SF_6 Capacitive Voltage Divider

Cattareeya Suwanasri and Thanapong Suwanasri

Abstract— *This paper aims to develop a 100 kV capacitive voltage divider. The divider was separated into high voltage and low voltage parts. The high voltage part was constructed from capacitors connected in series in order to obtain the capacitance as of 114.285 pF. The low voltage part was constructed from capacitors connected in parallel to obtain the capacitance as of 0.12 μF. This capacitive voltage divider was filled with three gas insulation as air, N_2 and SF_6 for each test in order to select the suitable gas insulation. The test procedures were followed the standard IEC 60060 - 2 (1994). The test records showed that the performance of the developed capacitive divider is within the designed standard.*

Keywords— **Capacitive voltage divider, measuring instrument, sulfur hexafluoride (SF_6).gas insulation.**

1. INTRODUCTION

The voltage divider is a simple tool for measuring the high voltage by using two impedances connected in series. It is a very useful device for high voltage measurement in several circuit e.g. insulation testing. The voltage divider can be used with resistive, inductive, or capacitive circuit elements. It can also measure the AC, DC or high voltage impulse voltage sources. However, capacitive dividers can usually used to measure the AC voltage, whereas it is not suitable for the DC input voltage measurement because the DC voltage could not pass through the capacitors. Capacitive voltage divider as shown in Fig. 1 produces an output voltage (V_{out}) which is a fraction of its input voltage (V_{in}).

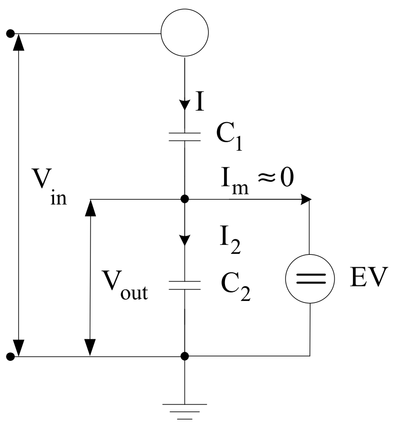

Fig. 1. Capacitive Voltage Divider [2]

where V_{in} = high voltage input (V)
V_{out} = low voltage output (V)
C_1 = high voltage capacitance (F)
C_2 = low voltage capacitance (F)
R_m = matching resistance (Ω)
EV = oscilloscope

Voltage division refers to the ratio of a voltage among the components of the divider. The 1000:1 is given in Eq. (1). The principle is that the current in series circuit is always equal. Therefore, the voltage ratio has C_1 in the numerator because of the inverse relationship between capacitive reactance and capacitance as shown in Eq. 1.

$$V_{out} = V_{in}\left[\frac{C_1}{C_1 + C_2}\right] \tag{1}$$

Since the voltage ratio of this capacitive voltage divider is opposite to resistive and inductive voltage divider, this should be carefully considered in output voltage calculation in order to avoid the mistake.

2. DESIGN AND CONSTRUCTION

Capacitive voltage divider has a large numbers of variables. The specification is given in Table 1. It is designed to meet the requirement of standard IEC 60060 - 2 (1994) [1]. The unit consists of two capacitors connected in series. The important components will be discussed.

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Table 1. Specifications of Capacitive Voltage Divider

Parameter	Specification
Rated voltage	100 kV
High voltage capacitance	113.00 pF
Low voltage capacitance	0.108
Test voltage	110% of rated voltage (V)
Frequency	50 Hz
Scale factor	1000:1
Dielectric medium	SF_6, N_2, Air
Accuracy	±1%

2.1 Electrode length

The capacitors connected in series must be installed in the cylinder, which is made from Acrylic. To prevent the external flashover, the relative electrical clearance from top electrode to ground should be 5 m/MV (rms.) for AC voltage. Thus, the total length of 100kV divider should be at least 0.5 m. However to have some safety margin in operation, the length of cylinder in this design is one meter long**.**

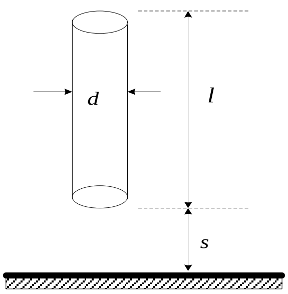

Fig. 2. Capacitor Cylinder

2.2 Stray capacitance

The unavoidable stray capacitors always occur between the divider and earth or the divider and grounded objects. A existence of stray capacitance can directly affect the measurement precision. Therefore, it should be investigated.

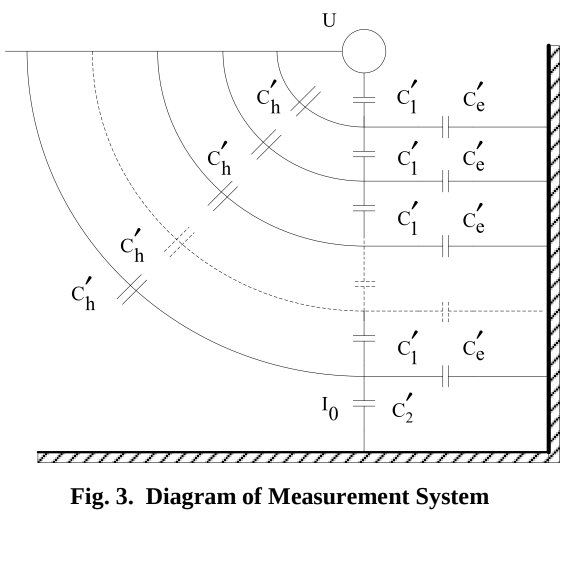

Fig. 3. Diagram of Measurement System

Fig. 3 shows the equivalent circuit diagram of measurement system that considered stray capacitance C'_e (pF), which is calculated as:

$$C'_e = \frac{2\pi\varepsilon l}{\ln\left[\frac{(2l)}{d}\sqrt{\frac{(4s+l)}{(4s+3l)}}\right]} \tag{2}$$

l = length of cylinder (m)
d = diameter of cylinder (m)
s = distance between cylinder-end to ground (m)
ε = permittivity of free space (8.854×10^{-12} F/m)

For the design as of *l*, *d*, and *s* are 1 m, 0. 20 m, and 0.20 m respectively, the stray capacitance is equal to 28.825 pF.

2.3 High voltage capacitance

The 100 kV capacitive voltage divider is designed for high voltage test up to 110% of rated voltage, which is 110 kV. The polypropylene film capacitors of rating $0.01\mu F$, 1600dc/650Vac are selected to use by connecting in parallel to obtain the capacitance as of $0.02\mu F$. At 110% of rated voltage, the number of capacitors is equal to 110 kV/650Vac = 169.2 or 170 pair or 340 capacitors. However, the total 350 capacitors are designed as 14-paralleled capacitors in a row and each row is connected in series up to 25 rows as shown in Fig. 4. Thus, the high voltage capacitance C_1 is 114.285 pF.

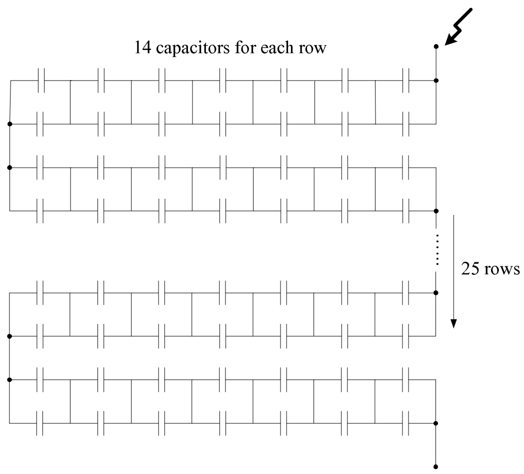

Fig. 4. Layout for HV Capacitance

2.4 Low voltage capacitance

The scale factor is designed as 1000:1. By using the formula of capacitive voltage divider in Eq. (1), the low voltage capacitance C_2 is 114.285*1000 pF = 0.114285 μF. Thus, 12-capacitors as of 0.01 μF are connected in parallel to obtain 0.12 μF. At the low voltage or output terminal the matching resistor of 50 Ω, which is equal to the surge impedance of coaxial cable, is connected to avoid the reflection of voltage wave.

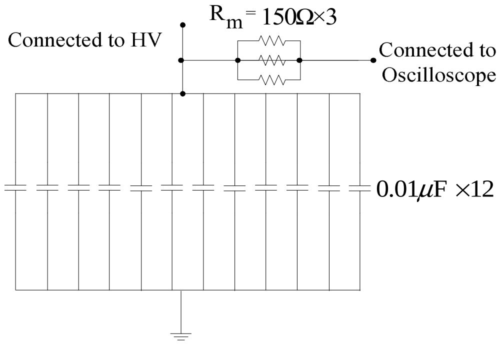

Fig. 5. Layout for LV Capacitance

3. EXPERIMENTAL SETUP

The acceptance tests on capacitive voltage divider are as follows.

3.1 Components measurement

The circuit in Fig. 6 is used to measure the resistance or capacitance by using RLC meter in order to compare the actual value with the designed value.

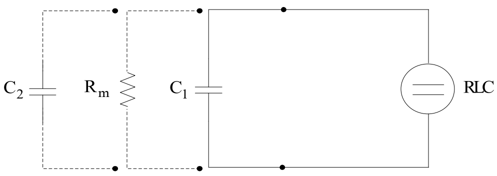

Fig. 6. Components of Measurement Circuit.

3.2 Withstand Voltage Test

A capacitor divider shall pass a dry withstand voltage test performed with a voltage of the required frequency or shape at a level of 110% of the rated measuring voltage. The procedure of withstand voltage tests is described in IEC 60-1 [3]. The equivalent circuit is given in Fig. 7.

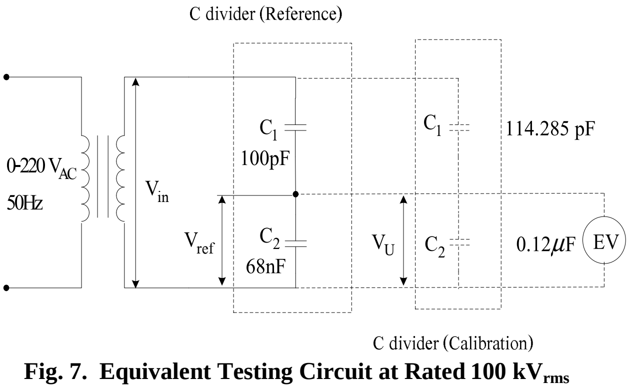

Fig. 7. Equivalent Testing Circuit at Rated 100 kV_{rms}

3.3 Determination of the Scale Factor

The circuit in Fig. 7 is used to determine the scale factor, which is calculated for the ratio of V_{in} and V_U. The designed value of scale factor is 1000:1.

3.4 Linearity Test

Using Fig. 7, values of the scale factor of the measuring system shall be measured at the minimum and maximum of the operating voltages and at three approximately equally spaced voltage or current between these extremes. These five values shall not differ by more than ±1% from their mean value.

3.5 Stability Test

Stability of the capacitor divider and the measurement system shall not vary by more than ±1% for the ranges of the ambient temperature and clearances given in the record of performance. The measuring instruments in Fig. 7 shall comply with the requirements of class 0.5 of IEC 51 [4] or shall be tested according to this standard if a peak voltmeter is used, its uncertainty shall be within ±1%.

4. EXPERIMENTAL RESULTS

The AC high voltage test circuit of rated 100 kV_{rms} is given in Fig. 8.

Fig. 8. Testing Circuit of Rated Voltage 100 kV_{rms}

This capacitive voltage divider was filled by gas insulation as air, N_2 and SF_6 for each test. The test procedures were followed the IEC 60060 - 2 (1994) standard.

Air-Insulated Capacitive Voltage Divider

In this test, air was filled in the cylinder of C_1 as gas insulation. However before any tests, the electrical value of the divider element must be measured. The results are presented in Table 2. The measured values show that the scale factor is 926:1 (113.000 pF/0.122 μF). The factors as capacitances and resistance are similar for N_2 and SF_6-insulation.

Table 2. Components Measurement

Component	Designed Value	Measured Value	% Error
C_1	114.285 pF	113.000 pF	1.12%
C_2	0.12 μF	0.122 μF	1.67%
R_m	50 Ω	49.93 Ω	0.14%

The pressure of air-insulation can be increased upto 2-bars in the cylinder. Actually for withstand test, the withstand voltage should rise up to 110 kV. However due to the poor dielectric withstand voltage of the air, there was an occurrence of corona discharge when the high voltage input was increased to nearly 30 kV. Then the withstand voltage test was stopped at that point to avoid electrical breakdown at higher voltage. The results show in Table 3. The divider can be operated against 30 kV for 60 second long.

Table 3. Withstand Test for Air-Insulated Voltage Divider

No.	Test Voltage (kV_{AC})	Time (Sec)	Result
1	30.18	60	Passed
2	30.06	60	Passed
3	30.04	60	Passed

The scale factor tests were performed at only 20 and 30 kV levels to avoid the corona discharge. The scale factors from the measurement shown in Table 4 are slightly different from the designed value as 1000:1. These result from the high and low voltage capacitors.

Table 4. Scale Factor Test for Air-Insulated Voltage Divider

No.	20 kV		30 kV	
	V_{in} (kV_{AC})	V_U(V_{AC})	V_{in} (kV_{AC})	V_U(V_{AC})
1	20.19	20.2	30.05	30.5
2	20.12	20.1	30.00	30.3
3	20.13	20.1	30.11	30.4
4	20.12	20.1	30.13	30.4
5	20.14	20.1	30.07	30.3
6	20.14	20.1	30.11	30.3
7	20.13	20.1	30.16	30.3
8	20.08	20.0	30.18	30.4
9	20.10	19.9	30.06	30.2
10	20.03	20.0	30.04	30.2
Avg.	20.11	20.07	30.09	30.33
Scale Factor	1001.9 :1		992.0 : 1	
% Error	0.19%		-0.8%	

The linearity test was also taken up to only 40 kV to avoid corona discharge. The results in Table 5 show that the average voltage ratio is 1.013. The upper limit for standard acceptance is (1+0.01)×1.013 =1.023 while the lower limit is (1-0.01)×1.013=1.002.

Table 5. Linearity Test for Air-Insulated Voltage Divider

V_{in}(kV_{AC})	V_{ref} (V_{AC})	V_U (V_{AC})	$\frac{V_U}{V_{ref}}$
10.12	10.12	10.3	1.017
20.03	20.03	20.4	1.018
30.03	30.03	30.6	1.018
40.04	40.04	40.0	0.999
Stop due to corona discharge			
Average			1.013

The voltage ratios were plotted in Fig. 9. The results show that only at 40 kV the voltage ratio exceeds the boundary.

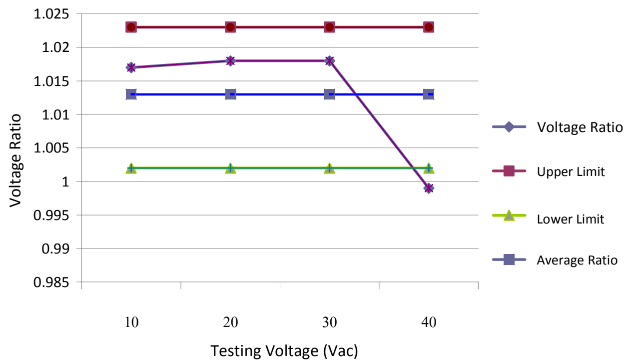

Fig. 9. Linearity for Air-Insulated Voltage Divider

For stability test, the test voltage of 30 kV was applied to stress the divider for 10 times. The mismatches of voltages were within ±3% as given in Table 6. Thus, it is acceptable up to the voltage 30 kV.

Table 6. Stability Test for Air-Insulated Voltage Divider

No.	V_{ref} (V_{AC})	V_U (V_{AC})	$\frac{V_U - V_{ref}}{V_{ref}} \times 100\%$
1	30.05	30.5	1.497%
2	30.00	30.3	1.000%
3	30.11	30.4	0.963%
4	30.13	30.4	0.896%
5	30.07	30.3	0.764%
6	30.11	30.3	0.631%
7	30.16	30.3	0.464%
8	30.18	30.4	0.728%
9	30.06	30.2	0.465%
10	30.04	30.2	0.532%
Average	30.09	30.33	0.794%

Nitrogen-Insulated Capacitive Voltage Divider

For withstand voltage test, the Nitrogen gas was pressured up to 2-bars in the cylinder. The corona discharge occurred when the high voltage input was raised to 80 kV. This corona discharge voltage was higher because of the better dielectric withstand voltage of Nitrogen gas than the air. When the corona inception voltage was known, the withstand voltage test was limited at 90 kV. The results of withstand voltage are shown in Table 7. The divider can be properly operated against the voltage of 90 kV for 60 second long without any damage.

Table 7. Withstand Test for N_2-Insulated Voltage Divider

No.	Test Voltage (kV_{AC})	Time (Sec)	Result
1	90.21	60	Passed
2	90.14	60	Passed
3	90.23	60	Passed

The scale factor tests were done at only 60 and 90 kV levels due to the corona at 90 kV. The scale factors from the measurement in Table 8 are slightly different from the designed value.

Table 8. Scale Factor Test for N_2-Insulated Voltage Divider

No.	60 kV		90 kV	
	V_{in} (kV_{AC})	V_U (V_{AC})	V_{in} (kV_{AC})	V_U (V_{AC})
1	60.05	60.5	90.04	90.4
2	60.13	60.6	90.07	90.4
3	60.09	60.6	90.17	90.6
4	60.17	60.7	90.05	90.4
5	60.05	60.6	90.1	90.4
6	60.01	60.5	90.08	90.5
7	60.01	60.4	90.02	90.3
8	60.05	60.5	90.14	90.5
9	60.04	60.5	90.15	90.5
10	60.16	60.7	90.08	90.4
Avg.	60.07	60.56	90.09	90.44
Scale Factor	991.9:1		996.1:1	
% Error	-0.0081		-0.0039	

The linearity test was also performed up to 90 kV due to the corona inception. The results were presented in Table 9. The average voltage ratio is 1.000. The upper limit for standard acceptance is (1+0.01)×1.000 =1.010 while the lower limit is (1-0.01)×1.000=0.990. The voltage ratios were plotted in Fig. 10. It shows that only at 10 kV the voltage ratio exceeds the boundary. At one voltage level of 10 kV only, less than five times out of ten times of the test the results are out of the boundary. Therefore, this divider is acceptable.

Table 9. Linearity Test for N_2-Insulated Voltage Divider

V_{in} (kV_{AC})	V_{ref} (V_{AC})	V_U (V_{AC})	$\frac{V_U}{V_{ref}}$
10.05	10.05	9.9	0.985
20.06	20.06	19.9	0.992
30.06	30.06	30.0	0.998
40.13	40.13	40.3	1.004
50.14	50.14	50.5	1.007
60.17	60.17	60.7	0.998
70.11	70.11	70.7	1.008
80.14	80.14	80.6	1.005
90.01	90.01	90.4	1.004
Stop due to corona discharge			
Average		1.000	

For stability test was performed 10 times at 90 kV, the mismatches of voltages given in Table 6 were within ±3%. Thus, it is acceptable up to the voltage of 90 kV.

SF6-Insulated Capacitive Voltage Divider

Because the test transformer was designed to operate up to 100 kV rms. maximum, the 110 % test was not possible. Thus the scale factor tests were done at only 50 and 100 kV levels. The scale factors from the measurement in Table 11 are slightly different from the designed value.

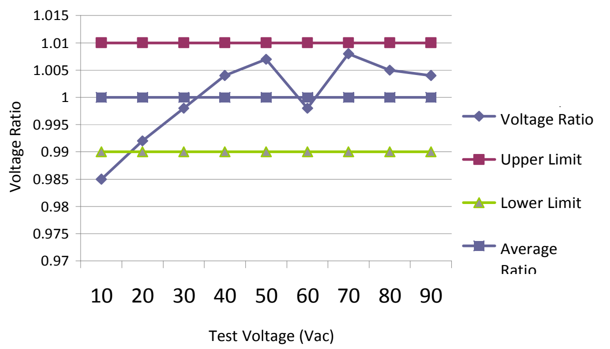

Fig. 10. Linearity for N_2-Insulated Voltage Divider

Table 10. Stability Test for N_2-Insulated Voltage Divider

No.	V_{in} (kV_{AC})	V_{ref} (V_{AC})	V_U (V_{AC})	$\frac{V_U - V_{ref}}{V_{ref}} \times 100\%$
1	90.04	90.04	90.4	0.399%
2	90.07	90.07	90.4	0.366%
3	90.17	90.17	90.6	0.476%
4	90.05	90.05	90.4	0.388%
5	90.10	90.10	90.4	0.332%
6	90.08	90.08	90.5	0.466%
7	90.02	90.02	90.3	0.311%
8	90.14	90.14	90.5	0.399%
9	90.15	90.15	90.5	0.388%
10	90.08	90.08	90.4	0.352%
Avg.	90.09	90.09	90.44	0.387%

Table 11. Scale Factor Test for SF_6-Insulated Voltage Divider

No.	50 kV		100 kV	
	V_{in} (kV_{AC})	V_U (V_{AC})	V_{in} (kV_{AC})	V_U (V_{AC})
1	50.15	50.1	100.2	101.5
2	50.15	50.1	100.1	101.4
3	50.02	49.9	100.2	101.5
4	50.05	50.0	100.0	100.9
5	50.10	50.0	100.1	101.2
6	50.12	50.1	100.0	100.7
7	50.12	50.0	100.0	100.8
8	50.01	49.9	100.1	101.0
9	50.01	50.0	100.1	101.9
10	50.08	50.0	100.2	101.0
Avg.	50.08	50.01	100.10	101.19
Scale Factor	1001.3 : 1		989.2 : 1	
% Error	1.3%		-1.08%	

Similar to the previous gases, SF_6-insulation was pressured up to 2-bars in the cylinder. The withstand voltage test was taken only up to 100 kV, which cannot reach 110 % of the designed voltage due to the limitation of the test transformer. However up to 100 kV, the voltage divider worked properly without corona discharge, because the dielectric withstand voltage of SF_6 is better than the air or Nitrogen due to the electro-negative gas property of SF_6.

Table 12. Withstand Test for SF_6-Insulated Voltage Divider

No.	Test Voltage (kV_{AC})	Time (Sec)	Result
1	100.1	60	Passed
2	100.1	60	Passed
3	100.2	60	Passed

The linearity test was also taken up to 100 kV due to the limitation of the test transformer. The results show that the average voltage ratio is 0.997. The results were plotted in Fig. 10, which shows that only at 10 and 100 kV the voltage ratios exceed the boundary. Then only two out of ten times of tested voltages are out of the boundary. The divider is acceptable.

Table 13. Linearity Test for SF_6-Insulated Voltage Divider

V_{in} (kV_{AC})	V_{ref} (V_{AC})	V_U (V_{AC})	$\frac{V_U}{V_{ref}}$
10.11	9.9	0.979	-2.077%
20.02	19.8	0.989	-1.098%
30.11	29.9	0.993	-0.697%
40.11	40.0	0.997	-0.274%
50.05	50.1	1.000	0.099%
60.07	60.3	1.003	0.383%
70.03	70.3	1.003	0.385%
80.09	80.3	1.002	0.262%
90.09	90.0	0.999	-0.099%
100.1	101.4	1.012	1.298%
10.11	9.9	0.979	-2.077%
Stop due to limitation of the test transformer			
Average		0.997	

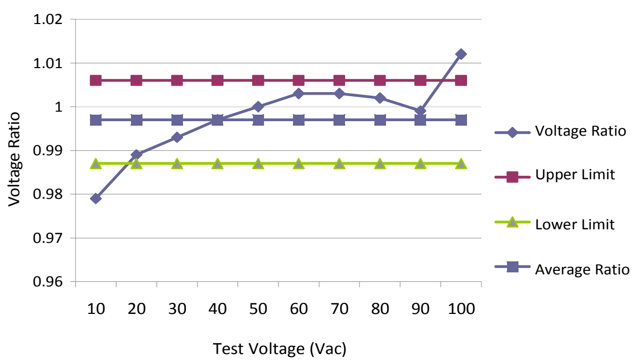

Fig. 11. Linearity for SF_6-Insulated Voltage Divider.

For stability test, the voltage up to 100 kV was performed. The calculated mismatches of voltages given in Table 14 were within ±3%. Thus, this voltage divider can reliably operate up to the voltage of 100 kV.

Table 14. Stability Test for SF_6-Insulated Voltage Divider

No.	V_{in} (kV_{AC})	V_U(V_{AC})	$\frac{V_U - V_{ref}}{V_{ref}} \times 100\%$
1	100.2	101.5	1.297%
2	100.1	101.4	1.298%
3	100.2	101.5	1.297%
4	100.0	100.9	0.900%
5	100.1	101.2	0.599%
6	100.0	100.7	0.700%
7	100.0	100.8	0.800%
8	100.1	101.0	0.899%
9	100.1	101.9	1.798%
10	100.2	101.0	0.798%
Averag	100.10	101.19	1.038%

Comparison between Air, N2 and SF6

In term of dielectric strength, the air-insulated voltage divider could operate up to 30 kV only due to the inception of corona. Thus, using of the air-insulation in the capacitive voltage divider yields the lowest operating voltage when compared with N_2 and SF_6 gas insulation. This is due to the poor dielectric property of the air.

Actually, the dielectric strength of the air and N_2 is not significantly different. However, the advantage of N_2 is that the contact erosion is less than the air under no O_2 condition. Comparison between N_2 and SF_6, when using N_2 there was a corona inception at 80 kV but no corona for SF_6 at 100 kV when both gases are pressurized at 2 bars. This means SF_6 has better dielectric strength than air and N_2.

5. CONCLUSION

A 100 kV capacitive voltage divider was designed, constructed, and tested. The experiments as components measurement, scale factor test, linearity test, withstand voltage test, and stability test are performed and reported. The tested results show that the capacitive divider can be properly operated as a measurement divider under the IEC 60060 – 2 (1994) standard. Due to withstand voltage, stability, and chemical properties, the SF_6 is proposed as the preferred insulation for this 100 kV capacitive voltage divider.

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