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Influence of SF_6/N_2 Gas Mixture Ratios on the Lightning Streamer Propagation Characteristics of 22 kV MV Circuit Breaker

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Abstract – In recent times, gas insulated medium voltage (MV) circuit breakers (CB) form a vital component in power system network, considering its advantages such as reduced size and safety margins. Gas insulation characteristics of circuit breakers are generally measured by lightning impulse (LI) test according to IEC standard 60060-1 as a factory routine test. Considering the environmental issues of SF_6 gas, many research works are being carried out towards the mixture of SF_6 gases for high voltage insulation applications. However, few reports are only available regarding the LI withstand and streamer propagation characteristics (at both positive and negative polarity of waveform) of SF_6/N_2 gas mixture insulated medium voltage circuit breakers. In this paper, positive and negative polarity LI tests are carried out on 22 kV medium voltage circuit breaker filled with SF_6/N_2 gas mixture at different gas pressures (1-5 bar) and at different gas mixture ratios. Important LI parameters such as breakdown voltage, streamer velocity, time to breakdown and acceleration voltage are evaluated with IEC standard LI (1.2/50 µs) waveform. Weibull distribution analysis of LI breakdown voltage data is carried out and 50% probability breakdown voltage, scale parameter and shape parameter are evaluated. Results illustrate that the 25% SF_6+75%N_2 gas filled insulation considerably enhances the LI withstand and breakdown strength of MV circuit breakers. LI breakdown voltage of circuit breaker under negative polarity shows higher value when compared with positive polarity. Results show that maintaining the gas pressure at 0.3 MPa (3 bar) with 10% SF_6 gas mixed with 90% N_2 will give optimum lighting impulse withstand performance of 22 kV MV circuit breaker.

Keywords: Circuit breaker, Weibull distribution, Lightning impulse, Gas insulation, Breakdown voltage, Streamer velocity.

1. Introduction

Electrical power network is protected by the high voltage (HV) and medium voltage (MV) circuit breakers capable of making, carrying and breaking currents under normal and fault conditions [1,2]. In recent times, gas insulated MV circuit breakers form a vital component in power system network, considering its advantages such as reduced size and safety margins [3,4]. MV circuit breakers consist of fixed and movable contacts. When the contacts of circuit breakers are separating under fault conditions, air blast or SF_6 gas is used as an arc quenching medium which acts as an arc extinguisher and also provides insulation between conducting parts [5-10].

In general, dielectric strength of SF_6 gas is higher than air medium. However considering its environmental impacts such as greenhouse effect, research works are being carried out to understand the different SF6 gas mixture performance for high voltage applications [11-20].

Beroual et al., [11] investigated the breakdown voltage of CO_2, N_2, SF_6, CO_2-SF_6 and N_2-SF_6 gases under AC, DC and lightning impulse voltage in a sphere-to-sphere electrodes configuration. Cookson et al., [12] presented the effect of metallic particle contaminants on the HV electrical breakdown in SF_6 and N_2-SF_6 gas mixtures. An Su et al., [13] studied the breakdown characteristics of short gap SF_6/ CF_4, under the flat plate and needle board electrodes at different gas mixture ratio of SF_6 from 0% to 100% and at different pressure from 0.1 MPa to 0.4 MPa (1-4 bar).

Failure of MV circuit breakers due to poor insulation design will disturb the reliability of the electric power network. In general, the insulation characteristics of MV circuit breakers are verified by AC power frequency and LI withstand test. LI test as per IEC 60060-1 is generally given more focus as a factory routine test since it confirms the surge overvoltage withstand capacity of MV circuit breakers [21-24]. With reference to the recent revisions made in IEC 60060-1 test procedures 2010, LI test waveform consisting of the front time T1=1.2 µs ± 30% , tail time T2=50 µs ±20%, peak voltage Vp within 3% and overshoot rate of 10% or less is acceptable.

Can Guo et al., [15] investigated the breakdown

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characteristics of SF_6/N_2 in varying electric field under standard lightning impulse. They demonstrated that the 50% breakdown voltage of SF_6/N_2 rises linearly with rise of gas pressure and the reversal phenomenon of polarity effect was found in SF_6/N_2 with different mixing ratio. However, still there is a need for understanding the LI discharge characteristics of real time circuit breaker filled with SF_6/N_2 gas mixture at different gas pressures under both positive and negative polarity of impulse waveform. Hu Zhao et al.,[16] studied the arc interruption capabilities of SF_6-CO_2 mixtures by carrying out tests with a 126 kV puffer gas circuit breaker prototype model. Considering these facts, in this paper, laboratory based LI tests at both positive and negative polarity of waveform as per IEC procedures are carried out on 22 kV MV circuit breaker. Important LI test parameters such as breakdown voltage, time to breakdown, streamer velocity and streamer acceleration voltage are evaluated at different SF_6/N_2 gas mixture ratios and at different gas pressures (1-5 bar) with the IEC standard LI waveform (1.2/50 μs). Weibull distribution analysis is carried out in order to estimate the 50% probability breakdown voltage.

2. 22 kV Circuit Breaker Prototype Specimen

Fig. 1 shows the photograph of the 22 kV medium voltage circuit breaker test specimen, supplied by Megawin Switchgears Salem, used for LI withstand test. It is a three phase, 22 kV, 600 A circuit breaker with 6 poles as shown in Fig. 1 with dimensions of 80x60x30 cm. RYB poles of circuit breaker were covered with silicone rubber bushing and it is of length 32 cm. Inside the chamber, each pole of the breaker has a fixed main contact at the top and moving contact at the bottom as shown in Fig. 2. Arcing contact is placed in the middle of both fixed and moving contact. Geometry of the fixed and moving contacts is similar in size and curvature to those mostly preferred in MV circuit breakers. Fig. 3 shows the schematic of different positions of circuit breaker contacts during opening and closing operations. Table 1 shows the technical specifications of the circuit breaker used in the test. Six organic glass sheets

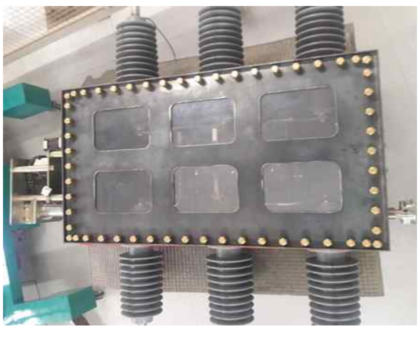


Fig. 1. Photograph of 22 kV MV circuit breaker test specimen used for LI withstand test with glass windows

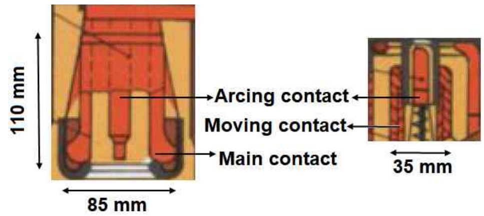


Fig. 2. Schematic of fixed main contact (left) and moving contact (right) of circuit breaker

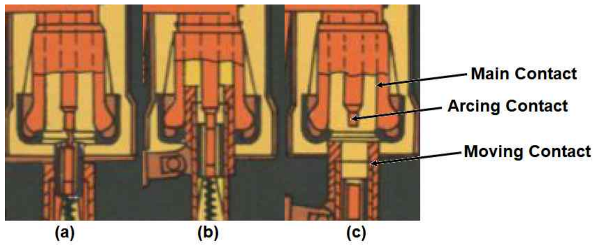


Fig. 3. Schematic of different position of contacts during operation (a) arcing contact closed (b) breaker main contact closed (c) arcing contact opened

Table 1. Technical specifications of circuit breaker

Performance Standards	IEC 62271-100/IS13118
Rated voltage	22.0 kV
Highest system voltage	24.2 kV
Rated current	600A
Short circuit breaking capacity	20.0 kA
Positive LI $V_{50\%}$ (100% SF_6, 0.5MPa)	158 kV
Negative LI $V_{50\%}$ (100% SF_6, 0.5MPa)	176 kV
Mechanical life for spring mechanism	50,000 operations

were provided on the top in order to have a view at the inner chamber of the circuit breaker. The minimum gap distance between any two conducting part inside the circuit breaker test chamber was maintained at 50 mm. Experiments were carried out at different gas pressure inside the test chamber varying from 0.1 MPa to 0.5 MPa (1-5 bar) representing the actual GIS. Entire test specimen was vacuumed below 0.1 MPa repeatedly two to three times before starting each experiment. Then the chamber was filled with gas mixture at different ratios such as 100%N_2, 5%SF_6+95%N_2, 10%SF_6+90%N_2, 25%SF_6+75%N_2 and waited for 30 minutes.

3. Lightning Impulse Experimental Works

Fig. 4 shows the block diagram of laboratory LI test setup used to understand the withstand and breakdown characteristics of SF_6/N_2 filled circuit breaker specimen. It consists of two units such as a DC charging device and a 3 stage LI generator connected with control panel. Input three phase AC voltage is transformed to high voltage AC and connected to a rectifier circuit to convert as high voltage DC. LI generator is connected with high voltage

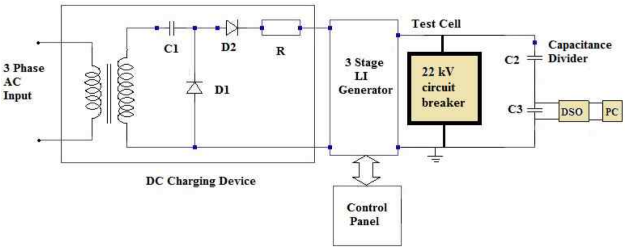


Fig. 4. Schematic diagram of laboratory LI test setup

Fig. 5. Photograph of 3 Stage, 300 kV LI Generator connected to the 22 kV circuit breaker specimen

DC input and works on the basic principle of Marx Impulse Generator circuit. Output of LI generator is connected with the 22 kV circuit breaker test specimen. Marx Impulse Generator circuit charges the capacitor bank in parallel and discharges in series to deliver the standard lightning impulse waveform of time period 1.2/50µs to the load.

Motorized control circuit integrated with PC based operation is used to alter the polarity of the LI generator and to alter the spark gap distance. Photograph of 3 stage, 300 kV (100 kV each stage) lightning impulse generator used in the present study is shown in Fig. 5. Standard HV 400 pF measuring capacitor is used for LI voltage measurement. All the tests were carried out at room temperature. Tektronix digital storage oscilloscope of 200 MHz, 2.5 GS/s is used to measure the LI waveforms and it is integrated with PC for storage.

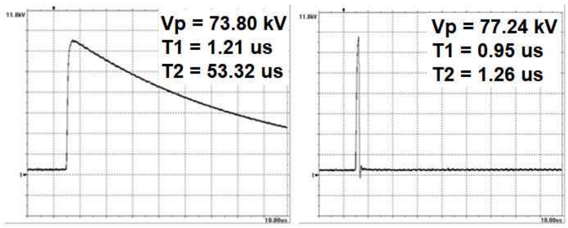
3.1 LI test procedure

LI withstand and breakdown tests were performed in the 22 kV circuit breaker specimen at both positive and negative polarity of waveform. Up and down test method was adopted as per IEC 60060-1 and the corresponding breakdown voltage, front time and tail time were measured. During each test, utmost care is taken to avoid pollution and dust free environment is maintained. Initially, test was started with low voltage settings and then gradually the test voltage was increased at a 10 kV step voltage. Voltage was elevated until the breakdown of the test specimen occurs. While conducting the test in one phase, other two phases are short circuited and attached to ground terminal. When compared with the up/down method of IEC procedures, the step voltage considered as 10 kV is smaller in this case, however it will be helpful to estimate the influence of the overshoot in the LI waveform. A 5 minutes time interval is maintained throughout the test between any two successive LI shots. Peak voltage and time to breakdown results of each test were stored for post processing.

4. Results and Discussion

4.1 Analysis of positive and negative LI breakdown and withstand waveforms of CB

Fig. 6 and 7 shows the typical lightning impulse



(a)

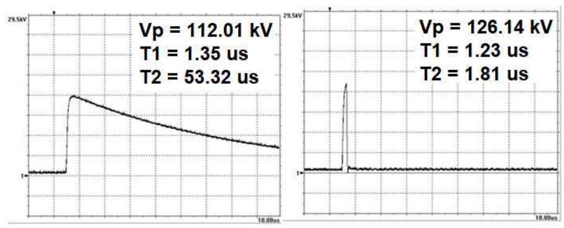


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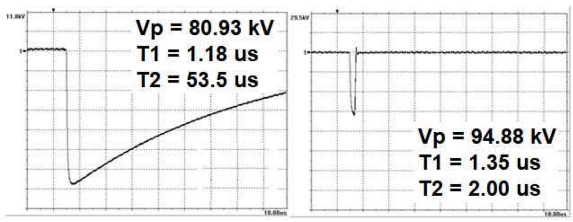
Fig. 6. Typical positive LI withstand (left) and breakdown (right) waveforms of CB with 0.5 MPa gas pressure at different %SF_6 concentration (a) 0% (b) 25%



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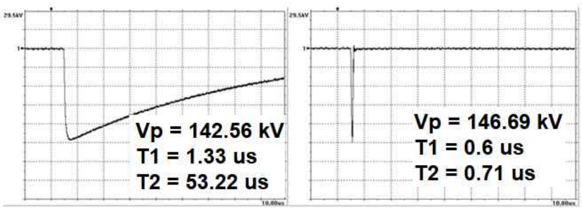

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Fig. 7. Typical negative LI withstand (left) and breakdown (right) waveforms of CB with 0.5 MPa gas pressure

withstand (right) and breakdown (left) waveforms obtained at constant gas pressure of 0.5 MPa with increasing concentration of $\%SF_6$ gas.

It is clear that increase in $\%SF_6$ gas content increases both withstand and breakdown strength of the specimen. LI withstand voltage of 100% N_2 is 74 kV, whereas when it is mixed with $25\%SF_6$ gas it increases upto 112 kV for the same gas pressure of 0.5 MPa. Similarly, 100% N_2 gas breakdown voltage is around 77 kV, whereas it increases upto 126 kV for 25% SF_6 gas. Fig. 6 also shows corresponding front time and tail time of the waveforms obtained at different $\%SF_6$ concentrations. Fig. 7 shows the similar trend of characteristics for negative polarity of LI voltage. In general, higher withstand and breakdown strength is observed with negative polarity than positive polarity irrespective of the $\%SF_6$ gas. Withstand voltage varies from 80 kV to 142 kV for 0% SF_6 to 25% SF_6 respectively. Similarly, breakdown voltage varies from 95 kV to 146 kV with increasing SF_6 gas ratio. Fig. 8 shows the withstand and breakdown voltage pattern trend with respect to increase in LI peak voltage. Failure and No Failure cases are shown in different markers.

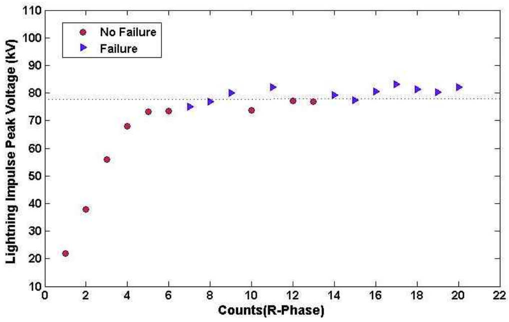
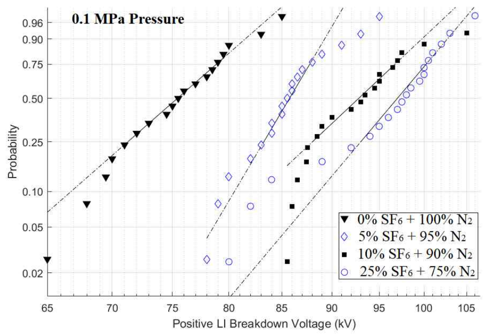
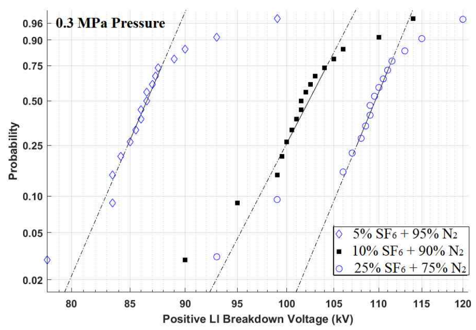


Fig. 8. LI withstand and breakdown pattern of $0\%SF_6$+ $100\%N_2$ gas with respect to increase in applied LI peak voltage at 0.1 MPa Pressure



(a)



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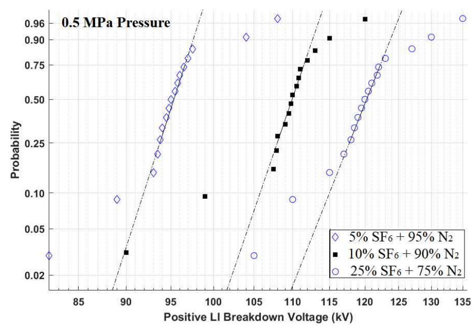


(c)

Fig. 9. Weibull probability distribution of Positive LI breakdown voltage values of CB at different SF_6+N_2 gas pressures (a) 0.1 MPa (b) 0.3 MPa (c) 0.5 MPa

4.2 Weibull distribution analysis of li breakdown voltage at different SF_6 gas ratios and pressures

Fig. 9 and 10 shows the Weibull distribution results of LI breakdown voltage values at both positive and negative polarity of waveform at different gas pressures and at different $\%SF_6$ gas ratios. At each experimental setting, 15 to 20 LI breakdown voltage values were measured and two parameter Weibull distribution analysis was carried out. Corresponding scale parameter (α) and shape parameter (β) of the Weibull analysis at each test case were computed and tabulated in Table 2 and 3. Shape parameter, which is inversely related with the distribution of data, is considerably high in all test cases. This confirms that the breakdown voltage values are lying in the close proximity. There is an obvious polarity effect shown by the summary of scale parameter results, i.e. scale parameters at negative

Table 2. Scale and Shape parameter of Weibull distribution of Positive LI breakdown voltage

Details	Scale parameter(α)			Shape parameter(β)		
Pressure (MPa)	0.1	0.3	0.5	0.1	0.3	0.5
$0\%SF_6+100\%N_2$	77.58	--	--	16.36	--	--
$5\%SF_6+95\%N_2$	87.72	89.09	97.8	19.93	17.44	17.4
$10\%SF_6+90\%N_2$	96.58	104.5	111.6	13.57	19.47	22.0
$25\%SF_6+75\%N_2$	98.68	111.3	123.5	18.84	21.73	18.3

Table 3. Scale and Shape parameter of Weibull distribution of Negative LI breakdown voltage

Details	Scale parameter(α)			Shape parameter(β)		
Pressure (MPa)	0.1	0.3	0.5	0.1	0.3	0.5
$0\%SF_6+100\%N_2$	99.1	--	--	14.5	--	--
$5\%SF_6+95\%N_2$	103.4	111.2	93.6	14.9	21.65	21.3
$10\%SF_6+90\%N_2$	126.2	133.4	141	20.8	21.24	25.4
$25\%SF_6+75\%N_2$	136.1	151.8	154	24.9	27.88	42.3

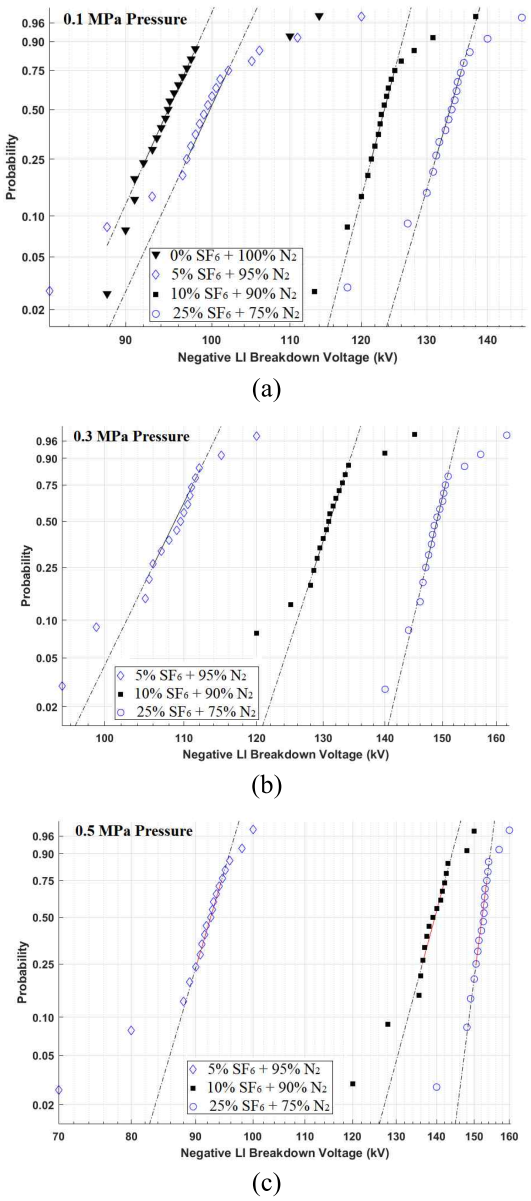


Fig. 10. Weibull probability distribution of Negative LI breakdown voltage values of CB at different SF_6+N_2 gas pressures (a) 0.1 MPa (b) 0.3 MPa (c) 0.5 MPa

polarity are higher than positive polarity. In general, with respect to increase in gas pressure, considerable increase in withstand and breakdown voltage is observed under both positive and negative polarity. It is also noted that % increase in withstand and breakdown values is not so high when the pressure increases from 0.3 MPa to 0.5 MPa. Whereas significant % increase in breakdown and withstand values are noted when pressure increases from 0.1 MPa to 0.3 MPa at both polarity of waveform. Results confirm that increase in gas pressure above 0.3 MPa and increase in %SF_6 gas above 10% shows considerable improvement in LI breakdown voltage irrespective of the polarity of waveform. $V_{50\%}$ probability breakdown voltage is computed from the Weibull analysis. Table 4 shows the summary of 50% probability breakdown voltage, its standard deviation and coefficient of variance under both positive and negative LI cases.

4.3 Analysis of Time to Breakdown at different SF_6 Gas Ratios and Pressures

In order to understand the acceleration voltage, it is

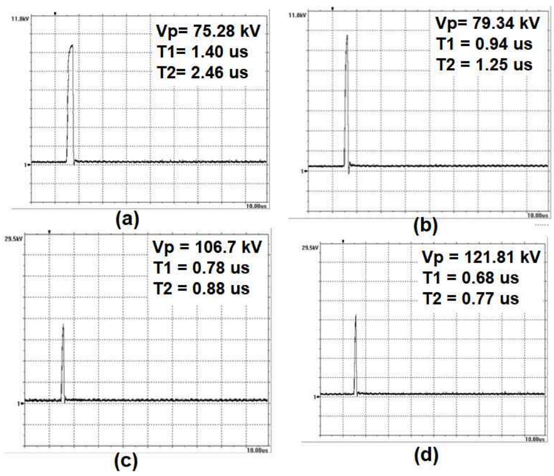


Fig. 11. Variations in tail time (T2) with respect to increase in applied LI peak voltage at 0.3 MPa Pressure of 5%SF_6+95%N_2 gas

Table 4. Summary of $V_{50\%}$ Positive and Negative LI breakdown voltage results

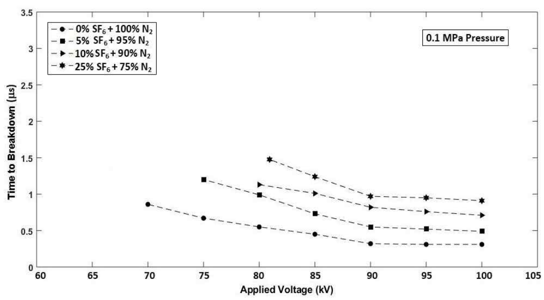
Details	Positive LI								
	0.1MPa			0.3 MPa			0.5 MPa		
	$V_{50\%}$ (kV)	Std Dev (kV)	s (%)	$V_{50\%}$ (kV)	Std Dev (kV)	s (%)	$V_{50\%}$ (kV)	Std Dev (kV)	s (%)
0%SF_6+100%N_2	76	5.18	6.89	--	--	--	--	--	--
5%SF_6+95%N_2	85.5	4.41	5.15	86.5	4.43	5.10	95.2	5.45	5.72
10%SF_6+90%N_2	93	6.45	6.90	102.5	5.32	5.12	110	6.62	6.08
25%SF_6+75%N_2	97	7.08	7.39	109.5	6.08	5.59	120	6.88	5.72

Details	Negative LI								
	0.1MPa			0.3 MPa			0.5 MPa		
	$V_{50\%}$ (kV)	Std Dev (kV)	s (%)	$V_{50\%}$ (kV)	Std Dev (kV)	s (%)	$V_{50\%}$ (kV)	Std Dev (kV)	s (%)
0%SF_6+100%N_2	95.0	6.31	6.58	--	--	--	--	--	--
5%SF_6+95%N_2	100.0	8.20	8.1	109	5.68	5.23	93	6.6	7.23
10%SF_6+90%N_2	123.5	5.61	4.54	131	6.36	4.88	140	6.9	4.98
25%SF_6+75%N_2	134.0	5.77	4.32	149	4.81	3.22	152	4.04	2.66

necessary to evaluate the time to breakdown and streamer velocity characteristics of gas medium. In this case, the applied voltage is slowly increased in steps above $V_{50\%}$ breakdown voltage and corresponding breakdown voltage and time to reakdown were recorded. Fig. 11 shows the variations in tail time with respect to increase in applied LI peak voltage at 0.3 MPa pressure of $5\%SF_6+95\%N_2$ gas. This clearly shows the reduction in time to breakdown (T2) value with increasing peak voltage Vp.

Understanding the influence of gas ratios and gas pressure on the lightning streamer propagation in the insulating medium is very important. If the medium provides stronger resistance against the travel speed of lightning streamer, then its insulating strength is higher. In this test, in order to understand the time to breakdown due to the streamer propagation, tests were carried out below and above $V_{50\%}$ breakdown voltage and corresponding tail time is noted. Fig. 12 shows the time to breakdown values of positive LI at different gas ratios and gas pressure with increasing applied voltage. It is noted that at lower pressure (0.1 MPa), with respect to increase in voltage, there is a considerable influence of $\%SF_6$ gas ratio, i.e. higher $\%SF_6$ gas has higher time to breakdown value. Whereas at higher gas pressure (0.3 and 0.5 MPa), when the voltage increases above 110 kV, then there is no significant difference in time to breakdown value irrespective of the $\%SF_6$ gas content. However, the streamer propagation is provided high resistance at 0.5 MPa and 25 % SF_6 gas ratio.

Fig. 13 (a,b,c) shows the variations in time to breakdown values of gas mixtures at different gas pressures with increasing applied voltage at negative polarity of LI waveform. In general, it is noticed that time to breakdown values of 25% SF_6 gas is higher when compared with other cases irrespective of the gas pressure and polarity of applied voltage. It is also noted that time to breakdown



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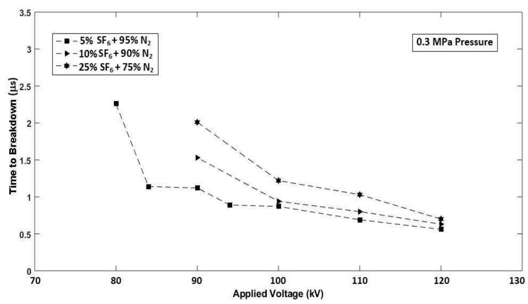

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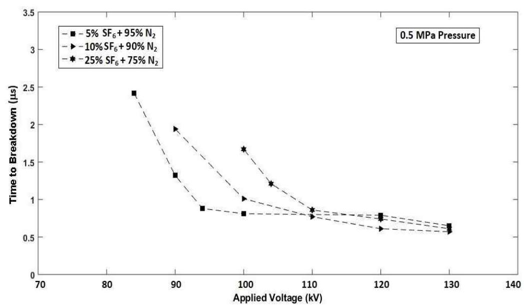

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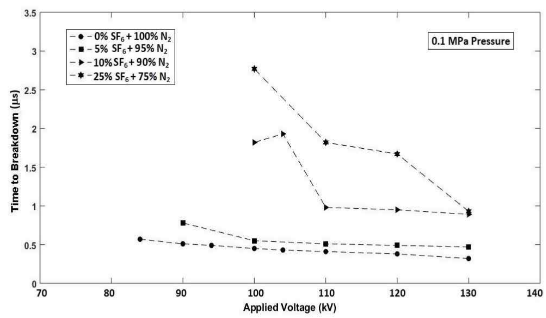
Fig. 12. Variations in positive LI time to breakdown values of CB with different SF_6+N_2 gas ratios at different gas pressure (a) 0.1 MPa (b) 0.3 MPa (c) 0.5 MPa



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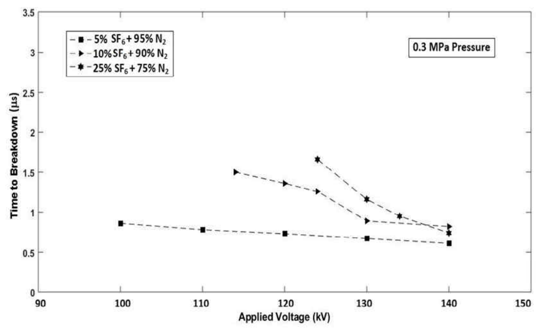

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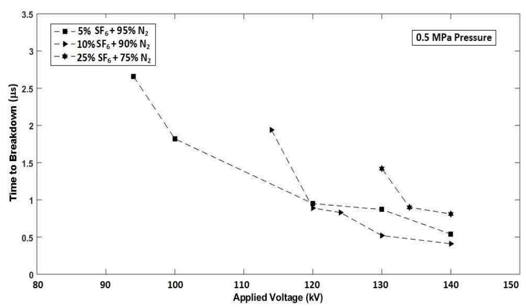

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Fig. 13. Variations in negative LI time to breakdown values of CB with different SF_6+N_2 gas ratios at different gas pressure (a) 0.1 MPa (b) 0.3 MPa (c) 0.5 MPa

value of 25% SF_6 gas starts at higher applied voltages when compared with 5% and 10% SF_6 gas content. In this negative polarity at 0.1 MPa, when the applied voltage increases above 110 kV, then there is no significant difference in time to breakdown between the different gas ratios. Whereas at high pressures in the range of 0.3 and 0.5 MPa, performance of 10% and 25 % SF_6 gas is somewhat better than 5% SF_6 gas mixture.

4.4 Analysis of Streamer Velocity at different SF_6 Gas Ratios and Pressures

In this case, streamer velocity is computed by taking the tail time and the minimum gap distance between the conductors in the circuit breaker.

Fig. 14 shows the variations in positive LI streamer velocity values of circuit breaker at different gas ratios and pressures. At 0.1 MPa low pressure, streamer propagation velocity is higher in the case of 100 % N_2 gas than 25%SF_6+75%N_2 gas mixture. At 0.5 MPa high pressure, when the voltage goes above 110 kV, there is no significant difference in streamer velocity of gas mixtures. Performance of 10%SF_6 gas mixture is more or less similar with 25% SF_6 gas at all pressures and at all applied voltage values. With respect to increase in pressure from 0.1 to 0.5 MPa, considerable reduction in streamer velocity of the gas mixtures are noticed irrespective of the %SF_6 gas content. From the results of positive polarity waveform, it is understood that 25% SF_6 gas mixture gives better performance than other tested specimens. However, since there is a little difference in results of 10% SF_6 gas and 25% SF_6 gas, 10% SF_6 may be considered for practical cases in order to minimize the usage of SF6 gas.

Fig. 15 shows the streamer velocity of gas mixtures at negative polarity of waveform. At low pressure of 0.1 MPa, the variations in streamer velocity with respect to increase in applied voltage follow a clear trend. Whereas at high pressure 0.5 MPa, when the voltage increases above 120

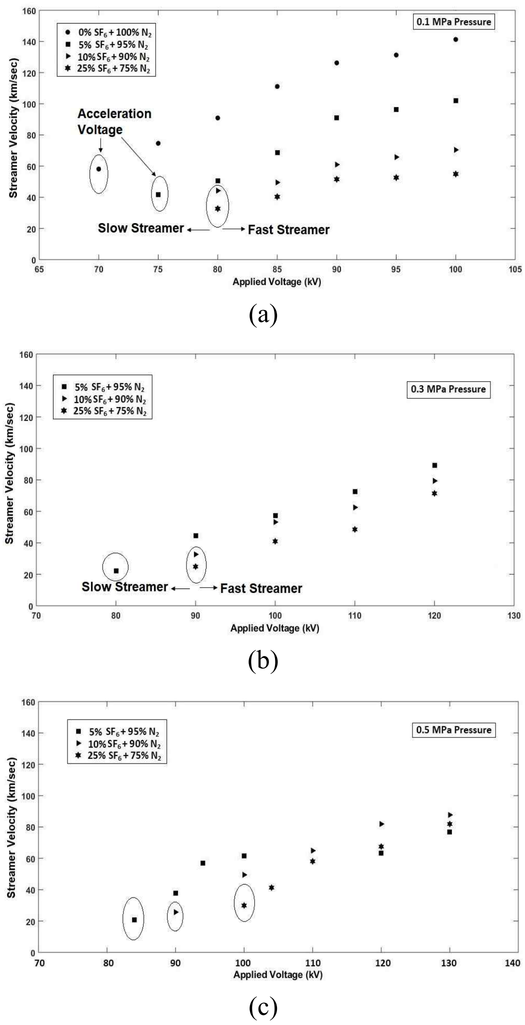

Fig. 14. Variations in positive LI streamer velocity values of CB with different SF_6+N_2 gas ratios at different gas pressure (a) 0.1 MPa (b) 0.3 MPa (c) 0.5 MPa

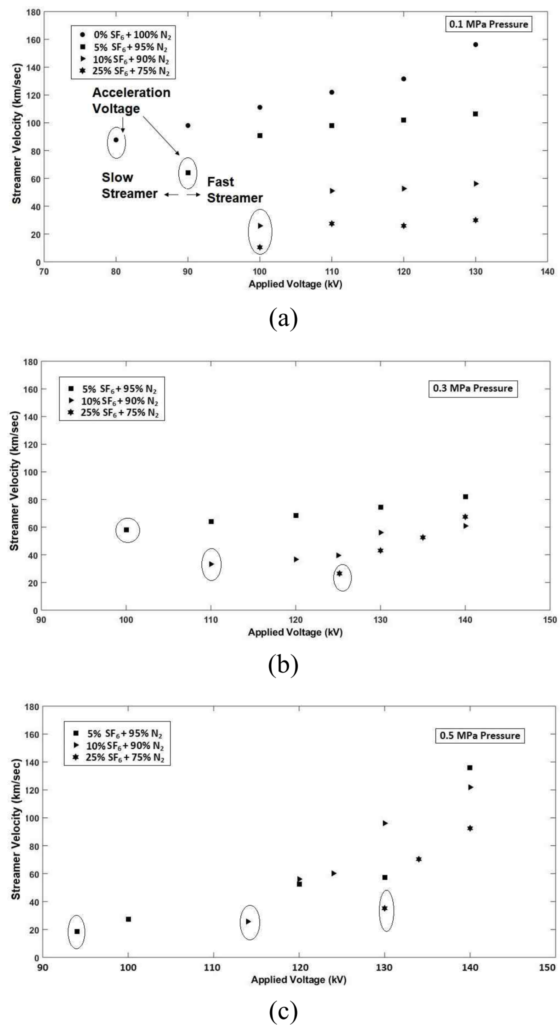

Fig. 15. Variations in negative LI streamer velocity values of CB with different SF_6+N_2 gas ratios at different gas pressure (a) 0.1 MPa (b) 0.3 MPa (c) 0.5 MPa

Table 5. Acceleration voltage (kV) of positive LI at different gas pressure and gas ratio

Acceleration voltage (kV)	0.1 MPa	0.3 MPa	0.5 MPa
$0\%SF_6+100\%N_2$	70	--	--
$5\%SF_6+95\%N_2$	75	80	84
$10\%SF_6+90\%N_2$	80	90	90
$25\%SF_6+75\%N_2$	80	90	100

Table 6. Acceleration voltage (kV) of negative LI at different gas pressure and gas ratio

Acceleration voltage (kV)	0.1 MPa	0.3 MPa	0.5 MPa
$0\%SF_6+100\%N_2$	80	--	--
$5\%SF_6+95\%N_2$	90	100	94
$10\%SF_6+90\%N_2$	100	110	114
$25\%SF_6+75\%N_2$	100	125	130

kV, then considerable increase in streamer velocity is noticed when compared with 0.3 MPa case.

Acceleration voltage is the voltage above which the streamer velocity in the insulating medium starts to increase fast. In Fig. 14 and 15, acceleration voltage values of each case are encircled. If the applied LI voltage is above acceleration voltage, then the streamer propagation will be fast and vice versa. Table 5 and 6 shows the summary of acceleration voltage values of positive and negative LI at different gas ratios. From the above results of positive LI, it is clear that 100 kV is the acceleration voltage above which streamer propagation velocity increases suddenly at high pressures(0.5 MPa). Under negative LI cases, 130 kV is the acceleration voltage above which the fast streamer is observed in the medium at 0.5 MPa.

From the results of $V_{50\%}$ breakdown voltage, time to breakdown, streamer velocity and acceleration voltage with increasing LI peak applied voltage, it is clear that 0.3 MPa (3 bar) gas pressure with 10% SF_6 gas gives optimal performance when compared with other cases.

5. Conclusion

Laboratory experiments on LI withstand and breakdown voltage characteristics of 22 kV MV circuit breaker prototype model filled with SF_6/N_2 gas mixtures at different ratios and pressures were conducted as per IEC procedures at 1.2/50 μs waveform of both positive and negative polarity. Important parameters such as 50% breakdown voltage, time to breakdown, LI streamer velocity and acceleration voltage of gas mixture ratios were evaluated. It is observed that addition of 10% of SF_6 gas with 90 % N_2 gives more or less similar lightning impulse characteristics when compared with 25% SF_6 gas mixed with 75% N_2. When the positive LI voltage increases above 100 kV, then a considerable reduction in time to breakdown and increase in streamer velocity is noted at 0.5 MPa (5 bar) gas pressure. This shows that maintaining the gas pressure at 0.3 MPa (3 bar) with 10% SF_6 gas mixed with 90% N_2 will give better lighting impulse withstand performance of 22 kV medium voltage circuit breaker. Summary of results reported in this work will be useful for gas insulated medium voltage circuit breaker manufacturers to plan optimal % concentration of SF_6 gas and pressure of the chamber.

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