole under dry conditions is higher than under wet conditions if lightning impulse polarity is the same.

## *The Polymer Suspension Insulators Plus Fiberglass Poles*

- The CFO voltage of a polymer suspension insulator plus a fiberglass pole under a positive lightning impulse is less than under a negative lightning impulse for the same test conditions.
- The CFO voltage of a polymer suspension insulator plus a fiberglass pole under dry conditions is higher than that under wet conditions if lightning impulse polarity is the same.
- The added CFO voltage strength is mainly decided by the tested pole length and lightning impulse polarity. It usually has a higher value under dry conditions than under wet conditions and varies from 70 kV/ft to 160 kV/ft.

- The discharge paths vary when the flashovers take place, the discharge could appear on the insulation components’ surfaces and in the air. In the wet tests, the discharge always occurred on the external surface of the pole.

*The Porcelain Pin Insulators Plus the Fiberglass poles*

- Under a positive lightning impulse, the CFO voltage of a porcelain pin insulator plus a fiberglass pole is less than under a negative lightning impulse for the same test conditions.
- The CFO voltage of a porcelain pin insulator plus a fiberglass pole under dry conditions is higher than under wet conditions if the lightning impulse polarity is the same.
- The added CFO voltage strength decreases with the increase of the tested pole length. It decreases from 200 kV/ft to 140 kV/ft.
- The discharges were observed to develop only on the surfaces of the insulator and the pole. It usually occurred on the external surface of the pole in the wet tests.

# Chapter IV

# THE ELECTRICAL DEGRADATION OF THE FIBERGLASS POLES

## Test Methods and Setup

### *Accelerated Aging Tests*

In electric power systems, the insulation materials are subjected to all types of stresses when they are in service. The aging mechanisms are various for each class of insulation material because the materials' inherent insulation characteristics are different from each other. Therefore, different insulation materials have different electrical degradation even when they are subjected to the same aging stresses. In order to predict the insulation life, it is significant to know how the stress or stresses degrade the material's insulation strength.

The natural aging process of insulation material would take a very long time to complete. Hence, it is unreasonable to conduct natural aging tests in the laboratory. Therfore, different accelerated aging tests have been proposed as alternatives to the natural aging tests. In the accelerated aging test, the insulation material is subjected to a much higher electric stress than normal stress. At the same time, the other non-electrical aging stresses are also applied to the tested insulation material if necessary. As a result, the electrical degradation results of insulation material can be obtained after a much shorter period of time. The results from accelerated aging tests are always used in the aging models to predict the insulation life.

Four types of accelerated aging tests were conducted based on the standards [10, 11, 12]. These accelerated aging tests include:

- 1000 Hours Aging in Clean Fog
- 1000 Hours Aging in Salt Fog
- 1000 Hours Aging in Clean Fog plus 25 kV AC Voltage
- 1000 Hours Aging in Salt Fog plus 25 kV AC Voltage

The fog chamber is the most widely used tool to conduct the accelerated aging tests in laboratory research, and it has been used for accelerated aging tests of other organic insulation materials. The dimensions of the used fog chamber are 3m×3m ×3m. Two sets of nozzles were mounted on the inner walls of the fog chamber to simulate the fog. One is for distilled or salt water, and the other is for compressed air. The fog was produced by a stream of compressed air flowing at right angle to the solution nozzle. The water flow rate was 0.4±0.1 liter/min [12]. In the salt fog tests, NaCl was added to the water to produce the salt fog. The NaCl content in the water was 10 ± 0.5 $kg/m^3$ [12]. The external electrical stress was applied to the tested samples through a porcelain bushing mounted on one of the walls of the fog chamber. According to the standard [12], the accelerated aging test duration should be 1000 hours. Figure 4.1 shows the setup for accelerated aging tests.

Fig. 4.1 The Setup of the Transformer and the Fog Chamber Used in the Accelerated Aging Tests.

Five sets of fiberglass samples were used in the accelerated aging tests and each set consists of nine fiberglass samples. The tested insulation length of these samples was chosen as 12 inches [11]. Two metallic bands, upper and bottom, were used as electrodes and tightly wrapped on the samples. The upper electrode is energized and the bottom electrode was grounded when external electrical stress is considered as an aging stress. To investigate the effect of samples' surface conditions on the material's electrical degradation, the nine tested samples were divided into three groups. The external surfaces of the first group of tested samples were kept intact, but some scratches were manually placed on the external surfaces of the second group. For the third group, five holes, each with 1 inch in diameter, were manually drilled in each sample. The samples with different surface conditions are presented in Appendix B. Two types of the fiberglass samples, brown and green samples, were used in these accelerated aging tests in order to investigate the electrical degradation of different fiberglass materials.

### *Electrical Tests Before and After Accelerated Aging Process*

The electrical degradation of insulation material is reflected by the decrease of its insulation strength. Therefore, the electrical degradation of fiberglass material can be obtained by evaluating its insulation strength before and after accelerated aging tests. According to "IEEE Recommended Practice for Specifying Distribution Composite Insulator" [10], "Standard Specification for Fiberglass-Reinforced Plastic Rod and Tube Used in Live Line" [11] and "IEEE Standard Techniques for High-Voltage Testing" [7], the electrical tests used to evaluate the insulation strength of fiberglass material are

- The lightning impulse tests

- The AC dry flashover tests
- The AC wet flashover tests

The alternating (AC) leakage current tests were conducted before and after the accelerated aging tests because the surface leakage current is an important indicator of material's insulation strength. The measured electrical parameters included AC leakage current, the AC dry flashover voltage and AC wet flashover voltage, and CFO voltages under dry and wet conditions. To improve the test accuracy, each sample was tested for three times and the average value of the three tests was chosen as the final result.

In the lightning impulse tests, a Marx multi-stage impulse voltage generator was used to generate the 1.2/50µs standard lightning impulse, and the up and down method was used to evaluate the CFO voltages of the samples. The measurement system is the same as for the CFO voltage tests of fiberglass pole. Also, the atmospheric condition correction factors were calculated and applied to the measured data by using the atmospheric condition correction formulas in Chapter II.

The single-phase AC testing transformer was used to perform the AC leakage current tests and AC flashover voltage tests. The digital multi-meters were used to monitor and measure the AC voltages and currents for the purpose of a higher accuracy. In the AC leakage current test, the upper electrode was energized and a shunt resistor was connected between the bottom electrode and ground. The measured voltage across the shunt resistor divided by the resistance of the shunt resistor is the leakage current flowing though the fiberglass sample.

The AC flashover and lightning impulse tests were conducted under dry and wet conditions. The positive lightning impulse was used to evaluate the CFO voltages. In the wet tests, the water supply system, precipitation rate, the vertical and horizontal components of standard rain, and water resistivity were the same as those specified in Chapter II.

## Test Results and Analysis

### *1000 Hours Aging in Clean Fog*

One set of brown fiberglass samples and one set of green fiberglass samples were tested in the 1000 hours clean fog accelerated aging test. The AC dry and wet flashover voltages, the AC leakage currents, and the CFO voltages were measured before and after the aging test. For each set of samples, the samples with undamaged external surfaces were labeled as No.1 to No.3, the samples with some scratches on their external surfaces were labeled as No.4 to No.6, and the samples with holes were labeled as No.7 to No.9.

The CFO voltages of the brown and green samples and their AC dry and wet flashover voltages are presented in Table 4.1 to Table 4.4, respectively. Under dry conditions, the AC leakage currents were measured as a function of the applied voltages. The applied voltage started from 10 kV, then it was increased 10 kV each time until the flashover occurred. The measured leakage currents at 100 kV are presented in Table 4.5.

Table 4.1 The CFO Voltages of Brown Samples Before and After 1000 Hours Aging in Clean Fog

| CFO<br>Sample | Dry Condition | | Wet Condition | |
|---|---|---|---|---|
| | Before (kV) | After (kV) | Before (kV) | After (kV) |
| No.1 | 212 | 212 | 156 | 152 |
| No.2 | 208 | 208 | 169 | 163 |
| No.3 | 208 | 207 | 161 | 157 |
| No.4 | 213 | 213 | 140 | 137 |
| No.5 | 202 | 202 | 137 | 134 |
| No.6 | 208 | 207 | 137 | 132 |
| No.7 | 214 | 213 | 176 | 172 |
| No.8 | 211 | 209 | 141 | 140 |
| No.9 | 207 | 206 | 158 | 157 |

Table 4.2 The CFO Voltages of Green Samples Before and After 1000 Hours Aging in Clean Fog

| CFO<br>Sample | Dry Condition | | Wet Condition | |
|---|---|---|---|---|
| | Before (kV) | After (kV) | Before (kV) | After (kV) |
| No.1 | 207 | 195 | 182 | 183 |
| No.2 | 207 | 198 | 177 | 145 |
| No.3 | 207 | 192 | 177 | 176 |
| No.4 | 205 | 189 | 172 | 164 |
| No.5 | 206 | 198 | 174 | 168 |
| No.6 | N/A | N/A | N/A | N/A |
| No.7 | 207 | 195 | 176 | 172 |
| No.8 | 207 | 196 | 173 | 163 |
| No.9 | 204 | 193 | 175 | 155 |

Table 4.3 The AC Dry and Wet Flashover Voltages of Brown Samples Before and After 1000 Hours Aging in Clean Fog

| AC<br>Sample | Dry Condition | | Wet Condition | |
|---|---|---|---|---|
| | Before (kV) | After (kV) | Before (kV) | After (kV) |
| No.1 | 135 | 130 | 45 | 43 |
| No.2 | 128 | 124 | 44 | 42 |
| No.3 | 130 | 130 | 47 | 45 |
| No.4 | 129 | 127 | 51 | 49 |
| No.5 | 127 | 111 | 43 | 41 |
| No.6 | 127 | 112 | 49 | 47 |
| No.7 | 126 | 129 | 60 | 58 |
| No.8 | 131 | 130 | 55 | 54 |
| No.9 | 125 | 47 | 43 | 15 |

Table 4.4 The AC Dry and Wet Flashover Voltages of Green Samples Before and After 1000 Hours Aging in Clean Fog

| AC<br>Sample | Dry Condition | | Wet Condition | |
|---|---|---|---|---|
| | Before (kV) | After (kV) | Before (kV) | After (kV) |
| No.1 | 119 | 126 | 74 | 57 |
| No.2 | 125 | 124 | 71 | 57 |
| No.3 | 123 | 122 | 72 | 52 |
| No.4 | 126 | 124 | 69 | 54 |
| No.5 | 124 | 124 | 72 | 52 |
| No.6 | N/A | N/A | N/A | N/A |
| No.7 | 125 | 129 | 70 | 55 |
| No.8 | 124 | 127 | 68 | 56 |
| No.9 | 123 | 124 | 65 | 50 |

Table 4.5 The AC Leakage Currents of Brown and Green Samples at 100 kV Before and After 1000 Hours Aging in Clean Fog

| AC Current / Sample | Brown Sample (at 100 kV) | | Green Sample (at 100 kV) | |
|---|---|---|---|---|
| | Before (μA) | After (μA) | Before (μA) | After (μA) |
| No.1 | 206 | 257 | 229 | 242 |
| No.2 | 231 | 1886 | 233 | 259 |
| No.3 | 216 | 226 | 220 | 310 |
| No.4 | 222 | 261 | 217 | 282 |
| No.5 | 236 | 2546 | 227 | 281 |
| No.6 | 248 | 2275 | N/A | N/A |
| No.7 | 207 | 237 | 200 | 252 |
| No.8 | 183 | 216 | 218 | 279 |
| No.9 | 190 | 217 | 221 | 302 |

The CFO voltages and AC flashover voltages under dry conditions are higher than under wet conditions for all of the tested samples. The wet AC flashover voltages are only about a half of the dry AC flashover voltages. Among the samples with different external surface conditions, the CFO voltages and AC flashover voltages did not show obvious differences.

After 1000 hours of aging in clean fog, there was no apparent decrease of the CFO voltages, especially in the dry tests. When the brown and green samples are compared, it is found that the CFO voltages of green samples decrease more than the brown samples after the aging tests. The AC flashover voltages after the aging tests are only slightly less than before the aging tests. The AC leakage currents of the samples have higher values after the aging tests. After the clean fog aging test, the leakage currents of three brown fiberglass samples are ten or more times higher than before the aging test. The magnitudes of the leakage currents are less than 3 milliamperes. The measured leakage currents of the green samples are only slightly higher than before the aging and they are in the range of microamperes.

From the lightning impulse, AC flashover, and leakage current tests, the electrical insulation strength of the tested fiberglass samples did not have a significant decrease after the clean fog test. As a result, the clean fog test has a negligible effect on the electrical degradation of fiberglass material when selected as an aging stress. Furthermore, the sample’s external surface condition is not an important factor on influencing the electrical degradation in the clean fog test.

After the clean fog aging test, the information on the electrical degradation of fiberglass samples is obtained by measuring their electrical parameters. It is noticed that the leakage current of the sample is a more sensitive indicator of electrical degradation than other electrical parameters, especially when the electrical degradation is not very obvious. In general, after the aging test, if the measured leakage current increases to a high magnitude, it can be concluded that obvious electrical degradation of the fiberglass material has occurred. The electrical degradation of insulation material could be estimated by analyzing such electrical parameters as leakage current, AC flashover voltage and CFO voltage.

### *1000 Hours Aging in Salt Fog*

One set of green fiberglass samples was used in the 1000 hours salt fog accelerated aging test. The same electrical tests were conducted for these samples before and after the aging test. The CFO voltages, the AC dry and wet flashover voltages, and AC leakage currents at 100 kV are presented in Table 4.6 to Table 4.8, respectively.

Table 4.6 The CFO Voltages of Green Samples Before and After 1000 Hours Aging in Salt Fog

| CFO | Dry Condition | | Wet Condition | |
|---|---|---|---|---|
| Sample | Before (kV) | After (kV) | Before (kV) | After (kV) |
| No.1 | 227 | 218 | 198 | 151 |
| No.2 | 224 | 207 | 201 | 149 |
| No.3 | 225 | 219 | 201 | 158 |
| No.4 | 224 | 209 | 197 | 143 |
| No.5 | 225 | 216 | 198 | 128 |
| No.6 | 226 | 208 | 200 | 132 |
| No.7 | 217 | 214 | 188 | 145 |
| No.8 | 215 | 207 | 187 | 144 |
| No.9 | 220 | 208 | 189 | 154 |

Table 4.7 The AC Dry and Wet Flashover Voltages of Green Samples Before and After 1000 Hours Aging in Salt Fog

| AC | Dry Condition | | Wet Condition | |
|---|---|---|---|---|
| Sample | Before (kV) | After (kV) | Before (kV) | After (kV) |
| No.1 | 136 | 114 | 61 | 37 |
| No.2 | 135 | 117 | 61 | 42 |
| No.3 | 137 | 114 | 61 | 42 |
| No.4 | 124 | 114 | 60 | 34 |
| No.5 | 134 | 99 | 60 | 36 |
| No.6 | 133 | 117 | 60 | 36 |
| No.7 | 134 | 102 | 58 | 35 |
| No.8 | 131 | 117 | 57 | 36 |
| No.9 | 131 | 115 | 59 | 36 |

Table 4.8 The AC Leakage Currents of Green Samples at 100 kV Before and After 1000 Hours Aging in Salt Fog

| Current / Sample | Green Sample (at 100 kV AC) | |
|---|---|---|
| | Before (μA) | After (μA) |
| No.1 | 206 | 432 |
| No.2 | 210 | 481 |
| No.3 | 205 | 849 |
| No.4 | 198 | 407 |
| No.5 | 174 | N/A |
| No.6 | 197 | 452 |
| No.7 | 179 | 641 |
| No.8 | 183 | 473 |
| No.9 | 203 | 532 |

The CFO voltages and AC dry and wet flashover voltages are apparently less than before the aging tests, especially in the wet tests. The leakage currents are two or three times higher than before the aging test. The electrical strengths of the tested samples have been decreased significantly after they were exposed to the salt fog for 1000 hours. After the salt fog aging test, the electrical test results are almost the same for the samples with different external surface conditions. This indicates that the sample's external surface condition has insignificant impact on its electrical degradation due to salt fog.

By comparing the test results from the clean fog test with those from salt fog test, it is found that the insulation strengths of the samples decrease after these aging tests. However, the salt fog test has a more negative impact on the sample's insulation strength than the clean fog test.

The fog was the only aging stress in these two types of accelerated aging tests. However, there are different reasons why the insulation strengths decreased after the aging tests. In the clean fog test, both sides of the sample's surfaces were thoroughly exposed to the fog. After a very long period of time, the fiberglass sample absorbed a small amount of the water on sample's surfaces. When the electrical tests were conducted after the aging test, the fiberglass sample's insulation strengths were decreased due to the water currently residing in the fiberglass sample even in the dry tests.

After the salt fog test, the salt granules on the samples' surfaces and water absorbed by fiberglass samples both have an impact on the decrease of insulation strengths of the samples. The tiny salt granules from salt fog would contaminate the surfaces of the samples in the salt fog test. Under dry conditions, these tiny salt granules have little effect on the electrical strengths; the absorbed water by fiberglass material is the main reason for its electrical degradation. This supports the test result that the CFO voltages and AC flashover voltages under dry conditions after the salt fog test are almost the same as those after the clean fog test. In wet tests, the tiny salt granules dissolved in the water droplets on the sample's surface. Therefore, the conductivity of water became very high, which makes the insulation strength of the fiberglass sample decrease greatly. As a result, the CFO voltages and AC flashover voltages under wet conditions are apparently less than before salt fog test. Also, the measured leakage currents increased two or three times due to surface's high conductivity.

The salt fog, another aging stress, was proved to have an impact on the fiberglass material's electrical degradation. On the other hand, its aging effect is limited since no tracking and erosion phenomena appeared on both sides of the samples' surfaces after the conducted test.

### *1000 Hours Aging in Clean Fog Plus 25 kV AC Voltage*

One set of green fiberglass samples was aged in clean fog for 1000 hours. At the same time, the AC voltage with a magnitude of 25 kV was applied to nine samples. The same electrical tests were performed for the samples. The CFO voltages, the AC flashover voltages, and leakage currents at 100 kV are presented in Table 4.9 to Table 4.11, respectively.

Table 4.9 The CFO Voltages of Green Samples Before and After 1000 Hours Aging in Clean Fog Plus 25 kV AC Voltage

| CFO<br>Sample | Dry Condition | | Wet Condition | |
|---|---|---|---|---|
| | Before (kV) | After (kV) | Before (kV) | After (kV) |
| No.1 | 222 | 206 | 202 | 181 |
| No.2 | 216 | 206 | 194 | 184 |
| No.3 | 222 | 209 | 195 | 183 |
| No.4 | 217 | 205 | 196 | 175 |
| No.5 | 213 | 204 | 195 | 175 |
| No.6 | 217 | 205 | 197 | 174 |
| No.7 | 217 | 200 | 180 | 168 |
| No.8 | 213 | 198 | 196 | 169 |
| No.9 | 213 | 196 | 200 | 169 |

Table 4.10 The AC Dry and Wet Flashover Voltages of Green Samples Before and After 1000 Hours Aging in Clean Fog Plus 25 kV AC Voltage

| AC<br>Sample | Dry Condition | | Wet Condition | |
|---|---|---|---|---|
| | Before (kV) | After (kV) | Before (kV) | After (kV) |
| No.1 | 119 | 113 | 61 | 58 |
| No.2 | 120 | 117 | 62 | 58 |
| No.3 | 131 | 123 | 62 | 58 |
| No.4 | 116 | 114 | 61 | 54 |
| No.5 | 116 | 115 | 60 | 54 |
| No.6 | 116 | 114 | 60 | 54 |
| No.7 | 116 | 111 | 59 | 51 |
| No.8 | 116 | 116 | 59 | 52 |
| No.9 | 117 | 115 | 59 | 49 |

Table 4.11 The AC Leakage Currents of Green Samples at 100 kV Before and After 1000 Hours Aging in Clean Fog Plus 25 kV AC Voltage

| Current / Sample | Green Sample (at 100 kV AC) | |
|---|---|---|
| | Before (μA) | After (μA) |
| No.1 | 163 | 171 |
| No.2 | 131 | 137 |
| No.3 | 160 | 176 |
| No.4 | 176 | 180 |
| No.5 | 165 | 227 |
| No.6 | 165 | 176 |
| No.7 | 161 | 175 |
| No.8 | 162 | 165 |
| No.9 | 149 | 192 |

The CFO voltages and AC flashover voltages decreased by a large amount after the aging test. Also, after the aging test, the increase of leakage currents after the clean fog plus AC voltage test is obvious but not as much as for the salt fog test. The electrical degradation of fiberglass samples is shown by the measured electrical parameters before and after the aging test. However, the samples with different external surface conditions still have similar insulation strengths after the aging test.

After exposed to clean fog and 25 kV/ft electrical stress for 1000 hours, the electrical test results, especially the CFO voltages, are less than those from the clean fog test. Hence, the external electrical stress has a significant impact on the electrical degradation of fiberglass material.

The electrical degradation caused by the salt fog test is more severe than that caused by the clean fog plus electrical stress test. However, based on the conducted tests, it cannot be concluded that the electrical degradation of fiberglass material caused by the salt fog test is more severe than clean fog plus electrical stress test, because the conducted accelerated aging tests only lasted 1000 hours and the applied external electrical stress is only 25 kV/ft. The fiberglass material might have less severe electrical degradation in the clean fog plus electrical stress test than in the salt fog test due to different aging procedures. If the duration of clean fog plus electrical stress test was extended to a longer time and/or a higher external electrical stress was applied to the tested fiberglass samples, there would be more severe electrical degradation. In some laboratory research, the duration of aging tests were extended, such as 2500 hours, in order to study insulation materials' abilities to resist electrical degradation and analyze their performances [16].

### *1000 Hours Aging in Salt Fog Plus 25 kV AC Voltage*

One set of green fiberglass samples was used in salt fog plus electrical stress aging test. In this aging test, the 25 kV/ft external electrical stress was applied to the samples when they were exposed to the salt fog in the fog chamber. All of them were damaged in less than 10 hours. The electrical tests were only performed before the aging test. The CFO voltages and the AC flashover voltages are presented in Table 4.12 to Table 4.13, respectively. In Table 4.14, the AC leakage currents at 100 kV, the recorded maximum leakage currents in the test, and the time to cause flashovers are presented.

Table 4.12 The CFO Voltages of Green Samples Before 1000 Hours Aging in Salt Fog Plus 25 kV AC Voltage

| CFO<br>Sample | Dry Condition | | Wet Condition | |
|---|---|---|---|---|
| | Before (kV) | After (kV) | Before (kV) | After (kV) |
| No.1 | 200 | N/A | 182 | N/A |
| No.2 | 200 | N/A | 183 | N/A |
| No.3 | 200 | N/A | 182 | N/A |
| No.4 | 197 | N/A | 177 | N/A |
| No.5 | 197 | N/A | 177 | N/A |
| No.6 | 198 | N/A | 177 | N/A |
| No.7 | 196 | N/A | 177 | N/A |
| No.8 | 195 | N/A | 176 | N/A |
| No.9 | 196 | N/A | 176 | N/A |

Table 4.13 The AC Dry and Wet Flashover Voltages of Green Samples Before1000 Hours Aging in Salt Fog plus 25 kV AC Voltage

| AC<br>Sample | Dry Condition | | Wet Condition | |
|---|---|---|---|---|
| | Before (kV) | After (kV) | Before (kV) | After (kV) |
| No.1 | 132 | N/A | 63 | N/A |
| No.2 | 127 | N/A | 63 | N/A |
| No.3 | 128 | N/A | 63 | N/A |
| No.4 | 132 | N/A | 62 | N/A |
| No.5 | 130 | N/A | 62 | N/A |
| No.6 | 129 | N/A | 62 | N/A |
| No.7 | 127 | N/A | 58 | N/A |
| No.8 | 128 | N/A | 61 | N/A |
| No.9 | 125 | N/A | 57 | N/A |

Table 4.14 The AC Leakage Currents of Green Samples at 100kV Before Aging in Salt Fog Plus 25 kV AC Voltage, Recorded Maximum Leakage Currents During the Aging Process, and Time to Cause Flashovers

| Current / Sample | AC Leakage Current Before Aging Test (at 100 kV AC, µA ) | Recorded Maximum Leakage Current During the Aging Process (mA) | Time to Cause Flashovers (Hour) |
|---|---|---|---|
| No.1 | 143 | 80~100 | 6.5 |
| No.2 | 146 | 70~90 | 4.5 |
| No.3 | 175 | 70~90 | 5.5 |
| No.4 | 129 | 75~85 | 6 |
| No.5 | 140 | 40~70 | 3.5 |
| No.6 | 169 | 55~70 | 5 |
| No.7 | 146 | 45~85 | 5 |
| No.8 | 148 | 50~75 | 4 |
| No.9 | 158 | 40~80 | 4.5 |

Some of the damaged samples are shown in Appendix B. The trackings are found on both sides of the samples' surfaces from the photographs in Appendix B. Some damaged samples have more visible tracking on their external surfaces, and the others have more visible tracking on their internal surface. It is known that the tracking of insulation material has the weakest insulation strength when the material is subjected to external electrical stress. Therefore, the discharge always takes place on those places where the tracking appears, and eventually the complete flashover would occur if the insulation strength of the tested insulation material became less than the applied electrical stress.

The development of tracking is described in the following sentences. After the fiberglass sample was exposed to the salt fog, the surface conductivity of the sample became very high due to salt water on its surfaces. Due to the high surface conductivity, high leakage current would flow through the surfaces of the sample when the electrical stress was applied. At some areas on the surfaces, the insulation strength was so low that local surface discharges would appear on those areas. The insulation of the fiberglass material was deteriorated under the combined effect of the local discharges, electrical stress, and salt fog. The local discharges on the surfaces of fiberglass sample will last a relatively long period of time such as several hours. During the process of local discharges, the insulation strength of the tested fiberglass material became less and less. Since the samples were subjected to electrical stress simultaneously, the decreased insulation strength means higher leakage current and more intensive local discharges, which would degrade the fiberglass material's insulation strengths at a faster rate. This phenomenon continued to develop until the tracking appeared on the surfaces and eventually resulted in flashover.

The previous analysis was supported by the following experimental phenomena. At the beginning of the aging test, tiny sparks were seen on the surfaces of the sample; after a while, these tiny sparks gradually evolved into more intensive local discharges. At the same time, the leakage currents increased and varied with a wider range. These sparks and local discharges will last several hours until the flashover happened.

Based on the test results, the salt fog, if combined with electrical stress, has the most severe impact on the electrical degradation of the fiberglass material. Therefore, the fiberglass pole is not suitable for those environments where salt fog occurs very frequently.

For each group of tested fiberglass samples, the minimum, average, and maximum values of the measured electrical parameters are listed in Table 4.15 and Table 4.16. Under clean fog aging, salt fog aging, and clean fog plus AC voltage 25 kV aging, the obtained test results, the CFO voltages, the AC flashover voltages, and AC leakage currents, didn’t change so much after the accelerated aging tests. The electrical degradation of fiberglass samples is not significant after these accelerated aging tests. The measured electrical parameters of fiberglass samples decreased dramatically after the salt fog plus AC voltage 25 kV aging test, which indicates that this types of accelerated aging test has a severe impact on the electrical degradation of fiberglass samples.

Table 4.15 The Minimum, Average, and Maximum Values of the Fiberglass Samples' Electrical Parameters, the Samples Aged in Clean Fog and Salt Fog.

| Electrical Parameters | | | Clean Fog | | | Salt Fog | | |
|---|---|---|---|---|---|---|---|---|
| | | | Min | Ave | Max | Min | Ave | Max |
| NO.1~ NO. 3 | CFO dry (kV) | Before | 207 | 207 | 207 | 224 | 225 | 227 |
| | | After | 192 | 195 | 198 | 207 | 215 | 219 |
| | CFO wet (kV) | Before | 177 | 179 | 182 | 198 | 200 | 201 |
| | | After | 145 | 168 | 183 | 149 | 153 | 158 |
| | AC dry (kV) | Before | 119 | 122 | 125 | 135 | 136 | 137 |
| | | After | 122 | 124 | 126 | 114 | 115 | 117 |
| | AC wet (kV) | Before | 71 | 72 | 74 | 61 | 61 | 61 |
| | | After | 52 | 55 | 57 | 37 | 40 | 42 |
| | AC current (μA) | Before | 220 | 227 | 233 | 205 | 207 | 210 |
| | | After | 242 | 270 | 310 | 462 | 587 | 849 |
| NO.4~ NO. 6 | CFO dry (kV) | Before | 205 | 206 | 206 | 224 | 225 | 226 |
| | | After | 189 | 194 | 198 | 208 | 211 | 216 |
| | CFO wet (kV) | Before | 172 | 173 | 174 | 197 | 198 | 200 |
| | | After | 164 | 166 | 168 | 128 | 134 | 143 |
| | AC dry (kV) | Before | 124 | 125 | 126 | 133 | 134 | 134 |
| | | After | 124 | 124 | 124 | 99 | 106 | 117 |
| | AC wet (kV) | Before | 69 | 71 | 72 | 58 | 60 | 60 |
| | | After | 52 | 53 | 54 | 35 | 36 | 36 |
| | AC current (μA) | Before | 217 | 222 | 227 | 174 | 190 | 198 |
| | | After | 281 | 282 | 282 | 407 | 416 | 452 |
| NO.7~ NO. 9 | CFO dry (kV) | Before | 204 | 206 | 207 | 215 | 217 | 220 |
| | | After | 193 | 195 | 196 | 207 | 210 | 214 |
| | CFO wet (kV) | Before | 173 | 175 | 176 | 187 | 188 | 189 |
| | | After | 155 | 163 | 172 | 144 | 147 | 154 |
| | AC dry (kV) | Before | 123 | 124 | 125 | 131 | 132 | 134 |
| | | After | 124 | 127 | 129 | 102 | 111 | 117 |
| | AC wet (kV) | Before | 65 | 68 | 70 | 57 | 58 | 59 |
| | | After | 50 | 54 | 56 | 35 | 36 | 36 |
| | AC current (μA) | Before | 200 | 213 | 221 | 179 | 188 | 203 |
| | | After | 252 | 278 | 302 | 473 | 549 | 641 |

Table 4.16 The Minimum, Average, and Maximum Values of the Fiberglass Samples' Electrical Parameters, the Samples Aged in Clean Fog Plus AC Voltage 25 kV and Salt Fog Plus AC Voltage 25 kV.

| Electrical Parameters | | | Clean Fog Plus AC Voltage 25 kV | | | Salt Fog plus AC Voltage 25 kV | | |
|---|---|---|---|---|---|---|---|---|
| | | | Min | Ave | Max | Max | Min | Ave |
| NO.1~ NO. 3 | CFO dry (kV) | Before | 216 | 220 | 222 | 200 | 200 | 200 |
| | | After | 206 | 207 | 209 | N/A | N/A | N/A |
| | CFO wet (kV) | Before | 194 | 197 | 202 | 182 | 183 | 183 |
| | | After | 181 | 183 | 184 | N/A | N/A | N/A |
| | AC dry (kV) | Before | 119 | 123 | 131 | 127 | 129 | 132 |
| | | After | 113 | 118 | 123 | N/A | N/A | N/A |
| | AC wet (kV) | Before | 61 | 62 | 62 | 63 | 63 | 63 |
| | | After | 58 | 58 | 58 | N/A | N/A | N/A |
| | AC current (μA) | Before | 131 | 151 | 163 | 143 | 155 | 175 |
| | | After | 137 | 161 | 176 | N/A | N/A | N/A |
| NO.4~ NO. 6 | CFO dry (kV) | Before | 213 | 216 | 217 | 197 | 198 | 198 |
| | | After | 204 | 205 | 205 | N/A | N/A | N/A |
| | CFO wet (kV) | Before | 195 | 196 | 197 | 177 | 177 | 177 |
| | | After | 174 | 175 | 175 | N/A | N/A | N/A |
| | AC dry (kV) | Before | 116 | 116 | 116 | 129 | 130 | 132 |
| | | After | 114 | 115 | 115 | N/A | N/A | N/A |
| | AC wet (kV) | Before | 60 | 61 | 61 | 62 | 62 | 62 |
| | | After | 54 | 54 | 54 | N/A | N/A | N/A |
| | AC current (μA) | Before | 165 | 169 | 176 | 129 | 146 | 169 |
| | | After | 176 | 194 | 227 | N/A | N/A | N/A |
| NO.7~ NO. 9 | CFO dry (kV) | Before | 213 | 214 | 217 | 195 | 196 | 196 |
| | | After | 196 | 198 | 200 | N/A | N/A | N/A |
| | CFO wet (kV) | Before | 180 | 192 | 200 | 176 | 177 | 177 |
| | | After | 168 | 169 | 169 | N/A | N/A | N/A |
| | AC dry (kV) | Before | 116 | 117 | 117 | 125 | 127 | 128 |
| | | After | 111 | 114 | 116 | N/A | N/A | N/A |
| | AC wet (kV) | Before | 59 | 59 | 59 | 57 | 59 | 61 |
| | | After | 49 | 51 | 52 | N/A | N/A | N/A |
| | AC current (μA) | Before | 149 | 157 | 162 | 146 | 151 | 158 |
| | | After | 165 | 177 | 192 | N/A | N/A | N/A |

## Conclusions

### *Before the Accelerated Aging Tests*

Before the accelerated aging tests, the CFO voltages of the fiberglass samples are about 210 kV under dry conditions and 170 kV under wet conditions. The AC flashover voltages are 120 kV under dry conditions and 70 kV under wet conditions. The leakage currents at 100 kV AC voltage are less than 300 µA for all the samples, and they have a linear relationship with the applied voltages.

### *After the Accelerated Aging Tests*

The electrical degradation caused by the clean fog test is very insignificant. When the clean fog test was performed with the specific electrical stress, the electrical degradation was still not very obvious. The conducted salt fog test also has a small impact on the electrical degradation of the fiberglass samples; however, the electrical degradation of the fiberglass samples happened very quickly when they are tested with electrical stress. The combined effect of salt fog and electrical stress on fiberglass material is the most important reason for electrical degradation.

# Chapter V

## CONCLUSIONS

Reviewing the results obtained from the tests in this thesis, the following conclusions on the fiberglass pole may be stated:

The CFO voltages of fiberglass poles have a linear relationship with the tested pole lengths. When the tested pole lengths are the same, the CFO voltage has the smallest value under wet conditions for positive lightning impulses and the highest value under dry conditions for negative lightning impulses. The CFO voltage strengths of fiberglass poles are higher than wood poles.

The CFO voltages of an insulator plus a fiberglass pole are higher than a fiberglass pole when measured under the same test conditions, lightning impulse polarities, and pole lengths. When a fiberglass pole serves as a second insulation component in a distribution line structure, the added CFO voltages from a fiberglass pole to a polymer suspension or a porcelain pin insulator are higher than the added CFO voltages from a wood pole, especially under wet conditions. The fiberglass pole can greatly improve the lightning impulse strength of a distribution line structure based on the test results in this thesis.

The electrical degradation of fiberglass materials is not very obvious after the following aging tests: the clean fog test, salt fog test, and clean fog test with the electrical stress. The salt fog test, if performed with the electrical stress, deteriorates fiberglass material much faster than the other three accelerated aging tests. As a result, the fiberglass pole should not be used in the area where salt fog occurs very frequently.

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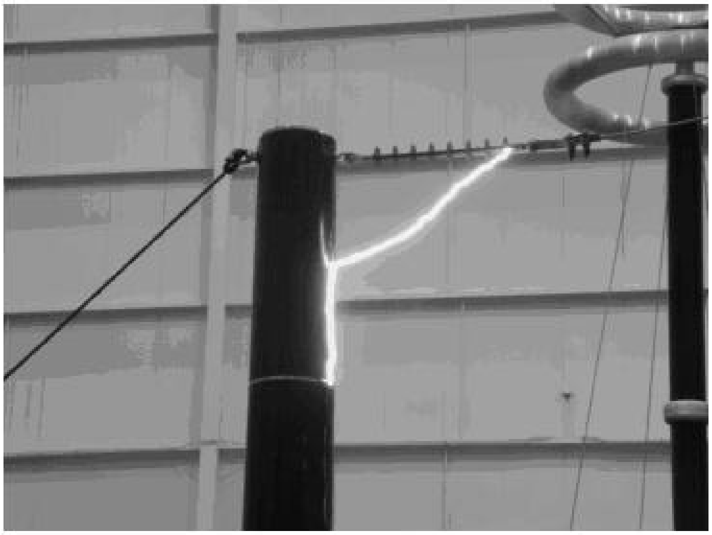
# APPENDIX A

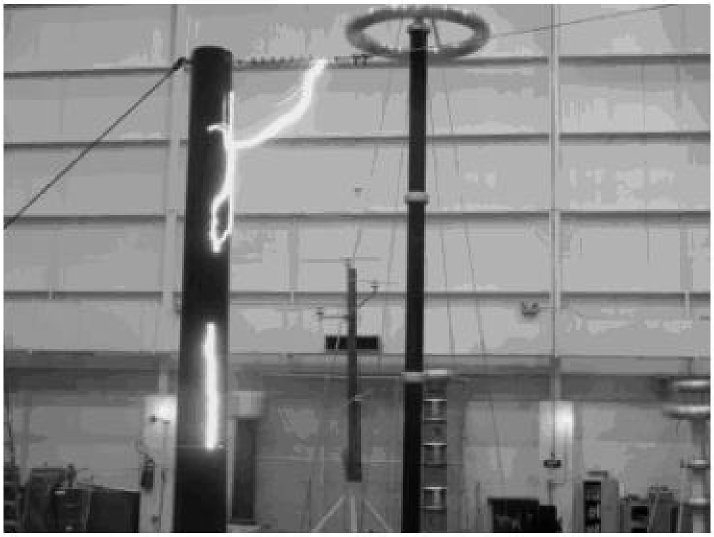
# PICTURES TAKEN DURING THE EVALUATION TESTS OF CFO VOLTAGES OF INSULATORS PLUS FIBERGLASS DISTRIBUTION POLES



The CFO Voltages of 35 kV Polymer Suspension Insulators Plus Fiberglass Poles Were Evaluated under Dry Conditions. The Tested Pole Length Is 2 Feet. The Discharge Path Consists of the Air Gap and the External Surface of the Pole.

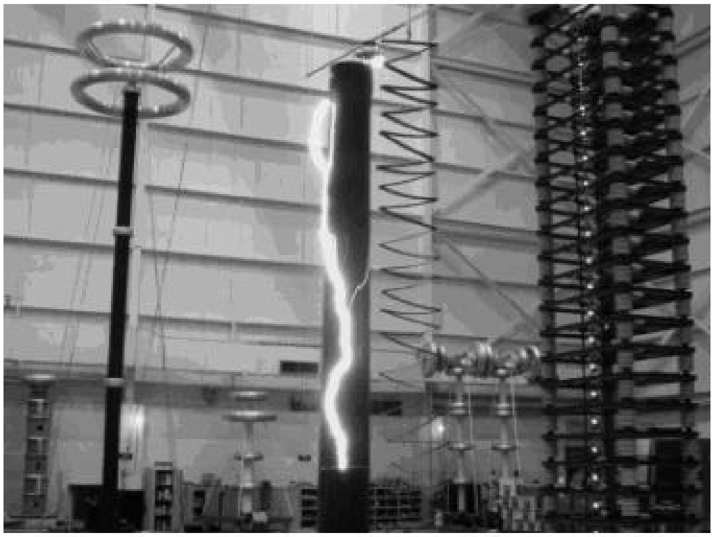
The CFO Voltages of 35 kV Polymer Suspension Insulators Plus Fiberglass Poles were Evaluated under Dry Conditions. The Tested Pole Length Is 8 Feet. The Discharge Path Consists of the Air Gap and the External Surface of the Pole.

The CFO Voltages of 35 kV Polymer Suspension Insulators Plus Fiberglass Poles Were Evaluated under Dry Conditions. The Tested Pole Length Is 8 Feet. The Discharge Path Consists of the Insulator Surface and Both Sides of the Pole's Surfaces.



The CFO Voltages of 35 kV Polymer Suspension Insulators Plus Fiberglass Poles Were Evaluated under Dry Conditions. The Tested Pole Length Is 8 Feet. The Discharge Path Consists of the Air Gap and Both Surfaces of the Pole.

The CFO Voltages of 35 kV Porcelain Pin Insulators Plus Fiberglass Poles Were Evaluated under Dry Conditions. The Tested Pole Length Is 3 Feet. The Discharge Path Consists of the Insulator Surface and Both Sides of Pole's Surfaces.



The CFO Voltages of 35 kV Porcelain Pin Insulators Plus Fiberglass Poles Were Evaluated under Dry Conditions. The Tested Pole Length Is 8 Feet. The Discharge Path Consists of the Insulator Surface and the External Surface of the Pole.

# APPENDIX B

# PICTURES TAKEN DURING THE ACCELERATED AGING TESTS AND THE ELECTRICAL TESTS FOR FIBERGLASS SAMPLES

The External Surface of the Sample Is Without Any Damage. The Tested Insulation Length Is 1 Foot.

The External Surface of the Sample Has Some Scratches. The Tested Insulation Length Is 1 Foot.

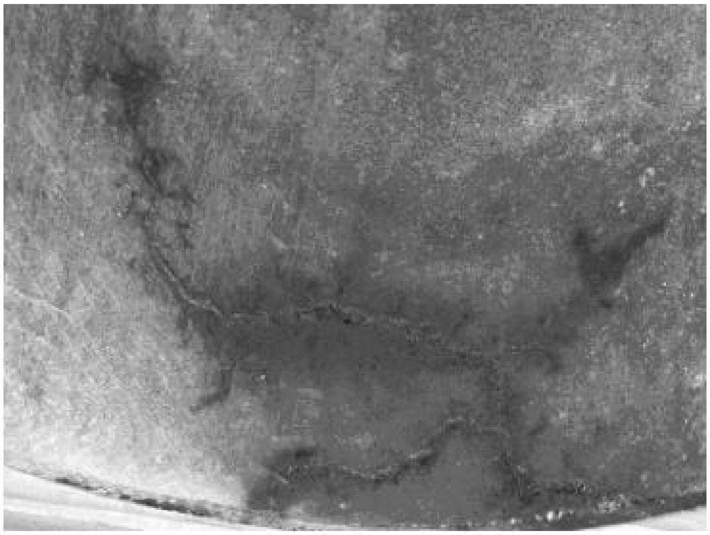
The Sample Has Five Holes (1 Inch In Diameter). The Tested Insulation Length Is 1 Foot.

The Tracking Appeared on the External Surface of the Sample (No.4, With Some Scratches) After a 6 Hour Aging in Salt Fog Plus 25 kV/ft Electrical Stress.

The Tracking Appeared on the Internal Surface of the Sample (No.4, With Some Scratches) After a 6 Hour Aging in Salt Fog Plus 25 kV/ft Electrical Stress.

The Tracking Appeared on the External Surface of the Sample (No.6, With Same Scratches) After a 5 Hour Aging in Salt Fog Plus 25 kV/ft Electrical Stress.

The Tracking Appeared on the Internal Surface of the Sample (No.6, With Same Scratches) After a 5 Hour Aging in Salt Fog Plus 25 kV/ft Electrical Stress.



The Tracking Appeared on the Internal Surface of the Sample (No.7, With Five Holes) After a 5 Hour Aging in Salt Fog Plus 25 kV/ft Electrical Stress.