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Effect of Ambient Conditions on Insulation Strength of High Voltage Protection Devices

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ABSTRACT

Overvoltage protection devices are the most important apparatuses in the power networks which decrease the cost of power network designing. High voltage protection devices such as spark gaps, surge arrestors, and pin & cap insulators are needed in a power system to protect the system from overvoltage by deflecting the cross-currents. In designing a power system, it is necessary to consider the strength of protection devices under different ambient conditions. Protection devices should be tested under different voltages to ensure the reliability of the power system. In this paper, the experimental activities were performed on the investigation of the performance of the spark gaps, arresters and contaminated insulator strings under impulse lightning voltage in High Voltage Lab at Mississippi State University and results are obtained consistently. For this test, IEEE standards were considered to accord the ambient conditions at laboratory with standards.

Index Terms — Overvoltage Protection, Spark Gap, Metal Oxide arrester, Ambient Conditions, Critical flashover Voltage (CFO).

1 INTRODUCTION

IN a power system, there is always the probability of going under overvoltage. Over-voltages that happen can be both external as lightning and internal as switching overvoltage. It is obvious to all engineers that lightning phenomena is the most considerable reason in failure of a power system and it can destroy many important component and equipment of power systems [1-5]. Protection devices are mostly exposed to many severe environmental conditions that change its properties. For example, high humidity and temperature significantly decreases withstand voltage. Also, contamination such as dust degrades cap and pin type insulators [6-8]. Electrical engineers are always trying to reduce this probability and enhance the systems reliability to prevent damages on equipment. In this regard, many different methods and devices are used to prevent conductors from breaking. Spark gaps and MO surge arrester operate during adverse conditions and during this test, they were exposed to hot and cold weather, while cap and pin type insulators operate in all conditions and were tested in contamination conditions.

Lightning Impulse is fast front overvoltage and the electrical strength of protection devices against external overvoltage that can appear in a power system because of lightning strokes is tested with impulse voltages in the lab that generates with Haefely MTS and Marx Generators. The critical flashover CFO of an insulation structure is commonly used to describe the insulation structure lightning impulse strength.

As an earlier paper on finding the results of an extensive

laboratory studies at Mississippi State University [9] in which the critical flashover voltages (CFO) of a variety of possible combination of insulating materials such as porcelain, polymers, and Fiberglass were obtained.

Environmental conditions are simulated in lab to test the properties of protection devices to guarantee its best performance at sever situations. The main purpose of this test is exploring characteristics of spark gaps, MO surge arrester, and cap & pin insulators under different ambient conditions. IEEE standard [10] is followed during the test to accord the laboratory conditions with standards.

This article is organized in the following way. Section 2 briefly discusses generation of the lightning impulse and calculating of correction factor. Section 3 presents the insulation strength and breakdown voltage of protective devices. The conclusions are discussed in Section 4.

2 GENERATION OF LIGHTNING IMPULSE AND CALCULATING CORRECTION FACTOR

2.1 HAEFELY MULTI TEST SET

Lightening Impulse should be applied to protection devices in order to test their reliability. For comparing the work of spark gap and arrester and the effects of ambient conditions in spark gap test, Haefely Multi Test Set(MTS) is used as is shown in Fig. 1. Fig. 1 shows the circuit and laboratory set-up for the generation of the standard lighting impulse. The capacitor C_1 is initially charged from the source and the

capacitor C_2 charges through R_1 and an impulse appears across the test. Then, C_1 and C_2 discharge through R_2 . Therefore, front time, t_1 is determined by R_1 , C_1 and C_2 and tail time, t_2 is determined by R_2 , C_1 , and C_2 .

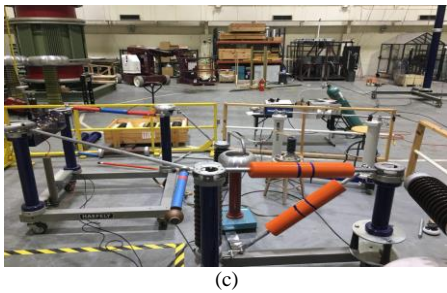
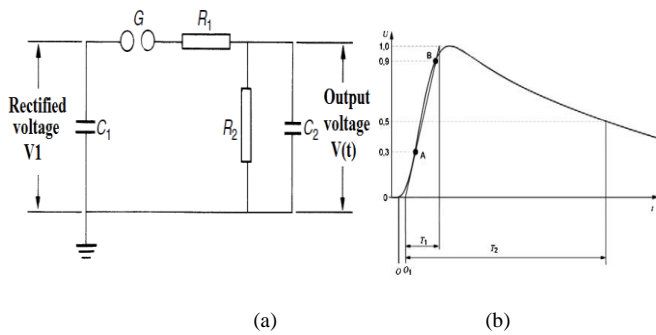


Figure 1: Impulse Voltage Generation System, (a)Equivalent Circuit of Impulse Voltage Generator (b), Standard Waveform of Impulse Voltage (c) Laboratory setup

Fig. 2 shows impulse voltage wave form in the lab and the values for R_s , R_p , C_k , T_1 , and T_2 are 245Ω , $84 \text{ k}\Omega$, 1 nf , $1.3 \mu\text{s}$, and $40.26 \mu\text{s}$, respectively.

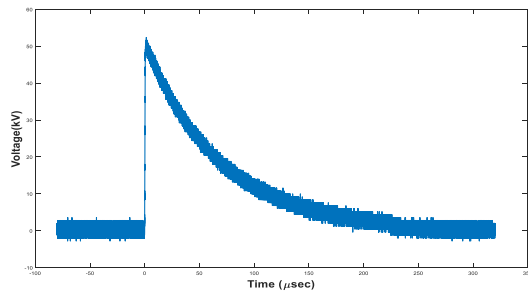


Figure 2: Impulse Voltage Wave form

Atmospheric conditions are different in different places and transmission lines and equipment with external insulations must work everywhere. This means that when the atmospheric conditions on components are different, correction factor is used to relate the test voltage values for insulation coordination to the standards. Correction factor value is calculated as (1).

$$\text{Correction Factor: } k_t = k_1 * k_2 \quad (1)$$

Where, k_1 is the air density correction factor and k_2 is the humidity correction factor.

2.2 MARX GENERATOR

For contamination test on pin and cap type insulators, high voltage impulse is needed which should be generated by Marx generator. Impulse generators for high voltage testing has been built up to now almost exclusively in the well-known Marx circuit. The basic principle of this circuit is the rapid series connection of charged capacitors where spark gaps are used to

make the series switching. In this paper, as it is shown in Fig. 2, ten stage Marx generator is used to produce voltage impulse of peak value as high as 400 kV .

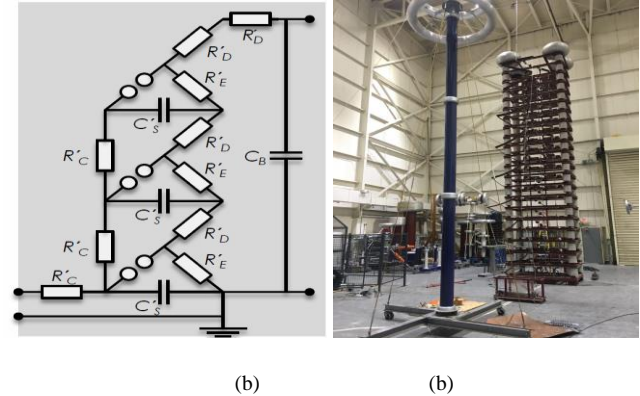


Figure 3: Impulse Voltage Generation System, (a) Test Circuit, (b) Marx generator

3 INSULATION STRENGTH / BREAKDOWN VOLTAGE OF INSULATING MATERIALS

Spark gap and surge arrestors protect electrical system from high voltages. But, their performances are different. This test focus on how these devices work when lightning impulses are applied. Also, the performance of pin and cap insulators will be observed under contamination conditions.

3.1 THE PERFORMANCE OF SPARK GAPS AND SURGE ARRESTORS

The output voltage from Haefley MTS is applied to spark gap at first and spark gap distance is set at 15 mm . Then, MO surge arrestor is used instead of Spark Gap. Finally, both surge arrestor and spark gap are in the circuit in series and one lightning impulse is applied. For different levels of voltages, 10 positive and 10 negative lightning impulses are applied for Spark Gap test and 5 positive and 5 negative lightning impulses are applied for Surge Arrestor test for each level of voltage. Fig. 4 shows the set-up for Spark Gap and Surge Arrestor connections. Also, the ambient conditions and correction factor are below:

Pressure (P): 1010.9 hpa

Temperature (T): $23.0 \text{ }^\circ\text{C}$

Humidity (RH): 46.3%

$K_1 = 0.98$, $K_2 = 1$

$K_t = K_1 * K_2 = 0.98$

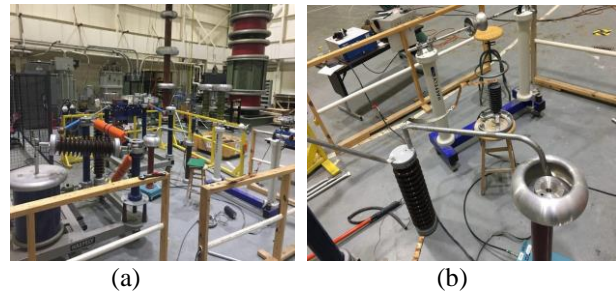


Figure 4: (a) Spark Gap setup, (b) Arrestor setup

In this test, correction factor k was almost 0.98 because the ambient conditions were near standards and CFO for spark gap just have a little difference in magnitude. The results are mentioned in Table. 1 and Table. 2. The results of the spark gap test are shown in Table. 1.

Table 1: Results for spark gap test

Charged Voltage	Positive Impulse		Negative Impulse	
	Average Breakdown Voltage(kV)	Steepness	Average Breakdown Voltage(kV)	Steepness
70 kV	52	130.8	53.44	153.6
	O= 8.5		O= 12	
	CFO = 50.26		CFO = 55.21	
80 kV	51.6	166	54.72	199.9
	O= 8.5		O= 12	
	CFO = 50.26		CFO = 55.21	
90 kV	49.04	195.6	54.62	244.5
	O= 8.5		O= 12	
	CFO = 50.26		CFO = 55.21	
115 kV	53.19	122.4	56.36	122.4
	O= 3.38		O= 4.55	
	CFO = 54.49		CFO = 55.27	
130 kV	54.98	131.7	55.22	131.7
	O= 3.38		O= 4.55	
	CFO = 54.49		CFO = 55.27	
150 kV	55.3	174.8	54.25	174.8
	O= 3.38		O= 4.55	
	CFO = 54.49		CFO = 55.27	

As it can be seen from the results, average breakdown voltages for negative impulse are more than positive voltages. CFO for negative impulse is also more than positive impulse. Due to the results, steepness does not affect the breakdown voltage and its trend is positive. The results of the spark gap test are shown in Table. 2.

Table 2. Results for surge arrester

Charged Voltage	Average Breakdown Voltage(kV)	
	Positive Impulse	Negative Impulse
70 kV	47.5	47.1
80 kV	48.4	48
90 kV	49.2	48.8
100 kV	53.5	53.7
120 kV	54.16	54.16
130 kV	56.4	57.1

The results of lightning impulse voltage test on MO surge arrester are shown in Fig. 5 and Fig. 6 for negative and positive impulses, respectively. In this test same as spark gap test, three different charging voltage level (70 kV, 80 kV and 90 kV) are chosen and five impulses applied in each voltage level. Fig. 5 shows three different bunches of MO surge arrester response to 70 kV, 80 kV and 90 kV negative lightning impulses, respectively. Also, as by increasing the charging voltage level the steepness would increase, it clears that the MO arrester showed faster response to 80 kV and 90 kV impulses than that of 70 kV. In addition, the residual voltage which is the voltage that appears between the terminals of an arrester during the passage of impulse current through the arrester is about -45 kV. Moreover, the residual voltage remained 45 kV for positive polarity, too. This residual value obtained for all groups during the MO surge arrester lightning withstand test for different values of charging voltages. Therefore, it concludes that the MO surge arrester residual voltage level does not relate to lightning impulse polarity and steepness. Unlike of spark gap which its performance makes the earth fault because of passing the lightning current into the ground, nonlinear resistors inside the MO arresters absorb the lightning impulse current and release it smoothly so that no voltage crest or earth fault happened into the power network. This fact is shown in Fig. 6.

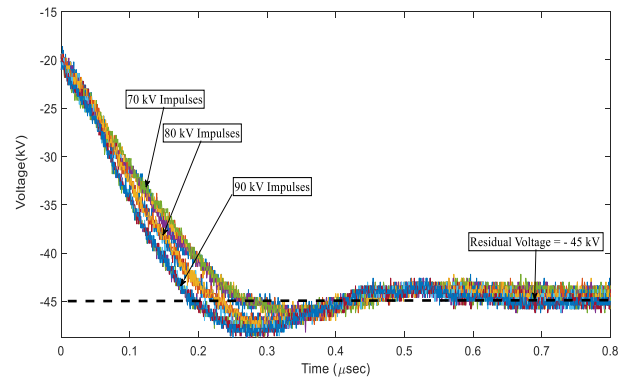


Figure 5: The response of 21 kV MO surge arrester to different negative lightning impulse levels.

In surge arrester test, increasing in voltage causes a little change and polarity does not have such effect on arrester's performance and this is acceptable because arrester's performance is independent from other components.

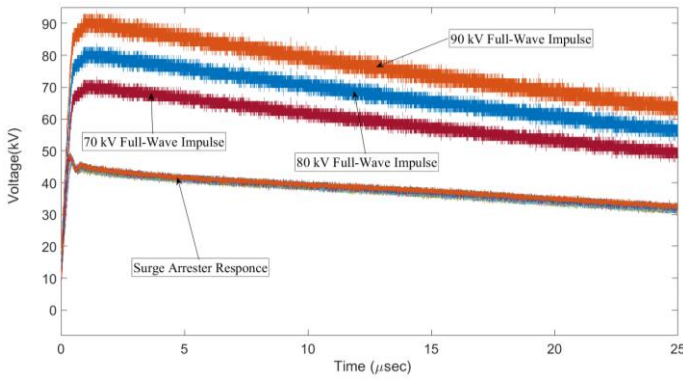


Figure 6: Wavwforms for MO surge arrester response with full-wave lightning impulses.

Fig. 6 shows the response of surge arrester with 70 kV lightning impulse and the green line shows the residual voltage. The surge arrester cut the impulse voltage above the residual voltage and gradually make it zero in order to prevent any fault in the network. Finally, the performance of combination of surge arrester and spark gap in series connection is tested. Fig. 7 and Fig. 8 show the set-up and breakdown voltages when voltage of 120 kV is applied. At first the series combination works as open circuit and after exceeding voltage of breakdown voltage, the insulation of spark gap breaks down and the voltage falls.

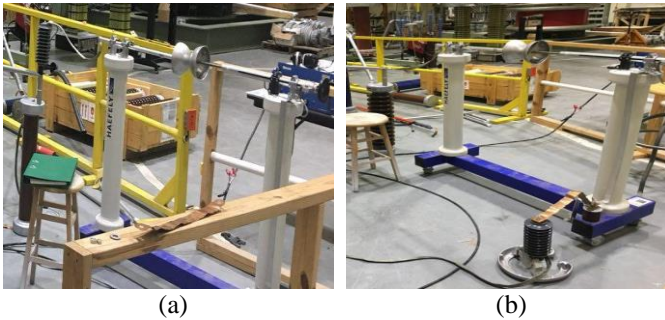


Figure 7: (a)Series setup of spark gap after arrester, (b) The series connection of arrester after spark gap

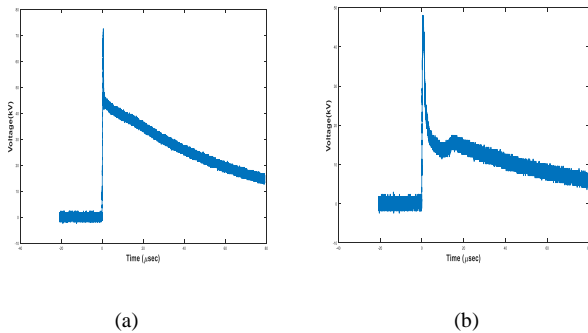


Figure 8: (a)The voltage waveform of Series Connection of arrester-SG, (b) The voltage waveform of series connection of SG-arrester

When spark gap and surge arrester are in series, breaks down is at higher voltage than their individual breakdown voltages and the residual voltage is still same as surge arrester test. Also, both arrester- SG and SG-arrester series connection

are tested separately and it was seen that the peak voltage at which breakdown happens at SG-arrester connection is lower. Also, for arrester- SG test the breakdown voltage is high and not only it is not good for power system, but also it is dangerous for spark gap. So, SG-arrester set-up is better suited to be used in a power system.

3.2 INFLUENCE OF AMBIENT CONDITIONS ON SPARK GAP OPERATION

The set-up is like to case A as it is shown in Fig. 8 and Needle-Needle spark gap is used. A heater is used to boil the water into steam and blow it between the gap in hot test and ice is used to make surrounding temperature cold during cold test. Distance for spark gap is set at 15 mm.

Impulse was generated like case A. Ambient condition is recorded and different levels of voltages, 10 positive and 10 negative lighting impulses of 140 kV were applied to the needle to needle spark gap for each level of voltage. Then, spark gap is covered with ice and ten lightning impulse is applied and breakdown voltage is recorded. Finally, the same process is done for hot test by blowing steam through the gap. Test set-up and impulse voltage flashover under normal condition is shown in Fig. 9. Ambient conditions and correction factor for normal condition are as below:

Ambient Temperature = 21 C
 Air Pressure 1002.1 hpa
 $K_1 = 0.986, K_2 = 1$
 $K_t = K_1 * K_2 = 0.986$
 Test Voltage = $45.5 \times 0.986 = 44.36$ kV

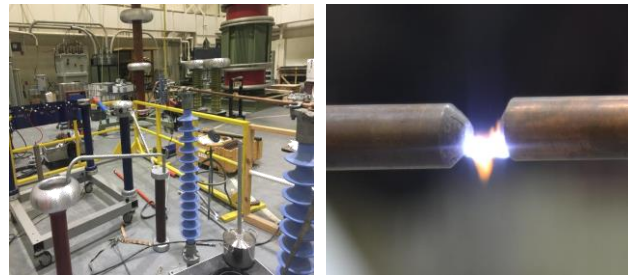


Figure 9: Spark gap impulse withstand test setup
 For cold test, test set-up and impulse voltage flashover under normal condition is shown in Figure 10. Ambient conditions and correction factor for cold condition are as below:

Ambient Temperature = 2 C
 Air Pressure 1000.4 hpa
 $K_1 = 1.05, K_2 = 1$
 $K_t = K_1 * K_2 = 1.05$
 Test Voltage = $45.5 \times 1.05 = 47.35$ kV

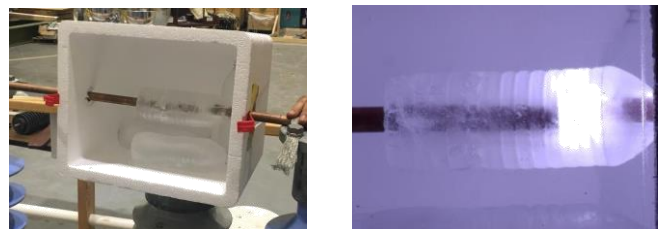


Figure 10: Cold test set-up and impulse voltage flashover across the rod-rod spark gap

For hot test, test set-up and impulse voltage flashover under hot condition is shown in Fig. 11. Ambient conditions and correction factor for hot condition are as below:

- Ambient Temperature = 2 C
- Air Pressure 1000.4 hpa
- $K_1 = 1.05, K_2 = 1$
- $K_t = K_1 * K_2 = 1.05$
- Test Voltage = $45.5 \times 1.05 = 47.35$ kV

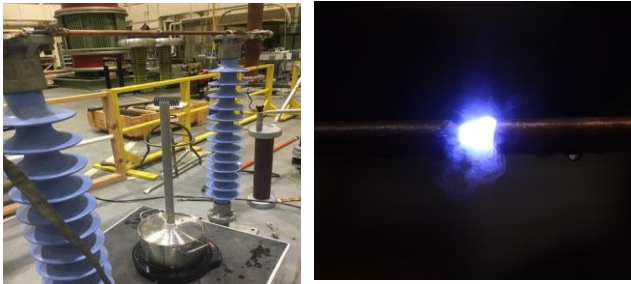


Figure 11: Hot test set-up and impulse voltage flashover across the rod-rod spark gap

Table 3: Results of different ambient conditions effect

Test Condition	Positive Impulse(kv)			Negative Impulse	
	Applied Voltage	σ(%)	CFO(kv)	σ(%)	CFO(kv)
Normal Condition	110	3.1	42.4	2.9	37.9
	120	5	43.3	4	40.8
	140	4.2	42.4	12	42.3
	150	6.3	41	2.4	38.2
Hot Test	110	8.8	53.1	1	40.8
	120	3.8	55.8	5.5	54.7
	140	4.4	54.4	0.7	59.6
	150	5.6	56.9	1.7	48.1
Cold Test	110	0.5	35.8	2.9	33.5
	120	2.4	39.9	2.2	44.9
	140	1.55	39.2	1.8	38.7
	150	3.5	39.6	8.9	39.4

The CFO and standard deviation is obtained in positive and negative test in normal condition, cold, and hot tests. The results show that in hot test the flashover voltage has increased with the increase in temperature and humidity, and in the cold test, the flashover voltage has decreased. So, the insulation strength increases with increase in temperature.

3.3 INFLUENCE OF CONTAMINATION ON BREAKDOWN VOLTAGE

In this case, effect of contamination on the break down voltage of pin and cap type insulators is studied. The lightning impulse is generated with Marx generator was explained in the second part. Four cap and pin type insulators

are in series connection for testing the insulation strength for different conditions such as Dry-Clean, Dry-Contaminated, Wet-Clean, and Wet-Contaminated conditions. Up and down method is used to find out the U_{50} (50% of disruptive voltage). Applied voltage is increased from 328 kV until a flashover happens. Then, voltage is decreased about 10 kV ($DV = 1\%$ TO 3% of U_{50}) until withstand condition obtained. Again, voltage is increased until another flashover happens. This process is repeated until we get to 20 events (changes from flashover to withstand condition and from withstand to flashover condition). The prepared test setup for measuring the withstand voltage of is shown in Fig. 12. Ambient conditions and correction factor for hot condition are as below:

- Ambient Temperature = 20.1 C
- Air Pressure 1009.4 hpa
- Relative Humidity = 44.7%
- $K_1 = 0.998, K_2 = 1$
- $K_t = K_1 * K_2 = 0.998$



Figure 12: Up and Down Withstand Test Setup

Fig. 13 shows the plot of voltages at flash over and withstand.

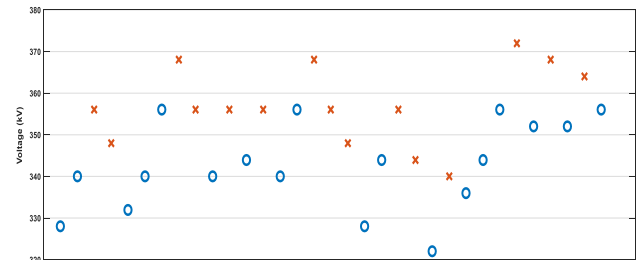


Figure 13: The dry contaminated porcelain insulator string up-and-down withstand test flashover and withstand voltage values.

As it is shown in the plot and calculated average flash over and standard deviation, the average value of flashover is 350kV and the standard deviation is equal to 12.16% which is more than 3% and is defined by standard in this test. Table. 4 shows the average flashover voltages of porcelain insulator string under different conditions.

Table. 4. The average flashover voltage of porcelain insulator string under different conditions.

Condition	50% DISRUPTIVE VOLTAGE(kv)
Wet&Contaminated	304.00
Wet&Clean	364.40
Dry&Contaminated	351.47
Dry&Clean	383.41

In this test the voltage reference(Dry-Clean) is 383 kV. In Dry-Contaminated test, breakdown voltage has 30 kV reduction and in Wet-Clean test the breakdown voltage has 20 kV reduction. In these two tests the Insulation Strength does not decrease, but in Wet-Contaminated condition, the break down voltage has 80 kV reduction and insulation strength of insulators decrease.

4 Conclusion

Different ambient conditions have different affects on protective devices in a power system. In this essay, such protective devices as spark gap, surge arrestor, and cap and pin insulators are tested under simulated lightning voltage. Haefely MTS and Marx generators are used to generate the impulse Lightning voltage. Due to difference between ambient and standard conditions, correction factor is used to accord the measures with standard. Due to the tests, it was found that breakdown voltage and CFO in negative impulse of spark gap test are higher than positive impulses and steepness would not change the average flashover voltage of spark gap. Results from arrestor tests show that the voltage across the spark gap does not change by changing in lightning impulse voltage. So, arrestor's performance does not relate to voltage level and the polarity. Also, the series combination of spark gap and arrestor with each other was also tested and for SG-arrestor connection where spark gap is connected to electrode and arrestor is grounded, the configuration will be more suitable for a power system because the breakdown voltage will be lower. The results of hot and cold test on spark gap show that breakdown voltage has increased with the increase in temperature and humidity because insulation strength of air in hot condition is more than in cold condition. Finally, due to explore on effect of contamination on the break down voltage of pin and cap type insulators, Dry-Clean insulators have high withstand voltages, but Wet-Contaminated insulators have low breakdown voltages. Therefore, in a power system it is necessary that influence on different factors such as ambient condition on protective devices be considered.

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