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Study on the electrical strength of distribution insulators under steep front, short duration pulse

Streszczenie: *(**Badania wytrzymałości elektrycznej izolatorów do sieci rozdzielczych w warunkach stromych udarów o krótkim czasie trwania**). Ważnymi czynnikami koordynacji izolacji są: krytyczne napięcie przeskoku (CFO) i charakterystyki napięciowo-czasowe V-t izolatorów w sieciach rozdzielczych 15 kV. Izolatory te zwykle projektuje się na napięcie piorunowe udarowe 1,2/50 μs, nie uwzględniając zachowania się ich pod działaniem krótkich udarów o stromym czole (SFSD). Udar napięciowy SFSD w porównaniu do udaru piorunowego stwarza większe zagrożenie dla izolatorów ze względu na dużą amplitudę napięcia. Proponowana jest seria badań laboratoryjnych dla określenia własności izolatorów przy oddziaływaniu udarów typu SFSD odpowiadających środowisku czasu E1 impulsu elektromagnetycznego typu HEMP. W opisanych badaniach zastosowano udary o czasie czoła 60 ns i czasie grzbietu krótszym niż 200 ns. Izolatory badano w warunkach na sucho i pod deszczem udarami o biegunowości dodatniej i ujemnej. Przedstawiono charakterystyki CFO i V-t badanych izolatorów.*

Abstract: *The CFO voltage and V-t characteristic of 15 kV power distribution insulators are important factors in insulation coordination design of power distribution systems. Insulation designs for distribution feeders are usually based on 1.2/50 µs lightning impulse, while insulator behavior under steep front short duration (SFSD) pulses is not concerned. Comparing with lightning impulse, SFSD impulse is more severe and destructive to insulators because of its high voltage magnitude. A series of laboratory tests are proposed to establish the insulator performance for the SFSD pulses environments typical from an early time (E1) environment of a high altitude electromagnetic pulse (HEMP) threat. The generated SFSD impulse in this study has a 60 ns front and less than 200 ns of the tail. The insulators are evaluated under dry and wet condition with both negative and positive polarity impulses. The CFO and V-t characteristics for these insulators are presented.*

Słowa kluczowe: izolatory do sieci rozdzielczych, krytyczne napięcie przeskoku (CFO), udar piorunowy, stromy udar o krótkim czasie trwania, wysięgniki drewniane
Keywords: distribution insulators, critical flashover voltage (CFO), lightning impulse, steep front short duration pulse, wood crossarm

Introduction

Approximately 78% of all electric power delivery to end-users is delivered via 15 kV class distribution lines. At present, considerable uncertainty exists as to whether typical insulation capability of these distribution assets will be sufficient to withstand the induced over-voltages due to the E1 environment of a HEMP threat. It has generally been observed that the faster impulse rise times and shorter duration pulse widths of the E1 threat will increase the level of the flashover voltage for these insulators and insulator plus crossarm combinations from voltage levels known for lightning environments, but the amount of increase is not well substantiated as of yet.

A series of High Voltage power lab tests are proposed to establish the insulator performance for the SFSD pulses environments typical from the E1 event. The laboratory experiments have the objective to determine the CFO voltage and V-t characteristics for 15 kV insulators alone and the insulators plus wood crossarms under SFSD pulses. The evaluation of the CFO voltage and V-t characteristics are conducted under dry and wet conditions for positive and negative polarity of the applied pulses.

Experiment Setup

The tested 15 kV insulators include standard ANSI 55-4, ANSI 55-3, ANSI 52-9, ANSI 52-1, and a 15 kV polymer suspension insulator. The picture of these insulators is shown in Figure 1. Experiment configurations for the 15 kV polymer insulator and insulator plus wood are shown in Figure 2. Test configurations for all the other insulators are similar. The generated pulses were in the range of 60 ns front and 150 ns tail. This shape of SFSD pulses was used in the CFO voltage evaluation.

In order to evaluate the V-t characteristic, the voltage was increased to obtain flash on front of the pulse, on shorter time, in the range from 40 ns to 150 ns.

The applied pulses used in the tests under dry and wet condition as well as on the positive and negative polarity were obtained with the same technique and have the same wave shape.

Fig. 1. Tested insulators, from the left: ANSI 55-4, ANSI 55-3, ANSI 52-1, ANSI 52-9, 15 kV Polymer Suspension.

The SFSD and standard lightning impulse will be applied to the conductor connected to the test insulator. Grounding will be attached either to the metal connection of the insulator or the aluminum tape wrapped around the wood crossarm.

CFO Voltage Under SFSD Pulses

In order to evaluate the CFO voltage, an up and down method is employed according to the IEEE Standard 4-1995. Table 1 shows the ratio of the measured CFO voltage under SFSD pulses to the CFO voltage under lightning impulses.

The CFO voltages under SFSD pulses are higher than under lightning impulses. For SFSD pulses, the CFO voltage under wet condition is higher than under dry condition. Under wet condition, the moisture scattered in the air hampered the developing of ionization. Therefore, the CFO voltage for SFSD pulses under wet condition is higher than under dry condition.

The CFO voltages and the *V-t* characteristics depend on the arc paths around the insulator and wood crossarm during the breakdown under the SFSD pulses. The arc path is different for each tested configuration. It consists of a few parts, arc around the insulator surface, in the air gap, and around the wood crossarm surface.

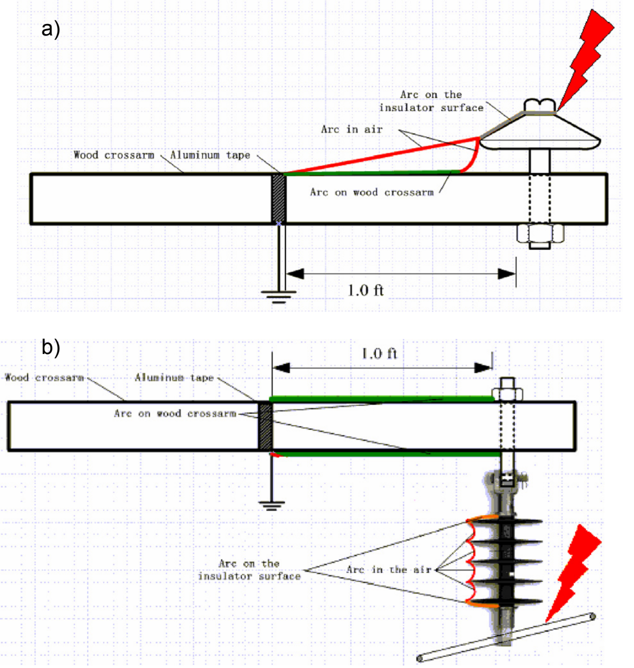

Fig. 2. The components of arc paths for insulator plus wood configurations;
a) ANSI 55-4 insulator plus wood,
b) 15 kV polymer suspension insulator plus wood.

Table 1. CFO voltage Ratio of SFSD pulse to Lightning Impulse of insulators

Model	Rated Voltage [kV]	Positive		Negative	
		Dry	Wet	Dry	Wet
ANSI 55-4	13,2	2,7	2,13	1,04	1,14
ANSI 55-3	11,5	1,7	1,98	1,06	1,28
ANSI 52-1	13,2	1,2	1,46	1,32	1,57
ANSI 52-9	13,2	1,3	1,47	1,36	1,6
Polymer	15	2,6	2,37	1,93	2,58

The shape of the insulator, the length of wood crossarm, and the configuration of the insulator with respect to the grounded tape are causing different electrical field distribution. Both of these factors (portions of the arc and electrical field distribution) have impact on the value of CFO voltage. Figure 2(a) shows the arc path of the insulator ANSI 55-4 plus wood crossarm. Figure 2(b) shows the arc path of the insulator ANSI 52-9 plus wood crossarm.

Under wet condition, the water on the insulator surface and wood crossarm surface are reducing electrical strength of these elements. The air gap under wet condition has higher electrical strength than under the dry condition. Under wet condition, the ionization phenomena in air are more difficult because the moisture make the atoms heavier and the electrons need higher energy to ionize the molecules. All of these components have effect on the measured CFO voltage.

When the electrical stress is higher at the energized conductor than at the grounded tape or ground of the insulator, the CFO voltage is lower for positive polarity of pulse. When at the energized conductor (for pin type or suspension insulator) the electrical stress is lower than the electrical stress at the grounded tape, the CFO voltage is lower at negative polarity of the pulse. This assumption is based on the theory of breakdown mechanism under lightning impulses. No theory is presented on generation of space charge for discharge under SFSD pulse. Figure 3 compares the CFO voltages of ANSI 55-3, and polymer insulators and insulator plus wood under different experiment conditions.

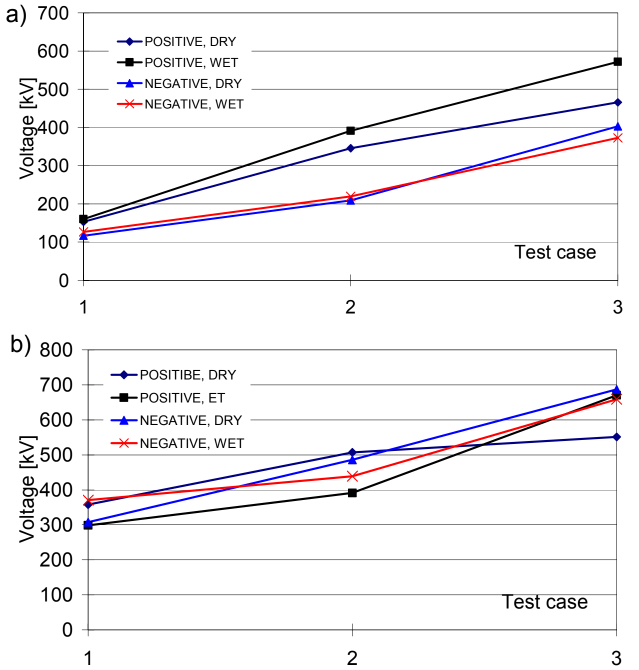

Fig. 3. CFO Voltage of ANSI 55-3 and 15 kV polymer and insulator plus wood under different test conditions;
(a) ANSI 55-3 insulator, (b) 15 kV polymer insulator.
Test case: 1- Insulator alone
2 - Insulator plus 0.5 ft wood
3 - Insulator plus 1.0 ft wood

V-t Characteristics Under SFSD Pulses

Evaluation of *V-t* characteristics was done under the same configuration as for CFO voltage determination. The curves of *V-t* characteristics under SFSD pulses have a higher value compared to the characteristics under lightning impulses. Breakdown voltage under short front of the SFSD pulses is higher than under lightning impulse. Figure 4 is presenting the *V-t* characteristic of 15 kV polymer insulator plus wood crossarm, for positive polarity under dry and wet condition.

The *V-t* characteristics of ANSI 55-4 insulator under different test conditions are presented as an example. The *V-t* curves of other insulators show the same tendency and the theoretical explanations are similar. Figure 5 and Figure 6 are presenting *V-t* characteristics for the insulator and plus wood crossarm for positive polarity at dry or wet condition.

Figure 7 presents the comparison of ANSI 55-4 insulator plus wood crossarm for positive polarity under dry and wet condition. For the ANSI 55-4 insulator and for the insulator plus 0,5 ft wood crossarm, the electrical strength for SFSD pulse is higher under wet condition than under dry condition because the arc is developing mostly in the air which contains lot of water and is harder to ionize the air gap. For the insulator plus 1 ft wood crossarm the length of the arc is developing mostly on the wood crossarm surface and therefore the electrical strength is lower under wet condition.

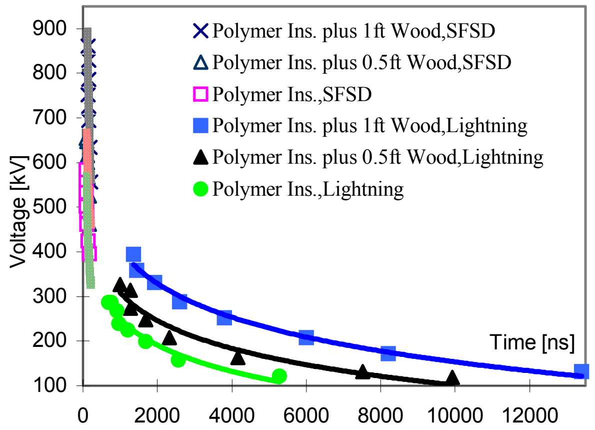

Fig. 4. *V-t* Characteristics of 15 kV Polymer Insulator, plus 0,5 ft. and plus 1,0 ft. Wood Crossarm, Wet Condition, Positive Polarity.

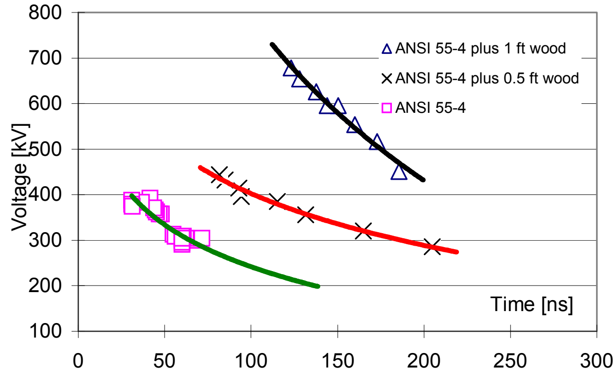

Fig. 5. *V-t* Characteristics of ANSI 55-4, plus 0,5 ft. and plus 1,0 ft. Wood Crossarm, Positive Polarity, Dry Condition.

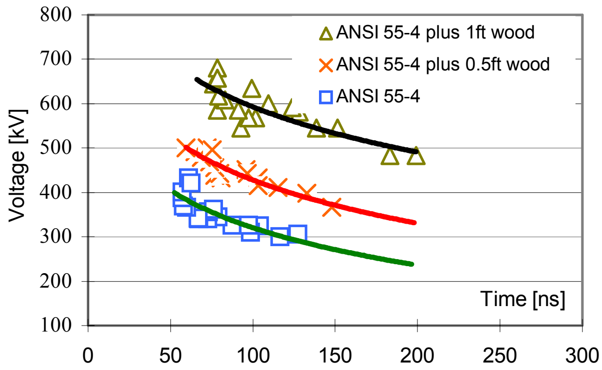

Fig. 6. *V-t* Characteristics of ANSI 55-4, plus 0,5 ft. and plus 1,0 ft. Wood Crossarm, Positive Polarity, Wet Condition.

Fig. 8 compares the electrical strength of the ANSI 55-4 insulator plus wood crossarm for SFSD pulses under dry condition for positive and negative polarity of the pulses. The breakdown voltage of SFSD pulses is lower at positive polarity for insulator and insulator plus 0,5 ft wood crossarm as compared to negative polarity pulses. The breakdown voltage for the insulator plus 1 ft. wood crossarm is lower at negative polarity. This is due to the change in the electrical field distribution and the electrical stress is higher at the grounded tape on the wood crossarm. The differences in breakdown voltage at positive and negative polarity are very small and are increasing with the longer section of wood crossarm.

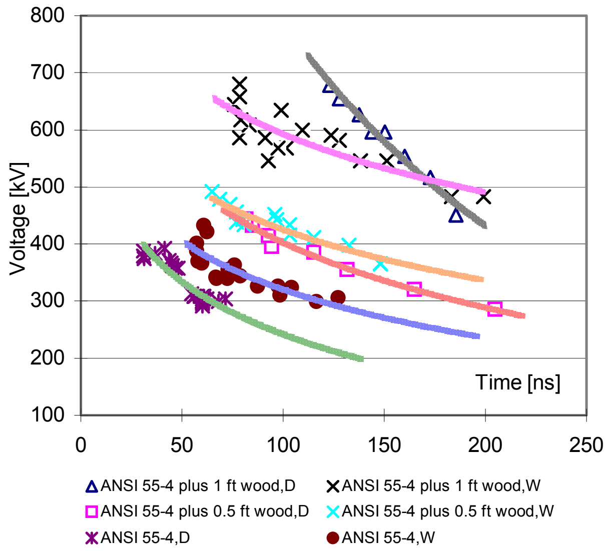

Fig. 7. *V-t* Characteristic of ANSI 55-4, plus 0,5 ft, and plus 1,0 ft. Wood Crossarm, Positive Polarity; Dry and Wet Condition.

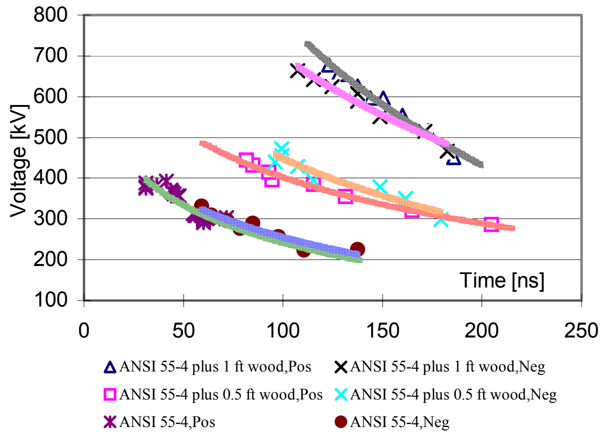

Fig. 8. *V-t* Characteristic of ANSI 55-4 insulator, plus 0,5 ft, and plus 1,0 ft. Wood Crossarm, Dry Condition; Positive and Negative Polarity.

The experimental configuration for the 15 kV polymer suspension insulator and the insulator plus wood crossarm is shown in Figure 2b. The CFO voltages and the *V-t* characteristics depend on the arc paths around the insulator and wood crossarm during the breakdown under the SFSD pulses. The arc path is different for each tested configuration. It consists of a few parts, arc around the insulator surface, in the air gap, and around the wood crossarm surface. The shape of the insulator, the length of wood crossarm, and the configuration of the insulator with respect to the grounded tape are causing different electrical field distribution. Both of these factors (portions of the arc and electrical field distribution) have impact on the value of CFO voltage and *V-t* characteristic of a specific insulator. As it is shown in Figure 2b, the arc in the air is much longer than for pin-type insulators such as the ANSI 55-4 (Fig. 2a).

Figure 9 to Figure 11 are presenting the *V-t* characteristic for 15 kV polymer suspension insulator. Figure 9 presents the *V-t* characteristic for positive polarity under dry condition. The character is similar as for the ANSI 55-4 insulator. The wood crossarm is increasing the electrical strength proportionally to the length of the wood crossarm. Figure 10 presents the *V-t* characteristic for positive polarity under wet condition. In a similar fashion, the wood crossarm is increasing the electrical strength of the insulation system.

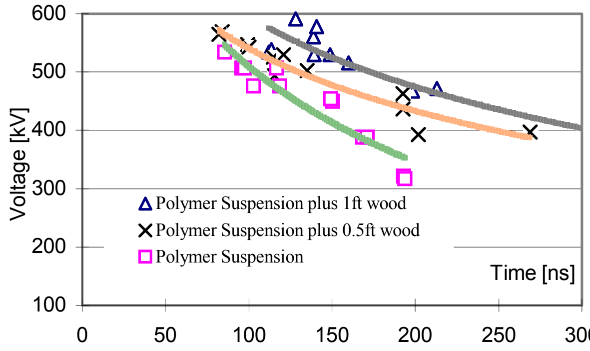

Fig. 9. *V-t* Characteristic of 15 kV polymer insulator, plus 0,5 ft., plus 1 ft., Wood Crossarm, Positive Polarity, Dry Condition.

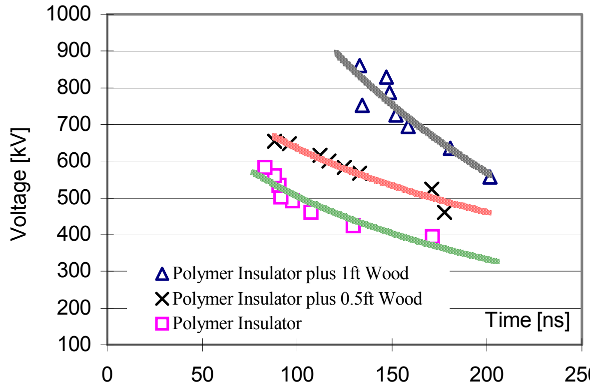

Fig. 10. *V-t* Characteristic of 15 kV polymer insulator, plus 0,5 ft., plus 1 ft., Wood Crossarm, Positive Polarity, Wet Condition.

In Figure 11, the *V-t* characteristic is presented for 15 kV polymer suspension insulator plus wood crossarm for positive polarity under dry and wet condition. For insulator only, the *V-t* characteristic under dry and wet condition has practically the same value. The *V-t* characteristic for the insulator plus wood crossarm under wet condition is above the *V-t* characteristic under dry condition.

Negative polarity *V-t* characteristic is lower than positive polarity under wet condition. For insulator and wood crossarm combination, the differences in breakdown voltage level are less noticeable. That is caused by the lower work function of the electrons than positive ions.

The impact of space charge under positive polarity is compensated by the lower value of the work function. *V-t* characteristic is much higher at positive polarity for the insulator alone (without wood) because the air gap around the insulator is short. No theory is presented on the generation of space charge for discharge under SFSD pulse.

In Figure 11, the impact of the wood crossarm on *V-t* characteristics is larger for the longer wood crossarm. The different components of the arc path during breakdown process and the changed electrical field distribution caused by the longer crossarm explain observation mentioned above.

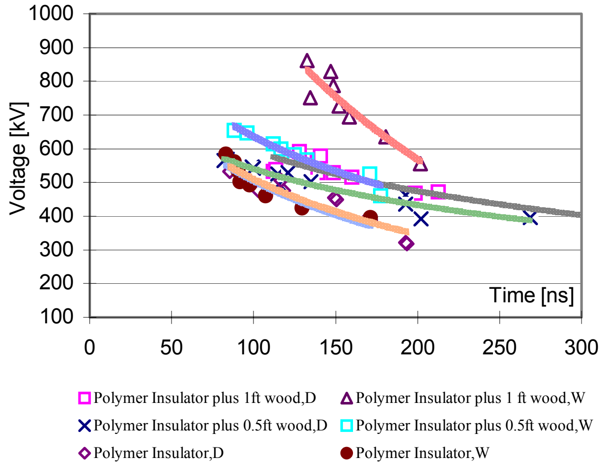

Fig. 11. *V-t* Characteristic of 15 kV polymer insulator, plus 0,5 ft., plus 1 ft., Wood Crossarm, Positive Polarity; Dry and Wet Condition.

During the measurement, it was observed that for combined insulation (insulator plus wood crossarm), the arc path depends very much on the configuration. For different type of insulators plus wood crossarm, the arc path is divided by part in air, on the insulator surface, and on the wood crossarm surface. Depending on which part dominates, the impacts of the wood crossarm to the total electrical strength will be increasing or decreasing under dry and wet condition.

Conclusions

a. Electrical strength, the CFO voltage, of insulators and combined insulation of insulators plus wood crossarm are higher at SFSD pulse than at lightning impulse.
b. The ratio of the increased strength at SFSD pulse to lightning impulse is approximately 2,2. This ratio for a specific configuration depends also on polarity of the pulse and atmospheric condition.
c. The pulse polarity and test condition have big impact on the added electrical strength by the wood crossarm.
d. The added CFO voltage by 1 ft. wood crossarm to evaluated insulators is in the range of 200-400 kV/ft.
e. The increase of electrical strength at shorter pulse is much larger for insulators with wood crossarm.

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