Detection Characteristics of a Novel Coupler for GIS PD Detection

Jae-Gu Choi*, Sang-Hwa Yi*, Kwang-Hwa Kim*, Ik-Soo Kim and Jae-Chul Kim*****

Abstract - An ultra high frequency (UHF) coupler possessing ultra wide band (UWB) characteristics ranging from hundreds of MHz to several GHz is desirable for the detection of the partial discharge (PD) pulses because the pulses propagate with rise time shorter than one nanosecond in a gas-insulated substation (GIS). Thus, the authors have proposed a log-periodic antenna for GIS PD detection. Various parameters of the coupler such as frequency bandwidth, coupler gain, radiation pattern, and coupler geometry were considered throughout the simulations. The experiments for the detection characteristics of the coupler were carried out in the mock-up GIS chamber. The results indicated that the detection characteristics of the coupler are dependent on the installation angle of the coupler, the position of the coupler in the hand hole and the existence of the spacer.

Keywords: UWB, UHF, coupler, gas-insulated substations, PD detection

1. Introduction

The scales of the electric power facilities in South Korea as well as other countries in the world are being enlarged due to an increase in the electric power demand. Gas-insulated substations (GIS) have been adopted due to greater compactness, security and reliability than the conventional substations. While the GIS has numerous advantages as shown above, there are some difficulties related to observing its inside condition, as well as measurement of failure and repair. Under these circumstances, when failure occurs in the electric power facilities, it takes a great deal of time and enormous financial cost to perform repairs. Therefore, it is essential to develop a technology detecting and analysing partial discharge (PD), which can be generated as a precursor before flashover if the insulation of power apparatus deteriorates. Thereby, the insulation characteristics in the SF_6 gas-insulated apparatus can be diagnosed in advance.

A number of PD detection methods using the various PD phenomena such as light, sound, vibration and electromagnetic waves have been proposed [1-4]. It is widely known that the ultra high frequency (UHF) method that detects the electromagnetic wave of the PD pulses in the gas insulated space is one of the most competitive methods for its high sensitivity and robustness to noises [5,6].

The UHF coupler is the most important component in the diagnostic system using the UHF method because it should be able to catch those pulses having a rise time shorter than one nanosecond [7], which means it should be an ultra wide band (UWB) coupler with the bandwidth ranging from hundreds of MHz to several GHz. Therefore, a UWB UHF coupler is more desirable for the detection of the PD pulses because the UWB characteristics of the detected PD signals have plenty of information for verifying the type and the location of the defect in the GIS.

However, there have been few studies concerning the UWB UHF coupler in the field of GIS PD detection both domestically and abroad [8], due to difficulties in the design of the UWB coupler and the matching circuit as well as onerous digital signal post-processing.

In this paper, the authors have proposed a planar log-periodic antenna as a UWB UHF coupler for GIS PD detection. Various parameters of the coupler such as return loss (S11), field distribution, coupler gain and radiation pattern were considered through the simulations and the measurements. The experiments for the detection characteristics of the coupler were carried out in the mock-up GIS chamber.

2. Antenna Theory

The analytical treatment of UWB antennas begins by assuming that an antenna, whose geometry is best described by spherical coordinates (r, θ, φ), has both terminals infinitely close to the origin and each is symmetrically disposed along the θ = 0, π-axes. It is understood that the antenna is perfectly conducting, that it is surrounded by an infinite homogeneous and isotropic medium, and that its surface or an edge on its surface is described by the curve

$$r = F(\theta, \varphi) \tag{1}$$

* Power Facility Diagnosis Research Group, KERI, Korea. (jgchoi@keri.re.kr)
** Reliability Center, KERI, Korea. (isk133@keri.re.kr)
*** Department of Electrical Engineering, Soongsil University, Korea. (jckim@ee.ssu.ac.kr)
Received July 4, 2003 ; Accepted October 16, 2003

where r represents the distance along the surface or edge.

If the antenna is to be scaled to a frequency that is K times lower than the original frequency, the antenna's physical surface must be made K times greater to maintain the equivalent electrical dimensions.

Thus, the new surface is described by

$$r' = KF(\theta, \varphi) \quad (2)$$

The new and old surfaces are not only similar but also congruent.

A general solution for the surface $r = F(\theta, \varphi)$ of the antenna is [9]

$$r = F(\theta, \varphi) = e^{a\varphi} f(\theta) \quad (3)$$

where $a = 1/K \cdot dK/dC$ and $f(\theta)$ is a completely arbitrary function.

Thus, for any antenna to have UWB characteristics, its surface must be described by (3). This can be accomplished by specifying the function $f(\theta)$ or its derivatives. Subsequently, the log-periodic antenna configuration will be introduced whose surfaces are described by (3).

If the geometries of Fig. 1 use uniform periodic teeth, we define the geometric ratio of the log-periodic structure by

$$\tau = R_n/R_{n+1} \quad (4)$$

And the width of the antenna slot by

$$X = r_n/R_{n+1} \quad (5)$$

The geometric ratio τ of (4) defines the period of operation. For example, if two frequencies f1 and f2 are one period apart, they are related to the geometric ratio τ by

$$\tau = f_1/f_2, \; f_2 > f_1 \quad (6)$$

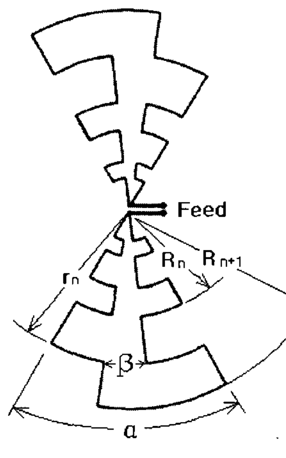
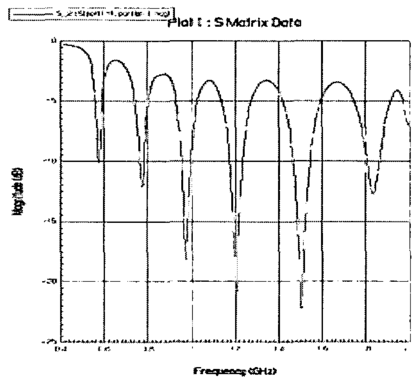


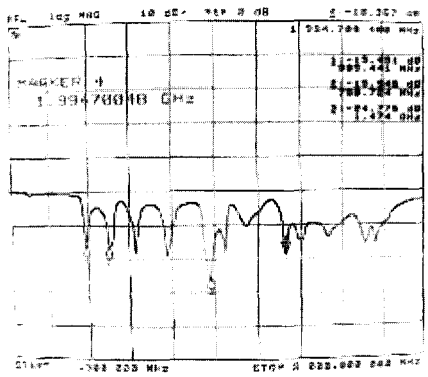
Fig. 1 Planar log-periodic antenna

3. Simulation Results and Discussion

Prior to the detection performance experiments with the proposed coupler in the laboratory, the authors investigated the return loss characteristics, the field distribution and the radiation pattern of the coupler in order to discover the optimum coupler for UWB UHF characteristics. The simulation tool, HFSS (high frequency structure simulator version 8.5) was used for the simulation.



(a) Simulated S11 (vertical (0 - -25): 5 dB/div, horizontal (400 – 2,000): 200 MHz/div)



(b) Measured S11 (vertical: 10 dB/div, horizontal (0 – 3,000): 300 MHz/div)

Fig. 2 S11 characteristics of the proposed coupler

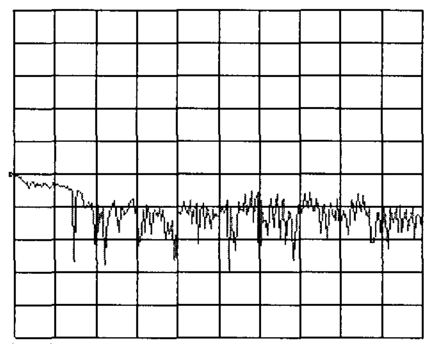


Fig. 3 S11 characteristics of the proposed coupler with the UWB matching circuit (vertical: 10 dB/div, horizontal (0 – 3,000): 300 MHz/div))

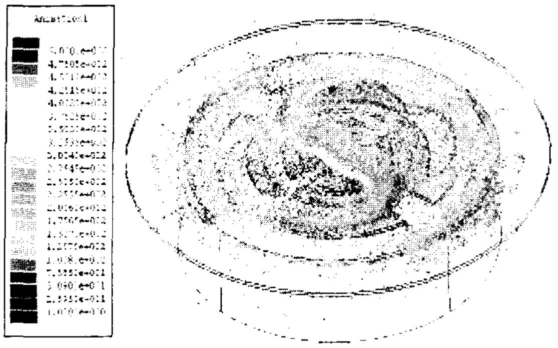


Fig. 4 Field distribution of the UHF coupler

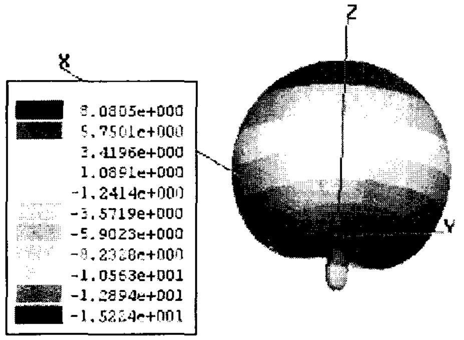


Fig. 5 Radiation pattern of the UHF coupler

The S11 characteristics of the coupler are shown in Fig. 2. In Fig. 2, (a) and (b) describe the simulated S11 and the measured S11, respectively. It can be seen that the simulated S11 and the measured S11 coincide well with each other in the bandwidth between 500 MHz and 2,000 MHz, which was the aimed bandwidth of the proposed coupler, with the exception of minor differences due to the gap between simulation and measurement. The coupler was matched with a UWB matching circuit to guarantee –10 dB S11 characteristics in the bandwidth. The result is shown in Fig. 3.

The field distribution of the coupler is shown in Fig. 4. In this case, the operation frequency is 1,000 MHz. It can be seen that the area of the strongest field distribution on the coupler surface agrees with a quarter wavelength of 1,000 MHz. In addition, we can assume the possibility that the installation angle of the coupler on the GIS hand hole will influence the detection sensitivity due to the unequal field strength on the edge of the coupler. The influence will be checked later in section 5.

The 3D radiation pattern of the proposed coupler is shown in Fig. 5. The highest gain is obtained in the forward side just as intended. The half power beam width (HPBW) of the coupler is about 80 degrees and the absolute gain (G_a) is 8.1 dBi. It is believed that the coupler can detect the signal efficiently in the GIB with this radiation pattern.

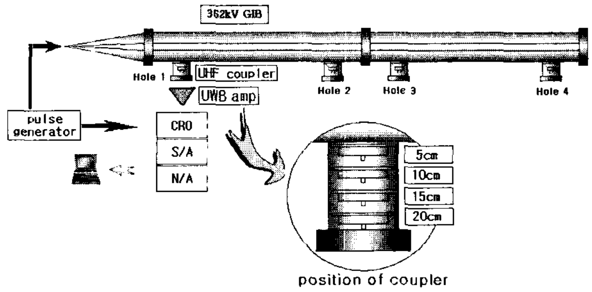


Fig. 6 Experimental setup for GIS PD detection

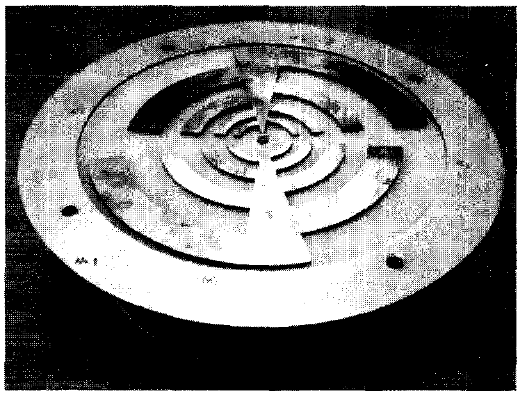


Fig. 7 Proposed UWB UHF coupler for GIS PD detection

4. Experimental Setup and Methods

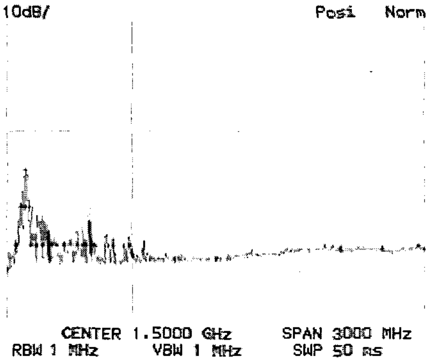
The experiments of the detection performance with the proposed UHF coupler were carried out using the 362 kV mock-up gas-insulated bus (GIB) shown in Fig. 6. The pulse generator emits pulses of 0.5 ns rise time through the conical coaxial bus for matching into the GIB. The signals detected by the UHF coupler in the hand hole were amplified by the UWB amplifier and analyzed by measuring instruments such as an oscilloscope (LeCroy, wavePro 960, 2 GHz / 16 GS/s, 16 Mpts), spectrum analyzer (Advantest, R3131A, 9 kHz – 3 GHz) and network analyzer (HP, 8753D, 30 kHz – 3 GHz).

The proposed UHF coupler for GIS PD detection is shown in Fig. 7. The wings of the coupler were made of brass. The feed of the coupler is connected to the N type connector through the UWB matching circuit in the cavity. The coupler was designed to be coupled to bandwidths between 500 MHz and 2,000 MHz.

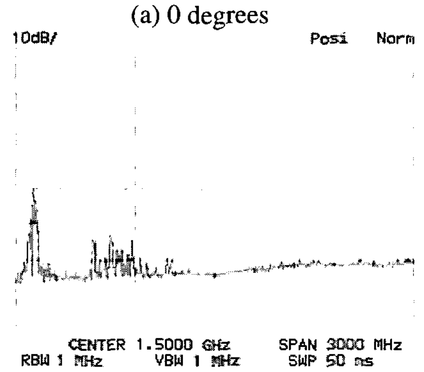
Three types of experiments were carried out in this study, i.e., (1) the effect of the installation angle of the coupler, (2) the effect of the coupler position in the hand hole and (3) the propagation characteristics in the GIB.

5. Experimental Results and Discussion

The frequency domain characteristics of the UHF coupler according to the installation angle of the coupler in the hand hole are shown in Fig. 8. In this case, the angle of the coupler in Fig. 7 was entitled to 90 degrees and the coupler rotated by 90 degrees from the above to 0 degrees.

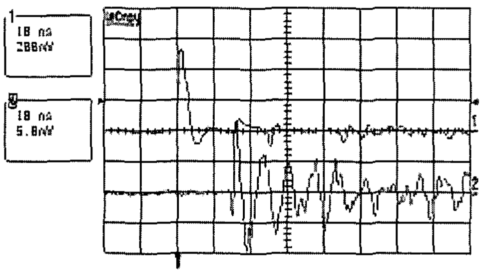


(a) 0 degrees

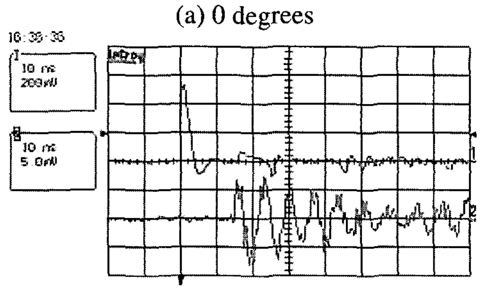


(b) 90 degrees

Fig. 8 Frequency domain characteristics of the UHF coupler according to the coupler angle (input charge: 40 pC, vertical: 10 dB/div, horizontal (0 – 3,000): 300 MHz/div)



(a) 0 degrees



(b) 90 degrees

Fig. 9 Time domain characteristics of the UHF coupler according to the coupler angle (top: input pulse (200mV/div), bottom: detected signal (5mV/div), horizontal: 10ns)

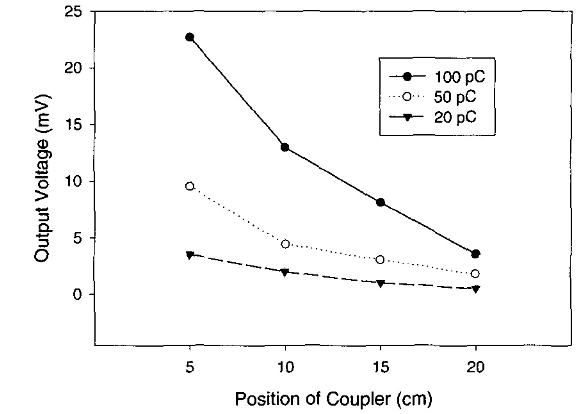


Fig. 10 Effect of the coupler position in the hand hole (coupler angle: 0 degrees)

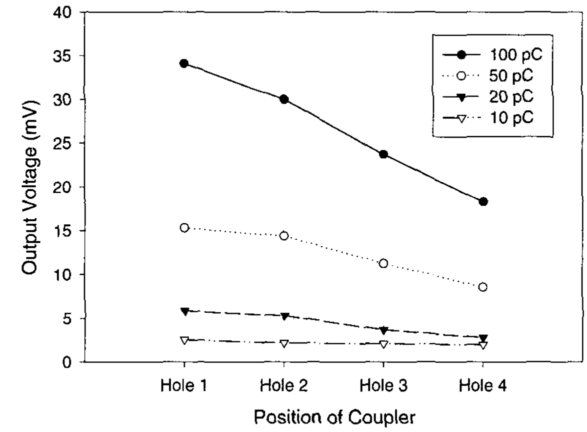


Fig. 11 Propagation characteristics in the GIB(coupler angle: 0 degrees)

As well, the detected signals from the coupler were amplified by the UWB amplifier with a gain of 20 dB. The spectrum was measured using the peak-hold method. From the spectra (a) and (b) in Fig. 8, it can be seen that higher modes are generating in the GIB because the input pulse from the pulse generator has 0.5 ns in rise time. The results show that the measured spectrum strongly depends on the installation angle. The spectrum between 300 MHz and 600 MHz decreases as the angle increases, while the spectrum between 600 MHz and 1,200 MHz increases as the angle increases. The reason for this is thought to be that the coupler at the installation angle of 90 degrees has greater sensitivity to higher modes. Therefore, considering these results, one should pay attention to installation of the coupler and choose the installation angle that best corresponds to the purpose.

The time domain characteristics of the coupler according to the installation angle are shown in Fig. 9. The results also indicate that the measured signals strongly depend on the coupler angle. The distortion of the first wave of the detected signal (the bottom wave in the figure) becomes severer as the angle increases. From the results of Fig. 8

and Fig. 9 together, it is evident that the distortion of the signals in the time domain influences the spectrum in the frequency domain.

Because the sensitivity of the coupler to propagated signals is highly dependent on the coupler position in the hand hole, the effect of the coupler position was checked in Fig. 6 and the result is shown in Fig. 10. In Fig. 10, the output voltage is highest at the 5 cm position, which is the closest to the central conductor as expected and most attenuated between the 5 cm and 10 cm positions. Therefore, the coupler should be placed near to the central conductor as long as the coupler does not deteriorate the field distribution in the chamber.

In addition, the propagation characteristics in the GIB were investigated through the 4 holes in Fig. 6 and the result is shown in Fig. 11. In Fig. 11, a great deal of signal attenuation occurs between holes 2 and 3 due to the conical spacer that is placed between them. The average attenuation rates between holes 1 and 2, between holes 2 and 3 and between holes 3 and 4 are 0.2 dB/m, 1.6 dB/m and 0.4 dB/m, respectively. From the above attenuation rates, it is evident that the spacer plays an important role in attenuation of the signal. It is thought that the couplers should be disposed in the GIS under careful consideration of high attenuation in spacers.

6. Conclusion

The log-periodic antenna was proposed as a UWB UHF coupler for GIS PD detection. Through a series of simulations taking place before the detection performance experiments, the following characteristics of the coupler were achieved, i.e., (1) return loss characteristics lower than –10 dB in the bandwidth, (2) field distribution on the coupler, (3) half power beam width of about 80 degrees and (4) absolute gain of 8.1 dBi. The following results of the experiments for the detection performance were found, (1) the coupler at the installation angle of 90 degrees has more sensitivity to higher modes, (2) the sensitivity of the coupler to propagated signals is very dependent on the coupler position in the hand hole, (3) the signal attenuates as much as 1.6 dB/m between holes 2 and 3 due to the conical spacer.

It has been found that the UWB low-noise amplifier with lower noise figure and higher gain is required to enhance the resolution of the spectrum. And, the conducting guard ring and the cavity decreased the characteristics of the coupler. Thus, they should be replaced with a non-conducting material.

Hereafter, further studies regarding polarization characteristics of the coupler and the higher modes in the GIB are needed. As well, PD pulses from real defects in SF_6 gas should be considered and the digital signal processing using the experimental results should be followed for a complete GIS PD detection system.

References

[1] D. F. Binns, A. H. Mufti and N. H. Malik, "Optical Discharge Detection in SF_6-insulated Systems", IEEE Transactions on Electrical Insulation, Vol. 25, No. 2, pp. 405-414, April 1990.

[2] L. E. Lundgaard, M. Runde and B. Skyberg, "Acoustic Diagnosis of Gas Insulated Substations; A Theoretical and Experimental Basis", IEEE/PES 1990 Winter Meeting, pp. 1-8, February 1990.

[3] Katsuaki Senba and Hiroshi Ishikawa, "Prediction and Preservation Techniques for GIS", MEIDEN REVIEW Series No. 101 1994 No. 2, pp. 47-51, 1994.

[4] M. D. Judd et al., "Partial Discharge Diagnostics for Gas Insulated Substations", IEEE Transactions on Electrical Insulation, Vol. 2, No. 5, pp. 893-905, October 1995.

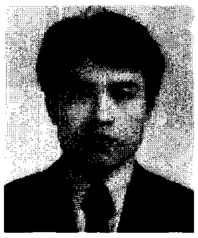
[5] J. S. Pearson, B. F. Hampton and A. G. Sellars, "A Continuous UHF Monitoring for Gas-insulated Substations", IEEE Transactions on Electrical Insulation, Vol. 26, No. 3, pp. 469-478, June 1991.

[6] T. Kimura, T. Harunami, N. Konma, K. Takata, K. Saitou, "GIS Insulation Monitoring System Using External Antenna", *CIGRE 130-05, Symposium Berlin* 1993.

[7] Baumgather, R. (1992). Partial Discharge-Part [illegible]:PD in GIS-Measurements and Practical Considerations. In: IEEE Electrical Insulation Magazine, Vol. 8, No. 1, pp. 16-26.

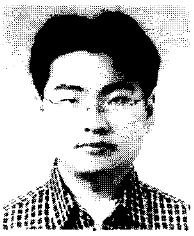
[8] Johnson J. H. Wang and Victor K. Tripp. Design of Multi-octave Spiral-Mode Microstrip Antennas, IEEE Transactions on Antennas and propagation, Vol. 39, No. 3, pp. 332 – 335, March 1991.

[9] Balanis, C.A. (1982). ANTENNA THEORY, pp. 542 - 553. John Wiley & Sons, Inc. New York.

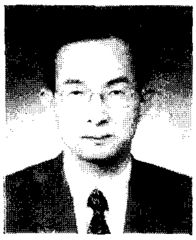


Jae-Gu Choi

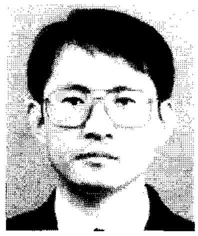
He received his B.E. and M.E. degrees in Electrical Engineering from Kyoungpook National University, Daegu, Korea in 1994 and 1996, respectively. Currently, he is a Senior Researcher at the Korea Electrotechnology Research Institute (KERI) in Korea. His research interests include high voltage engineering and its applications, and digital signal processing. He is a member of the Korean Institute of Electrical Engineers (KIEE).



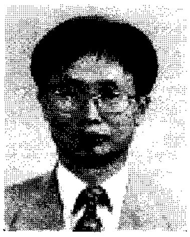
Sang-Hwa Yi
He received his B.E. degree in Electronic Engineering from Korea University, Seoul, Korea in 2001 and his M.E. degree in Electronic Engineering from the Pohang University of Science and Technology in 2003. Currently, he is a Researcher at the Korea Electrotechnology Research Institute (KERI) in Korea. His research interests include high voltage engineering and microwave engineering. He is a member of the Korean Institute of Electrical Engineers (KIEE).



Kwang-Hwa Kim
He received his B.E., M. E. and Ph. D. degrees in Electrical Engineering from Pusan University, Pusan, Korea in 1981, 1983 and 1992, respectively. Currently, he is a Principal Researcher and the Director of the Power Facilities Diagnosis Research Group at the Korea Electrotechnology Research Institute (KERI) in Korea. His research interests include the diagnosis of power facilities, high voltage engineering and its applications. He is a member of the Korean Institute of Electrical Engineers (KIEE).



Ik-Soo Kim
He received his B.E., M.E. and Ph. D. degrees in Electrical Engineering from Pusan University, Pusan, Korea in 1981, 1983 and 2000, respectively. Currently, he is a Principal Researcher at the Korea Electrotechnology Research Institute (KERI) in Korea. His research interests include high voltage engineering and its applications. He is a member of the Korean Institute of Electrical Engineers (KIEE).



Jae-Chul Kim
He was born in Chonbuk, Korea, 1955. He received his B.S.E.E. degree from Soongsil University, Korea, 1979, and M.S.E.E. and Ph.D. degrees from Seoul National University, Korea, in 1983 and 1987, respectively. He has served as a professor of Electrical Engineering at the Soongsil University since 1988.