Re-ignition System using Vacuum Triggered Gap-switch for Synthetic Breaking Test

Seung-Jae Park† , Yoon-Taek Suh*, Dae-Won Kim*, Maeng-Hyun Kim*, Won-Pyo Song and Hee-Seog Koh*****

Abstract - The synthetic breaking test method was developed to evaluate the breaking performance of ultra high-voltage circuit breaker and made up of two independent circuits; current source circuit and voltage source circuit. In application of this test method, it is necessary to extend the arc of the test breaker. So, the new re-ignition system using VTGS (Vacuum Triggered Gap-Switch) was constructed to improve the efficiency and reliability of this test. In this re-ignition system, VTGS operates in high vacuum state of 5×10^{-7}torr and control system consists of the triggering device and the air M-G (Motor-Generator). This re-ignition system showed the operating characteristics, such as delay time (t_d) and jitter time (t_j) not exceeding 5 μs and 1 μs respectively, and had the operating voltage of 25~150kVdc at the gap distance of 24mm.

Keywords: arc extension, re-ignition system, synthetic breaking test, triggering device, VTGS

1. Introduction

In general, the direct breaking test method that produces the test voltage and current from single power source, such as high capacity short-circuit generator, is most ideal in evaluating the breaking performance of circuit breaker. However, for the breaking performance evaluation of ultra high-voltage circuit breaker, alternative test method is required due to the capacity limitation of the test facilities. Therefore, most short-circuit testing laboratories have adopted the synthetic breaking test method that at zero of the power frequency test current superimposes two separated sources; current source which supplies the rated power frequency test current and voltage source which produces the rated test voltage [1]-[3]. In this synthetic breaking test method, the re-ignition system is needed to extend the arc of the test breaker. And gap-switch plays an important role in the re-ignition system [4].

VTGS (Vacuum Triggered Gap-Switch), which has the properties such as the wide operating voltage range and the short delay time, has substituted for the conventional air gap-switch [5]-[8].

KERI (Korea Electro-technology Research Institute) also constructed the new re-ignition system using VTGS. This VTGS was developed by applying the interrupter for vacuum circuit breaker rated on 38kV, 40kA. And control system consisted of the triggering device and the air M-G (Motor-Generator).

Accordingly, this paper describes the design features and experimental results of VTGS, control system and the newly constructed re-ignition system.

† Corresponding Author: Testing and Evaluation Division, Korea Electro-technology Research Institute, Korea. (parksj@keri.re.kr)
* Testing and Evaluation Division, Korea Electro-technology Research Institute, Korea.
** Hyosung Corporation, Korea.(wpsong@hyosung.com)
*** Dept. of Electronic and Electrical Engineering, Kyungnam University, Korea. (powersys@kyungnam.ac.kr)
Received April 18, 2005 Accepted July 12, 2005

2. Synthetic breaking test and arc extension

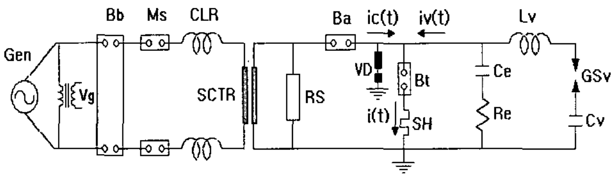
2.1 Synopsis of the synthetic breaking test

Fig. 1(a) depicts the synthetic breaking test circuit using the parallel current injection method which is most generally adopted. The current source circuit is made up of short-circuit generator and transformer and supplies the rated power frequency test current under the low voltage of approximately 20kV. And the voltage source circuit provides the rated test voltage by using the pre-charged capacitor (Cv) [9].

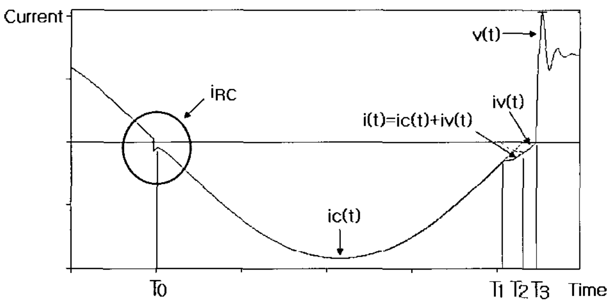
As illustrated in Fig. 1(b), if gap-switch (GSv) for the voltage source circuit is triggered at T_1, earlier 500~1000 μs than zero (T_2) of the power frequency test current ($i_C(t)$), the high-frequency injection current ($i_V(t)$) of the voltage source circuit is superimposed on ic(t) and flows into the test breaker (Bt). Just after the test breaker interrupts the total test current ($i(t)=i_C(t)+i_V(t)$) at T_3, the test voltage(v(t)) which consists of TRV(Transient Recovery Voltage) and RV(Recovery Voltage) is applied between contacts of the test breaker.

2.2 Arc extension in the synthetic breaking test

Since the current source circuit voltage is much lower than the rated voltage of the test breaker in the synthetic breaking test method, current may be interrupted in shorter arcing time than that of the direct breaking test method. So, in order to maintain the arc of the test breaker, the re-ignition current (i_{RC}) with high rate of rise should be injected at current zero (T_0) earlier 0.5cycle than the final current zero (T_2) of the power frequency test current (ic(t)), as shown in Fig. 1(b).



(a) Circuit for synthetic breaking test



(b) Test voltage and current

Where,
Gen: Short-circuit generator, Bb: Back-up breaker,
Ms: Making switch, CLR: Current limiting reactor,
SCTR: Short-circuit transformer, RS: Re-ignition system,
Cv, Lv, Re, Ce: Elements of voltage source circuit,
GSv: Gap-switch for voltage source circuit,
Ba: Auxiliary circuit breaker, Bt: Test breaker,
ic(t): Power frequency test current of current source circuit,
iv(t): Injection current of voltage source circuit,
i_{RC}: Re-ignition current, i(t): Total test current,
v(t): Test voltage

Fig. 1 Synthetic breaking test method

3. Re-ignition system

3.1 Operation of the re-ignition system

In the re-ignition system shown in Fig. 2, the re-ignition current generated by the discharges of the charging voltage (Er) through series resistor (R) lets the test breaker not interrupt the power frequency test current of the current source circuit. The operating process of this re-ignition system is illustrated as followings.

① High-voltage (Er) of approximately 100~150kVdc is charged in capacitor (C) through the step-up transformer (Up Tr) and the rectifier unit (D).

② If making switch (Ms) is closed in Fig. 1(a), the current source circuit is activated and the synthetic breaking test process starts. At T_0 of Fig. 1(b), the triggering device (TD) is activated by the optical signal of CZA (Current Zero Anticipator) [10] and the triggering signal is transferred into the triggering electrode of gap-switch (GSr).

③ Once gap-switch (GSr) is electrically short-circuited by the triggering signal, the charging voltage (Er) discharges through series resistor (R) and generates the re-ignition current. Fig. 3 shows the re-ignition currents with positive and negative polarity.

④ This re-ignition current is injected on the power frequency test current (ic(t)) and prevents the test breaker from interrupting this current, which results in the arc extension to the next current zero.

⑤ Lastly, the residual voltage of capacitor (C) discharges via dumping resistor (Rd), when dumping switch (Sd) is closed.

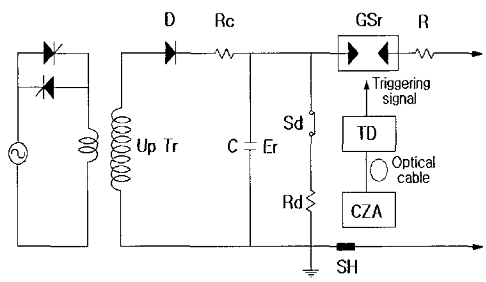
Design of the re-ignition system is based on the breaking properties of the test breaker. For instance, in order to get the successful arc extension for SF_6 gas circuit breaker, it is generally required to have the charging voltage of 60~150kVdc and the re-ignition current which exceeds 2.0kAp in magnitude and 300 ㎲ in width.

The newly constructed re-ignition system was designed with reference to the above criteria and its parameters are described below.

(a) Capacitor (C)
- Charging voltage (E_r): 60~150kVdc
- Capacitance: 4.3 ㎌ (=6.4 ㎌×2/3)

(b) Series resistor (R): 35Ω

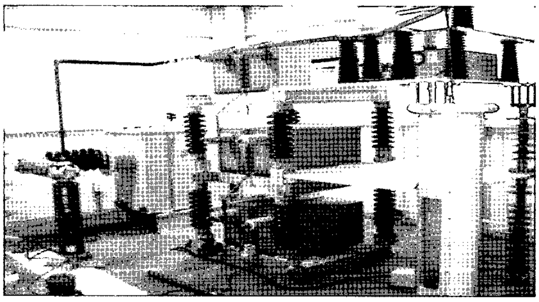
(c) Re-ignition current
- Magnitude: 1.71~4.28kAp
- Time constant: τ=150 ㎲ (35Ω×4.3 ㎌)
- Width: 450 ㎲



Where,
Up Tr: Step-up transformer, D: Rectifier unit,
Rc: Charging resistor, C: Capacitor, Er: Charging voltage
GSr: Gap-switch for re-ignition system, R: Series resistor,

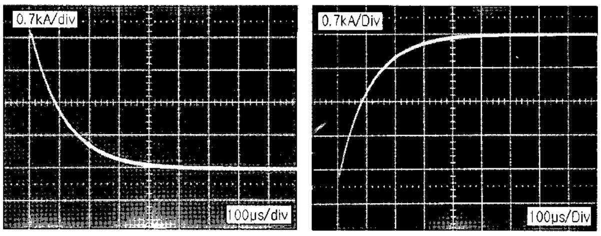
TD: Triggering device, CZA: Current zero anticipator,
SH: Current shunt, Sd: Dumping switch,
Rd: Dumping resistor

(a) Circuit diagram



(b) Photograph

Fig. 2 Re-ignition system



(a) Positive charging (Er=120kVdc) (b) Negative charging (Er=-120kVdc)

Fig. 3 Re-ignition current (i_{RC})

The polarity changer was also installed on this system to change the charging polarity to either positive or negative, because polarity of the re-ignition current should be identical to that of the power frequency test current for extending the arc of the test breaker.

3.2 Vacuum triggered gap-switch and control system

Gap-switch (GSr) and its control system adjust the injection timing of the re-ignition current. Up to recently, the air gap-switch increasing the insulation strength by using the compressed air has been generally used for GSr. But this air gap-switch has revealed several defects in high-voltage application, such as long delay time (t_d) and jitter time (t_j). Accordingly, in order to improve these problems, VTGS (Vacuum Triggered Gap-Switch) and its control system were developed as shown in Fig. 4. Control system consisted of the triggering device and the air M-G(Motor-Generator).

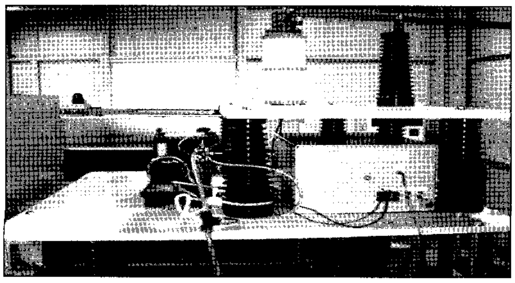
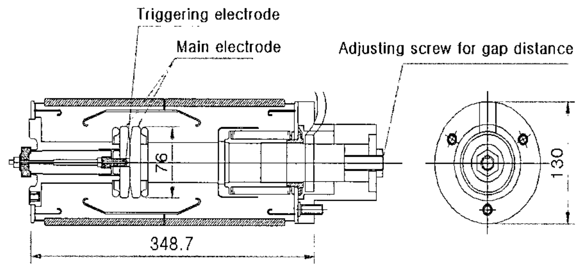


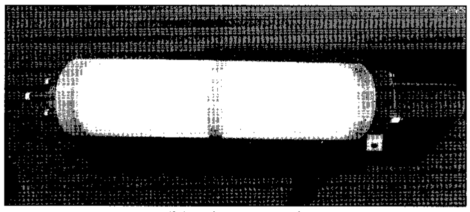
Fig. 4 Photograph of VTGS and control system

3.2.1 Vacuum triggered gap-switch

Gap-switch(GSr) of the re-ignition system should basically have the dielectric strength to withstand the high-voltage and be electrically short-circuited by the triggering device in the short delay time. And, where the test breaker becomes open in the synthetic breaking test with O-CO or CO operating duty, GSr should withstand the high-voltage of maximum 200kVp, occurring by the maximum charging voltage(Er, 150kVdc) and the TRV peak voltage (approximately 50kVp) of the current source circuit. Because this voltage is approximately higher 2~3 times than the operating voltage of the re-ignition system, gap distance of GSr may be also increased in proportion to this voltage. And the long distance generally gives rise to the bad effects on the operating characteristics of GSr, such as long delay time and jitter time.



(a) Drawing

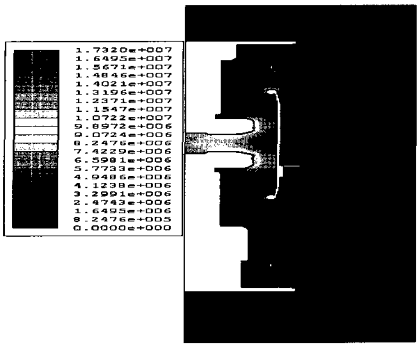


(b) Photograph

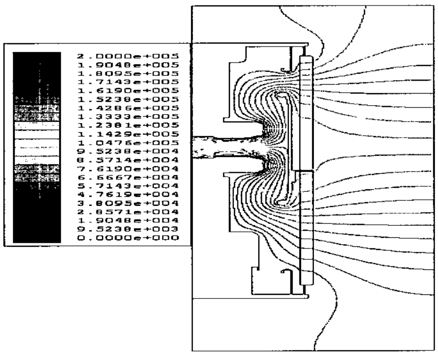
Fig. 5 VTGS (Vacuum Triggered Gap-Switch)

For improving these problems, VTGS shown in Fig. 5 was developed as GSr. This VTGS was designed by adopting the interrupter of 38kV, 40kA vacuum circuit breaker. The moving part of VTGS was designed to adjust the gap distance between the main electrodes up to 30mm and the triggering electrode was installed in the center of the fixed electrode.

The main electrodes had 76mm in diameter and were made from Cu-Cr alloy to get the superior arc withstanding property. The inside of VTGS maintains high vacuum state of 5×10^{-7}torr and distance between the fixed electrode and the triggering electrode is 1.5mm with inserting Teflon for insulation. Fig. 6 shows the electric field analysis of VTGS with the gap distance of 24mm.



(a) Equi-potential surface



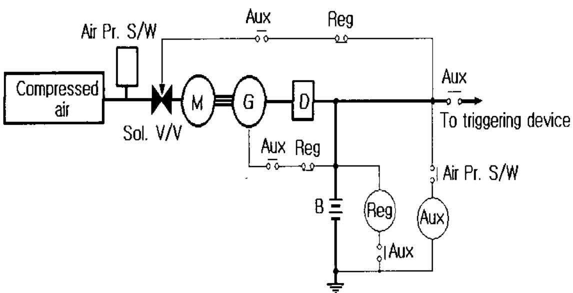
(b) Equi-potential line

Fig. 6 Electric field analysis for VTGS

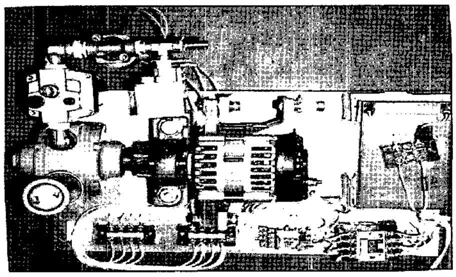
3.2.2 Air M-G (Motor-Generator)

In Fig. 2(a), the triggering device is installed on the high potential of capacitor (C). Therefore, the special power supply which has the insulation strength against voltage exceeding 200kVac from earth is required for supplying the power to the triggering device.

For this purpose, air M-G (Motor-Generator) using the compressed air was designed as shown in Fig. 7. First of all, air motor (M) transforms energy of the compressed air into the mechanical energy. If the compressed air is fed into air pressure switch (Air Pr. S/W), solenoid valve (Sol. V/V) is open to start the air motor. Generator (M) directly connected with the air motor through shaft generates 10Vac and battery (B) is charged at 12Vdc through the rectifier unit (D). This charged voltage provides the power into the triggering device.



(a) Circuit diagram



(b) Photograph

Fig. 7 Air generator

Battery voltage is monitored and regulated as the constant level. If battery voltage exceeds 15Vdc, ‘Reg’ is energized to close Sol. V/V and to stop the motor. And if battery voltage falls below 11Vdc, ‘Reg’ is de-energized to open Sol. V/V and to restart the motor.

In this air M-G, the average air consumption is 400L/min and the rated output is 10Vac, 100W.

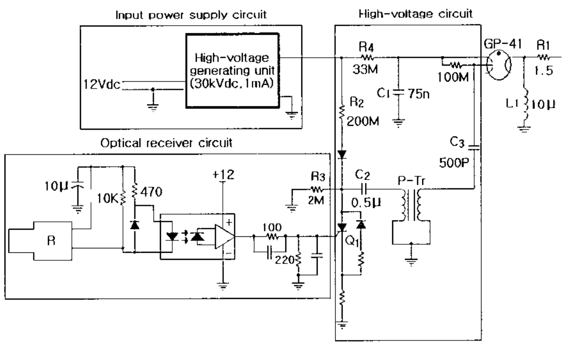
3.2.3 Triggering device

Triggering device of Fig. 8 consists of three parts;

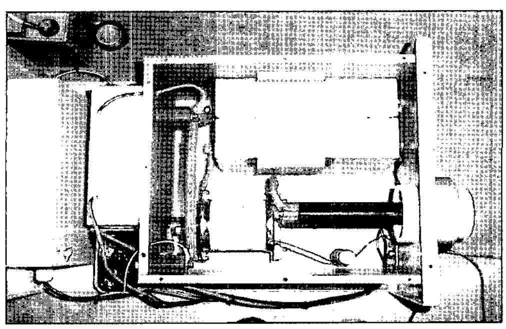
① Input power supply circuit that provides the power for the charging of capacitor (C_1=75nF) and other accessories

② Optical receiver circuit that converts the optical signal transmitted from CZA into the electrical pulse signal to trigger GP-41

③ High-voltage circuit that produces the triggering pulse of 30kVp to operate VTGS



(a) Circuit diagram



(b) Photograph

Fig. 8 Triggering device

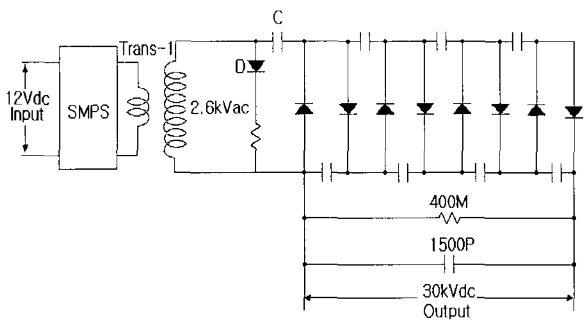
Operating process of this triggering device is described as followings.

① In Input power supply circuit, 12Vdc supplied from battery is transformed and boosted to 2.6kVac by SMPS (Switching Mode Power Supply) and transformer (Trans-1) of high-voltage generating unit. High-voltage generating unit of Fig. 9 boosts 2.6kVac up to 30kVdc. This output voltage charges capacitor (C_1) up to 30kVdc by charging resistorR_4 (33 MΩ). And this voltage is also divided by R_2 (200MΩ) and R_3 (2MΩ) and charges capacitorC_2 (0.5μF) up to 300Vdc.

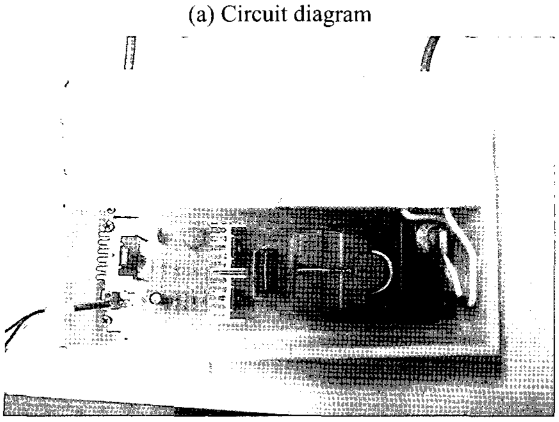
② Optical receiver (R) converts the optical signal transmitted from CZA into the electrical signal to operate thyristor (Q_1).

③ If thyristor (Q_1) operates, voltage (300Vdc) of capacitor C_2 discharges through the primary winding of pulse transformer (P-Tr) and the pulse voltage of 10kVp occurs in the secondary winding. This pulse voltage (10kVp) is delivered to the triggering electrode of gap-switch (GP-41) via coupling capacitor C_3 (500pF).

④ If GP-41 is triggered, voltage (30kVdc) charged in C_1 discharges through Reactor(L_1) and generates the triggering pulse signal. This signal is transferred into the triggering electrode of VTGS through resistorR_1 (1.5Ω).



(a) Circuit diagram



(b) Photograph

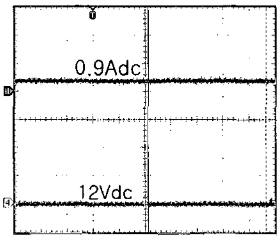
Fig. 9 High-voltage generating unit with 30kV, 1mA

4. Experimental results of the re-ignition system

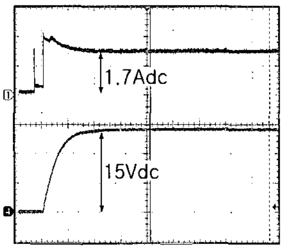
In order to evaluate the performance of the re-ignition system, power consumption of the air M-G was investigated first. And the operating characteristics of the triggering device and the re-ignition system were evaluated.

4.1 Power consumption

When the triggering device illustrated in 3.2.3 became no-loaded after completing the charging process of 30kVdc on capacitor (C_1), power consumption was approximately 10W as shown in Fig. 10(a). And when the triggering device became full-loaded with the recharging process on capacitor (C_1), power consumption reached approximately 20W as shown in Fig. 10(b).



(a) Power consumption of no-load condition



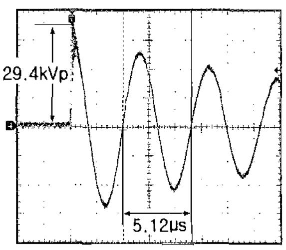
(b) Power consumption of full-load condition

Fig. 10 Power consumption of the triggering device

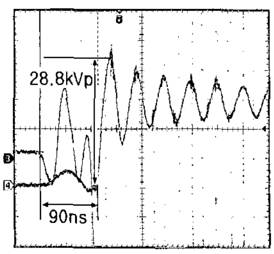
4.2 Operating characteristics of the triggering device

The triggering device must be able to generate more than voltage required to activate VTGS and its delay time and jitter time be as small as possible. Hence, in order to analyze the pulse voltage that represents characteristics of the triggering device, experiments with open condition and load condition were performed as shown in Fig. 11.

In experiment of open condition with disconnecting the output terminals from VTSG, the pulse voltage of approximately 30kVp and 195kHz occurred as shown in Fig. 11(a). And in experiment of load condition with connecting the output terminals to VTSG, the pulse voltage had rising time of 17ns, peak value of 30kVp and delay time not exceeding 100ns as shown in Fig. 11(b).



(a) Output of open condition



(b) Output of load condition

Fig. 11 Characteristics of the triggering device

4.3 Operating characteristics of the re-ignition system

In order to estimate the operating characteristics of the re-ignition system, experiments were performed with changing the charging voltage (Er) from 25kVdc to 150kVdc and with output terminals of the re-ignition system short-circuited in Fig. 2(a). In these experiments, magnitude of the re-ignition current and the operating characteristics such as delay time (t_d) and jitter time (t_j) were analyzed. Table 1 demonstrates that delay time was maintained approximately within the range of 3~5 μs and jitter time did not exceed 1 μs. In these experiments, the gap distance of VTGS was fixed at 24mm, even though the charging voltage was varied. Based on these results, the normal operating voltage of this system was set at 100kVdc.

Table 1 Experimental results of the re-ignition system

Charging voltage (Er, kVdc)	Magnitude of re-ignition current (kAp)	Delay time (t_d, μs)	Gap distance of VTGS (mm)
24.0	0.68	3.84	24
34.5	1.02	3.84	24
44.8	1.23	4.37	24
54.9	1.48	4.37	24
74.9	2.03	4.21	24
85.7	2.31	3.96	24
95.3	2.53	3.96	24
105.0	2.83	3.97	24
115.0	3.11	3.97	24
124.5	3.43	3.97	24
136.5	3.65	3.88	24
148.7	4.13	3.88	24

5. Conclusion

Most short-circuit testing laboratories have vigorously made an efforts on developing the new synthetic test methods and test facilities to enable the performance evaluation more efficient and closer to the service condition of the power system. KERI (Korea Electrotechnology Research Institute) has also been carrying out the studies for constructing the world-class test facilities with government assistance, since 2000.

As a part of these studies, KERI constructed the new re-ignition system using VTGS. And the normal operating voltage of this system was set at 100kVdc to obtain the efficient arc extension and the stable system operation.

This system considerably improved the efficiency and reliability of the synthetic breaking tests and following results were obtained.

(1) VTGS (Vacuum Triggered Gap-Switch)

VTGS showed the operating voltage of 25~150kVdc and the insulation strength of 200kVp with the fixed gap distance of 24mm. And the delay time did not exceed 100ns.

(2) Triggering device and air M-G (Motor-Generator)

Triggering pulse of the triggering device was designed as 30kVp. And also, air M-G was developed to supply the power to the triggering device and had the insulation strength of 200kVac. This air M-G makes it possible to protect the triggering device from the external surge voltage and to prevent malfunctions or troubles due to the external noise.

(3) Re-ignition system

In newly constructed re-ignition system, width and energy of the re-ignition current were increased by 35% compared to the old system. This re-ignition system had the superior operating characteristics, such as delay time and jitter time not exceeding 5 μs and 1 μs respectively.

In this study, VTGS was developed only as gap-switch for the re-ignition system with the operating voltage of 150kVdc. But, it may be essential to develop gap-switch for the voltage source circuit that requires the operating voltage of 500kVdc, in order to get the test qualities more highly upgraded.

Acknowledgements

This work was supported by the Ministry of Science and Technology, Republic of Korea.

References

[1] S. Managanaro and S. Rovelli, "A new circuit for synthetic auto-reclosing test duties under short-circuit conditions on high power circuit breakers," IEEE Transactions, PAS, Vol. 96, No. 5, pp 1620-1630, September-October, 1977.

[2] S. Managanaro and H. H. Schramm, "Application of synthetic auto-reclosing circuit for testing high-voltage circuit-breakers," IEEE Transactions, Vol. PAS-99, No. 6, pp. 2223-2231, 1980.

[3] L. Vander Sluis, G. C. Damster, H. W. Kempen, and W.A. Vander Linden, "Synthetic test methods : Experience and future developments," CIGRE Report 30, August-September 1992.

[4] G. C. Damstra, "An arc re-ignition circuit with triggered vacuum gap, "IXth International Symposium on Discharges and Electrical Insulation in Vacuum," Eindhoven, The Netherlands, Book of Abstracts, pp. 151-153 September 1980.

[5] G. E. Farrall, "Low voltage firing characteristics of a

triggered vacuum gap," IEEE Transactions on Electron Devices, Vol. ED-13, No. 4, pp. 432-438, April 1966.
[6] G. R. Govinda Raju, R. Hackam, and F. A. Benson, "Breakdown mechanisms and electrical properties of triggered vacuum gaps," Journal of applied Physics, Vol. 47, No. 4, pp. 1310-1317, April 1976.
[7] F. T. Warren, J. M. Wilson, J. E. Thompson, R. L. Boxman, and T. S. Sudarshan, "Vacuum switch trigger delay characteristics," IEEE Transactions on Plasma Science, Vol. PS-10, No. 4, pp. 298-301, December 1982.
[8] J. M. Wilson, J. E. Thompson, R. L. Boxman, and T. S. Sudarshan, "Breakdown time of a triggered vacuum and low-pressure switch," Proceedings: Tenth International Symposium on discharges and Electrical Insulation in Vacuum, " Colombia, South Carolina, pp. 268-272, October 1982.
[9] IEC 62271-101: "High-voltage switchgear and controlgear-Part 101: Synthetic testing," 17A/696/CD, 2004.
[10] KERI, "Study to promote the efficiency of High-Power Lab.," 1994.

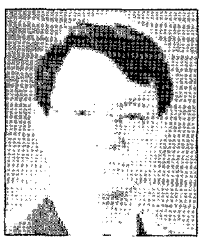
Seung-Jae Park
He received his B.S. degree in electrical engineering from Kwang-woon University, and M.S. degree from Kyungnam University. Currently he works as a Researcher in Korea Electro-technology Research Institute. His research interests are electrical transient analysis, synthetic test method and breaking phenomena.

Yoon-Taek Suh
He received his B.S. degree in electrical engineering from Youngnam University, and M.S. degree from Changwon University. Currently he works as a Researcher in Korea Electro-technology Research Institute. His research interests are measuring system, synthetic test method and breaking phenomena.

Dae-Won Kim
He received his B.S. and M.S. degrees in electrical engineering from Soongsil University. Currently he works as a Researcher in Korea Electro-technology Research Institute. His research interests are direct test method and breaking phenomena.

Maeng-Hyun Kim
He received his B.S., M.S. and Ph.D. degrees in electrical engineering from Kyungnam University. Currently he works as a Head of High-power testing Department in Korea Electro-technology Research Institute. His research interests are test facility design and breaking phenomena.

Won-Pyo Song
He received his B.S. degree in nuclear engineering from Seoul University and M.S. degree in electrical engineering from Kyungnam University. Currently he works as a Director in Hyosung Corporation. His research interests are circuit breaker design and breaking phenomena.



Hee-Seog Koh
He received his B.S. in electrical engineering from Busan University, M.S. degree in electrical engineering from Donga University and Ph.D. degree from Joongang University. Currently he works as a Professor in Kyungnam University. His research interests are power system analysis and economics.