

Article

Comparison of the Interrupting Capability of Gas Circuit Breaker According to SF₆, g³, and CO₂/O₂ Mixture

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Abstract: In the study, an interrupting performance test on the 145 kV gas circuit breaker is performed according to three different gases: SF₆, g³ (5% NovecTM4710 with 95% CO₂), and CO₂(70%)/O₂(30%) gases. Thanks to research advancements, it is confirmed that CO₂ and g³ (5% NovecTM 4710) gases, respectively, have 40% and 75% dielectric strength, compared to that of SF₆ gas. The filling pressure and transient recovery voltage criteria of each gas were determined differently in order to compare the maximum interrupting performance of each gas. The pressure of SF₆ gas was determined to be 5.5 bar, which is typically used in circuit breakers. The pressure of the other two gases was determined to be 8.0 bar (the maximum available pressure of the test circuit breaker) to find the maximum interrupting performance. Moreover, the rate-of-rise of transient recovery voltage of SF₆ was determined as 10 kV/μs, which is the value at the state of maximum interrupting performance of the test circuit breaker with SF₆. On the other hand, the rate-of-rise of transient recovery voltages of g³ (5% NovecTM4710 with 95% CO₂) and CO₂(70%)/O₂(30%) gases were, respectively, determined as 4~5 kV/μs to find the interruption available point. The characteristics of arc conductance, arc current, and arc voltage near the current zero, and post-arc current are analyzed to compare the interrupting performance, according to different arc-quenching gases. The arc current is measured using a current transformer (Rogowski coil), and a signal processing method of the arc current and arc voltage is introduced to increase the reliability of the interrupting performance results. As a result of the test, it is confirmed that the critical arc conductance for all test conditions converged within a certain range and the value is around 0.7 mS. In addition, the critical current slope just before the current zero-crossing during the interrupting process is shown to be 1.8 A/μs between interruption success and failure. Consequently, it is verified that the CO₂(70%)/O₂(30%) mixture and g³ (5% NovecTM4710 with 95% CO₂) have a similar arc extinguishing performance and SF₆ has a relatively higher extinguishing performance than that of CO₂(70%)/O₂(30%) mixture and g³ (5% NovecTM4710 with 95% CO₂) under the aforementioned filling pressure and TRV conditions.

Keywords: arc conductance; arc current; current zero measurement; high-voltage gas circuit breakers; interrupting capability; post-arc current; Rogowski coil; quenching gases

1. Introduction

SF₆ gas has been widely used for high-voltage equipment, such as gas circuit breaker (GCB) and gas-insulated switchgear (GIS), because of its excellent insulation and arc-quenching capability [1,2]. SF₆ is also stable, non-toxic, and has no ozone depletion potential (ODP). However, SF₆ has extremely

high global warming potential (GWP), which is about 23,500 times higher than carbon dioxide (CO₂) with the same mass, according to 2013 report of Intergovernmental Panel on Climate Change (IPCC) [3–5]. For this reason, the interest in alternative to SF₆ gas has increased as a part of GWP mitigation in the high-voltage circuit breaker area.

The types of gases considered as alternative gases are natural gases, which refer to the composition of atmosphere, SF₆ gas mixtures with natural gases, SF₆ gas mixtures with fluorocarbons, fluorinated gases except for SF₆ (perfluorocarbons (PFCs)) and other new gases [5–9]. Table 1 shows the properties of several gases where E_{cr} is the critical electric field strength, MW is the molecular weight, T_b is the boiling point in Celsius temperature.

Natural gases, dry air, CO₂, and nitrogen (N₂) are stable and have very low greenhouse effects as their Global Warming Potential (GWP) is, respectively, 1, 0, and 0 and the Ozone Depletion Potential (ODP) of all of them are zero [1,10]. They can be used as insulation medium for low voltage applications. However, those are not acceptable for the high voltage applications due to low relative dielectric strength, which is 40% lower than SF₆ [8].

The mixtures of SF₆ with natural gases (SF₆-N₂, SF₆-CO₂) and fluorocarbons (SF₆-CF₄ and SF₆-C₂F₆) are acceptable as insulation medium and already have been used for the power industry although they have lower dielectric strength than SF₆ [1,8]. However, the fundamental problem of GWP has not been resolved as those contain SF₆ [8].

As fluorinated gases, some PFCs have excellent dielectric strength but they are not suitable as SF₆ alternative gas because they have a high GWP between 5000 and 12,000 [5–7]. In terms of CF₃I, it has a higher dielectric strength than SF₆ and GWP less than 5 [5–7]. However, it is also inappropriate as an alternative to SF₆ because of its high boiling point and mutagenic characteristics [1,5,11].

The 3MTM company has developed other fluorine-based insulating gases, which are called NovecTM4710 (C₄F₇N) and NovecTM5110 (C₅F₁₀O). NovecTM4710 has a higher molecular weight and a higher boiling point, and a dielectric strength 1.4 times greater than SF₆. In particular, it has much lower GWP (2100) than SF₆ [12]. However, it is recently discovered that some genetic mutation is positive through in vitro testing [13]. Therefore, its use may be limited in the industry. NovecTM5110 even has higher dielectric strength and lower GWP characteristics than NovecTM4710. However, it may have limitations depending on the usage environment due to its high boiling point of 26.9 °C, as shown in Table 1.

Table 1. Properties of different gases.

Item	E_{cr}	MW(g/mol)	GWP	Lifetime	T_b (°C)	Ref.
SF ₆	1	6	23,500	3200 year	−64	[1,14,15]
CO ₂	0.3	44	1	<15 year	−78.5	[1,14,15]
N ₂	0.36	28	0	Infinity	−195.8	[1,14,15]
O ₂	0.3	32	0	Infinity	−183	[1,14,15]
CF ₄	0.39	88	50,000	6300 year	−128	[14,15]
CF ₃ I	1.23	196	0.45	<1 day	−22.5	[1,14]
C ₄ F ₇ N	2.2	195	2100	30 day	−4.7	[14,15]
C ₅ F ₁₀ O	2.0	266	<1	0.04 day	26.9	[14,15]

Among the aforementioned alternative gases, CO₂ has recently received a lot of attention due to its higher interruption performance than that of other natural gases and has a much lower GWP than that of SF₆, although CO₂ has much lower dielectric strength than SF₆ [16]. Some companies have begun research on the CO₂ circuit breaker, and even actually launched the products in low-voltage power grid systems [1]. Moreover, research has been conducted to optimize the design of the CO₂ circuit breaker for high-voltage applications [17]. Therefore, it is necessary to study the extinguishing characteristics of each gas, which is an important factor in circuit breaker design and may be a promising alternative to SF₆. In particular, several researches on the mixture of CO₂ with O₂ have been conducted as O₂ has good arcing time constant (1.5 μs), compared to CO₂ (15 μs) and N₂ (220 μs) [18].

Toshiba Corp. investigated that admixture of O₂ gas to CO₂ gas caused reduction of post-arc current in the short-line fault interruption and also increase of lightning impulse breakdown voltage, compared to pure CO₂ gas [18]. Zhenghong Xu investigated the research on the reduced critical breakdown fields of CO₂-based mixtures. The results showed that O₂ and CH₄ improve the dielectric properties of CO₂ in practical use due to those result in a higher reduced critical breakdown field [19].

In this study, the interruption performance is compared according to different arc-quenching gases such as SF₆, g³ (5% NovecTM4710 with 95% CO₂), and a mixture of CO₂ and O₂ (70% and 30%, respectively). Each gas was injected into a gas circuit breaker designed for SF₆ and the interrupting performance of each gas was compared under the different filling pressure and the rate-of-rise of transient recovery voltage conditions.

The current and voltage signal processing method is introduced to improve the reliability of the interrupting performance test results. Finally, the interrupting performance is compared through the test for arc current, arc voltage, arc conductance, and post-arc current.

2. Experimental Setup

2.1. Test Circuit

In alternative gas research, it is most efficient in terms of economy to use the existing equipment and to replace only the type of arc-quenching gas. In the study, an experiment was performed by changing only the type of arc-quenching gas using a 145 kV 40 kA circuit breaker designed for SF₆.

Figure 1 shows the test circuit. Instead of using a generator to control the voltage and current of the circuit, a simple synthetic test circuit was used consisting of separate current and voltage sources. The definition of the circuit components are shown in Table 2. The main breaking current and the injection current are synthesized near the breaking instant, and the transient recovery voltage (TRV) is supplied through an injection current circuit that operates just before the interruption.

The representative parameter values of current and voltage sources are shown in Table 3. A circuit with R_f and C_f in series adjusts the voltage rise rate, and it is connected with a 0.5 nF capacitor (C_{VD}) of the voltage divider in parallel between the two poles of the circuit breaker. The total capacitance (C_p), consisting of these two, determines the magnitude of arc current that enters the zero point at breaking time due to the arc-circuit interaction with the arc voltage. MS is to operate current source part, ACB is for protecting the current source part, VD is to divide voltage level, and R_f and C_f are for regulating the TRV.

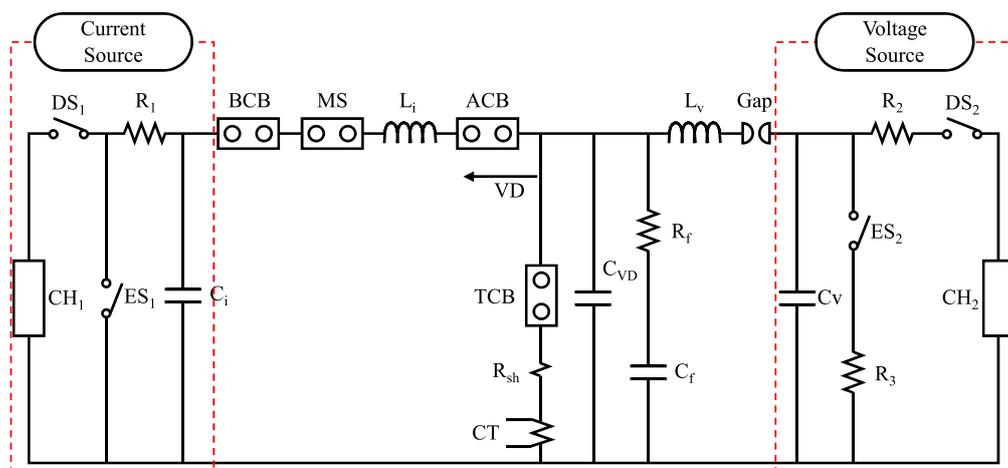


Figure 1. Synthetic test circuit for breaking.

Table 2. Definition of circuit components.

Item	Definition
Current source part	CH ₁ Charger for current source capacitor
	DS ₁ Disconnecting switch for current source
	ES ₁ Earthing switch for current source
	R _i Resistor for current source
	L _i Reactor for current source
	C _i Capacitor for current source
Voltage source part	CH ₂ Charger for voltage source capacitor
	DS ₂ Disconnecting switch for voltage source
	ES ₂ Earthing switch for voltage source
	R _v Resistor for voltage source
	L _v Reactor for voltage source
	C _v Capacitor for voltage source
Others	R _f Resistor for TRV
	C _f Capacitor for TRV
	C _{V_D} Capacitor of voltage divider
	BCB Back-up circuit breaker
	MS Main switch
	TCB Test circuit breaker
	ACB Auxiliary circuit breaker
	R _{sh} Shunt resistor
	CT Current transformer (Rogowski coil)
Gap Gap to control voltage source	

Table 3. Parameter values of current and voltage source parts.

Item	Unit	Value	
Current source part	CH ₁	kV	5.6
	C _i	μF	45,000
	L _i	mH	0.156
Voltage source part	CH ₂	kV	14
	C _v	μF	88
	L _v	mH	0.824

2.2. Voltage and Current Measurement Scheme

Figure 2 shows the voltage and current measurement scheme. Voltage is measured by a voltage divider and current is measured by Rogowski. All signals are connected to the oscilloscope through a coaxial cable. The specifications of all sensors are represented in Table 4.

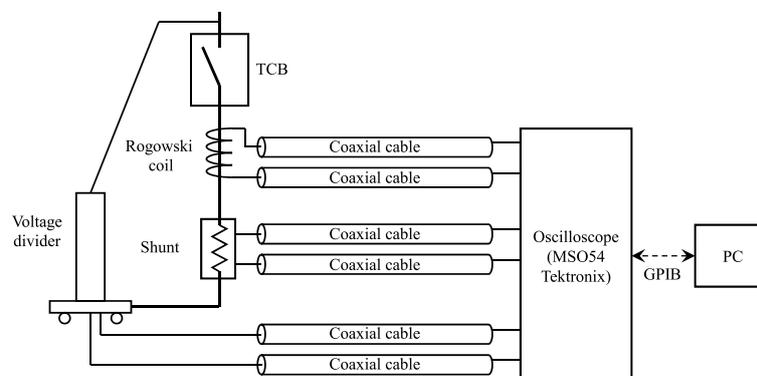
**Figure 2.** Voltage and current measurement scheme.

Table 4. Specifications of measurement sensors.

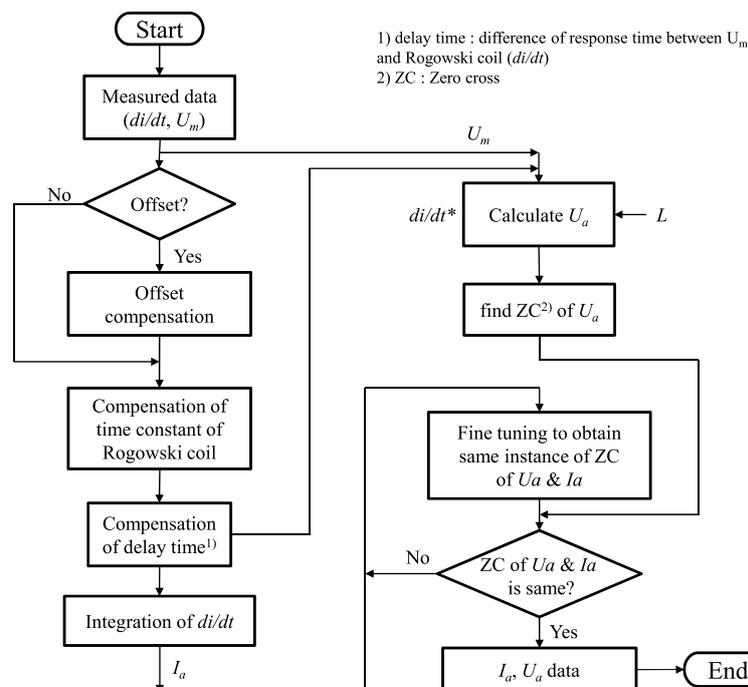
Item	Unit	Specification
Voltage Divider (RCR 600)	Rated Voltage	kV 600
	Capacitance	pF 500
	Ratio	- 2000:1
Shunt (SH-R 160kA)	Resistance	mΩ 0.63
Oscilloscope (MSO54)	Sampling Rate	MS/s 62.5
	Record Length	Mpts 1.25
Rogowski coil	Output	V/A/μs 1V/4.9A/μs

3. Current and Voltage Signal Processing at Current Zero Point

The arc current and arc voltage are required for hundreds of ns before the zero point in order to obtain the interrupting performance. Thus, the phase of current and voltage is a very important factor to improve the reliability of interrupting performance. In practice, the closer the actual zero point of the current and voltage is, the more reliable the interrupting performance result.

This study measures a current slope signal by the Rogowski coil, and it is converted into a current signal through an integral process. However, it is difficult to find the actual current zero point through this current signal since the current has a smooth shape near the current zero. Therefore, this section introduces the phase compensation method of arc current and arc voltage.

Figure 3 shows the procedure for obtaining the arc current and arc voltage signals that are synchronized from the actual measured current slope and arc voltage. The main compensation targets are the offset value included in the measurement signal, the response delay time between the Rogowski coil and the voltage divider, and the delay time due to the difference in the transmission line length. The arc current and arc voltage processed by this process should have the same zero point because the arc has the resistive characteristic. This criterion is used in the fine-tuning process at the end of the proposed procedure.

**Figure 3.** Procedure of current and voltage signal processing at current zero.

4. Comparison of Interrupting Performance According to Different Arc-Quenching Gases

4.1. Interrupting Test Condition

In order to compare the interrupting performance according to the arc extinguishing medium of the circuit breaker, three types of gases—SF₆, g³(5% NovecTM4710 with 95% CO₂), and CO₂(70%)/O₂(30%) mixture at 5.5bar, 8.0bar, and 8.0bar, respectively, were injected into the same circuit breaker. Furthermore, 90% of short-line fault (SLF90) tests are carried out for measuring both the arc current and the arc voltage then the arc conductance were calculated.

The interrupting test conditions for each arc-quenching gas are shown in Table 5. P is the absolute pressure, t_{arc} is the arcing time, R_f and C_f are the circuit parameters of the TRV circuit, dv/dt is the rate-of-rise of TRV (RRRV), and S/F indicates the success or failure of the interruption. The voltage divider affecting the RRRV is the same and its capacitance is given as constant 0.5 nF in all cases.

In the study, different filling pressures and TRVs were applied to the tests of each gas in order to compare the maximum interrupting performance of g³ (5% NovecTM4710 with 95% CO₂) and CO₂(70%)/O₂(30%) gases with that of SF₆ gas. The pressure of SF₆ gas was determined to be 5.5 bar, which is typically used for SF₆ circuit breaker. The other two gases have much lower dielectric strength than that of SF₆ gas. Thus, the interrupting performance was analyzed by increasing the filling pressure up to 8 bar, the maximum allowable pressure of the test circuit breaker, in order to investigate how much the interrupting performance of g³ (5% NovecTM4710 with 95% CO₂) and CO₂(70%)/O₂(30%) follow the SF₆ gas through pressure increase.

In addition, the boundary between the success and failure of the interruption is determined by changing the initial voltage slope of TRV. The RRRV of SF₆ gas was determined as 10 kV/μs, which is the value at the state of maximum interrupting performance of the test circuit breaker with SF₆ gas. On the other hand, the RRRVs of g³ (5% NovecTM4710 with 95% CO₂) and CO₂(70%)/O₂(30%) gases were, respectively, determined as 4~5 kV/μs to find the interruption available point.

Table 5. Test conditions of circuit breaker with arc-quenching gases.

Item	P (bar)	T(°C)	t_{arc} (ms)	R_f (ω)	C_f (nF)	dv/dt (kV/μs)	S/F
SF ₆	5.5	20	16.2	500	1.0	10.0	S
			15.9	500	1.0	10.0	F
g ³	8	20	15.0	150	7.8	4.3	S
(5 %Novec TM 4710/95 %CO ₂)			14.3	150	9.8	4.8	F
CO ₂ /O ₂	8	20	15.6	150	7.8	4.3	S
(70%/30%)			15.7	150	9.8	4.8	F

4.2. Arc-Conductance Behavior

Figure 4 shows the arc conductances of each gas as a function of interruption success and failure. The arc conductances was calculated by measured current and voltage. This is to estimate the arc conductance corresponding to the boundary between success and failure of each gas and to confirm how these boundary values relate to each extinguishing gas.

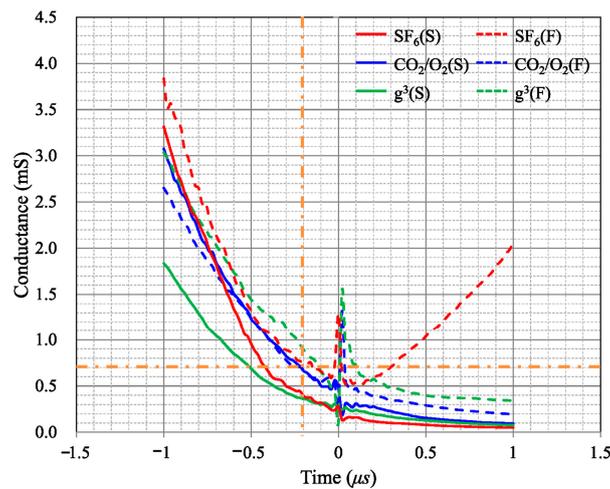


Figure 4. Characteristics of arc conductance according to interrupting success and failure of SF₆, CO₂/O₂, and g³ gases.

KEMA has suggested a conductance range of SF₆ before 200 ns from the current zero-cross (G200) is between 0.81 mS~3.0 mS [20,21]. Table 6 shows the G200 characteristics for each gas obtained from the test results in Figure 4. It is verified that the 0.7 mS is determined as the boundary of success and failure of SF₆ gas, and 0.9 mS and 0.7 mS are determined as the boundary of success and failure of g³ (5% NovecTM4710 with 95% CO₂) and CO₂(70%)/O₂(30%), respectively. Therefore, it is determined that critical value of the study is acceptable although it is somewhat smaller than the minimum value of the suggested range by KEMA.

Table 6. Arc-conductance (G200) according to gases.

Extinguishing Gas	Pressure (bar)	Conductance (mS)	
		[Test Condition: dV/dt (kV/μs)]	
		Success	Failure
SF ₆	5.5	0.4 [10.0]	0.77 [10.0]
g ³ (5% Novec TM 4710/95% CO ₂)	8.0	0.36 [4.3]	0.9 [4.8]
CO ₂ /O ₂ (70%/30%)	8.0	0.7 [4.3]	0.7 [4.8]

Increasing the TRVs of g³ (5% NovecTM4710 with 95% CO₂) and CO₂ (70%)/O₂(30%) equal to that of SF₆ decreases the capacitance between arc contacts. The reduced capacitance causes an increase in arc-conductance because a large current due to the arc-circuit interaction is applied shortly before the current zero-cross. As the arc-conductance increases, higher cooling power is required. Therefore, if the TRVs of g³ (5% NovecTM4710 with 95% CO₂) and CO₂ (70%)/O₂(30%) are increased to that of SF₆, the circuit breaker cannot interrupt the current because it requires higher cooling power.

4.3. Interrupting Current Behavior

Figures 5 and 6 show the same current traces near the current zero, based on two different time points. Figure 5 shows the current traces, based on the zero point of the arc current (I_a). When the interruption is successful, it is investigated that the current slope of SF₆ gas is steepest and that of the g³ is the gentlest. This means that SF₆ gas can interrupt the current under more severe current condition. Figure 6 shows the comparison of interrupting current, based on the main current is zero. The red numbers indicate interruption failures and the black numbers indicate the case of interruption success. It is confirmed that the interruption is performed at different instants in the current zero-cross

of the main circuit current. In particular, the current slope approaching the current zero is smaller when the interruption is successful than when the interrupting is failed. This phenomenon makes the arc energy between the arcing contacts small and makes the interruption relatively easy. The boundary between success and failure is found to be between $1.41 \text{ A}/\mu\text{s}$ and $1.97 \text{ A}/\mu\text{s}$.

Figure 7 shows the several test results according to each gas. The x -axis is the current magnitude at $1 \mu\text{s}$ before current zero-cross, and the y -axis is the current slope of the main current at current zero-cross. It is investigated that the red dotted line on the y -axis at $1.8 \text{ A}/\mu\text{s} | t = 0$ is the critical current slope of the main current, which indicates the failure and success of the interrupting. The upper and lower parts of this critical current slope were, respectively, determined as boundary of success and failure cases, and the magnitude of the current, with the critical current slope of $1.8 \text{ A}/\mu\text{s}$, is compared to evaluate the interrupting capability.

The current values of the corresponding extinguish gas are about 5.5 A for g^3 (5% NovecTM4710 with 95% CO_2) and CO_2 (70%)/ O_2 (30%) mixed gas and 8.5 A for SF_6 . When this current value is large, it is evaluated that the extinction characteristics are excellent and the interrupting performance is good. It is noticed that the relationship between the magnitude of the current and the slope is linear in the case of g^3 (5% NovecTM4710 with 95% CO_2) and CO_2 (70%)/ O_2 (30%) gases otherwise the current slope remains lower than the threshold level until a certain current magnitude in the case of SF_6 .

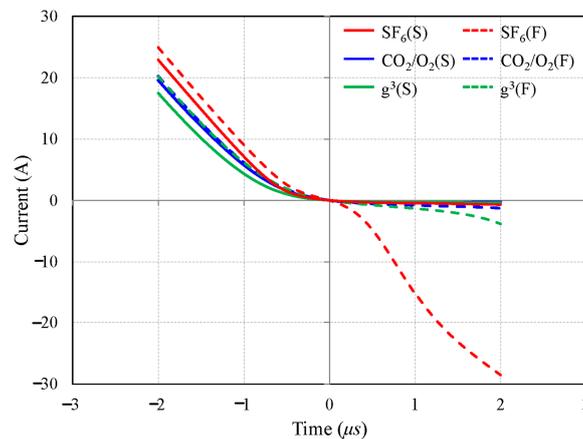


Figure 5. Comparison of interrupting current behaviors based on current zero-cross time according to interrupting success and failure of SF_6 , CO_2/O_2 , and g^3 gases.

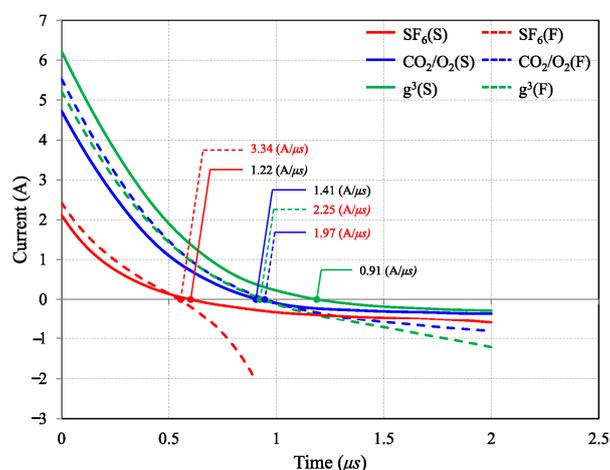


Figure 6. Comparison of interrupting current behaviors according to interrupting success and failure of SF_6 , CO_2/O_2 , and g^3 gases.

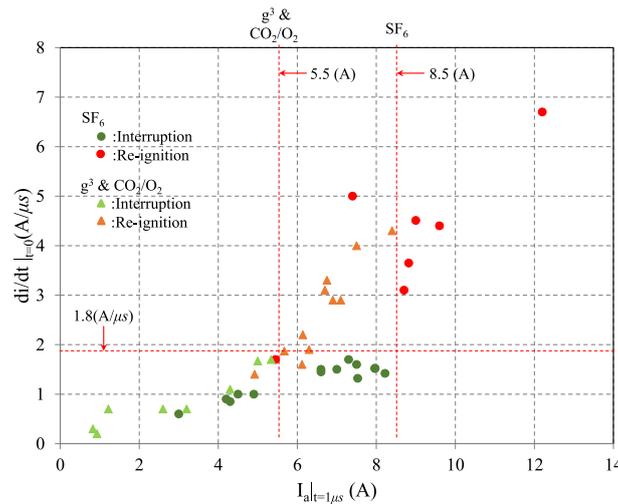


Figure 7. Comparison of interrupting performance according to SF₆, CO₂/O₂, and g³ gases (The di/dt value at zero cross point according to change in I_a value at the time point of 1 μs).

Figure 8 shows the post-arc current characteristics. The failed cases are indicated by dot lines. In the case of SF₆, the post-arc current is increased up to −28 A at 2 μs when the interrupting fails. Thus, it is represented up to −4.5 A for the comparison with other post-arc current characteristics. In particular, it is verified that the post-arc current values are less than 0.5 A at 0.5 μs when the interrupting is successful.

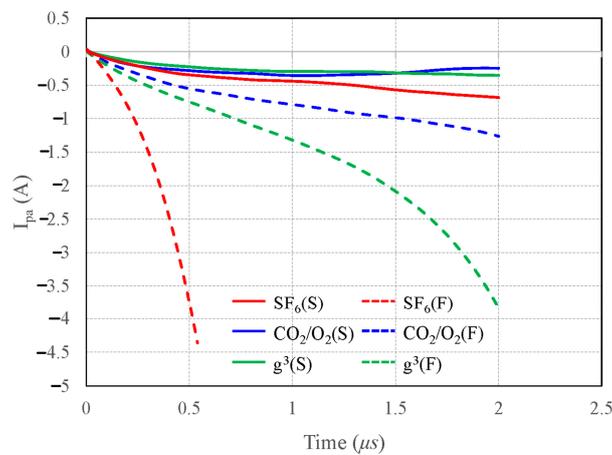


Figure 8. Comparison of post-arc current (I_{pa}) according to SF₆, CO₂/O₂, and g³ gases (post-arc current behaviors within 2 μs).

5. Conclusions

The results obtained from the measurement characteristics of the current measuring device near the current zero and the breaking performance of the breaker under several test conditions are as follows.

The current measurement is performed near the zero point of the interrupting current with Rogowski coil and signal processing method is introduced to verify the suitability of the zero current measurement. Interrupting performances for SF₆, g³ (5% NovecTM4710 with 95% CO₂), and CO₂(70%)/O₂(30%) gases are compared based on the suggested processing method.

The 0.7 mS is investigated as the boundary of success and failure of SF₆ gas and 0.9 mS and 0.7 mS are investigated as the boundary of success and failure of g³ (5% NovecTM4710 with 95% CO₂) and CO₂(70%)/O₂(30%) gases, respectively. It is investigated that the threshold of an arc conductance to

determine the success and failure of the interrupting is slightly less than the minimum values of the region suggested by KEMA.

In addition, the main current slope at the point of interruption is analyzed to distinguish the success and failure of the interruption based on the value of $1.8 \text{ A}/\mu\text{s}$ independent of the type of gases and the capacitance of the arcing contacts. Finally, it is verified that the extinguishing characteristics of g^3 (5% NovecTM4710/95% CO_2) and CO_2 (70%)/ O_2 (30%) are similar and SF_6 has relatively higher extinguishing characteristics than the other gases.

Author Contributions: All authors contributed to the preparation of this research. W.-Y.L., Y.-H.O. and H.-J.J. determined the concept. J.-U.J. and H.-S.O. conducted experiments. W.-Y.L. conducted writing—original draft preparation. J.-K.P. conducted investigation of introduction and writing—review and editing. Supervision was performed by W.-Y.L. and H.-J.J. All authors have read and agreed to the published version of the manuscript.

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