韓國電磁波學會論文誌 第 9 巻 第 3 號 1998年 6月 論文 98-9-3-08

Parameters of the Electric and Magnetic Fields Due to Cloud-to-Ground Lightnings

낙뢰에 의한 전계와 자계 파형의 파라미터

Bok-Hee Lee · Chang-Hwan Ahn

이복희 · 안창환

Abstract

One of the topics concerning the electromagnetic compatibility of modern electronic circuits is to take protection from transient overvoltages caused by not only cloud-to-ground lightnings but also induced lightning discharges. In this paper, the vertical electric and horizontal magnetic fields from cloud-to-ground lightnings were measured and analyzed. The electric and magnetic fields waveforms associated with cloud-to-ground lightnings have several subsidiary peaks which decrease with time. There were not much differences between the electric and magnetic field due to long distance cloud-to-ground discharges. Average values of 10~90 % rise times of electric fields are 4.65 μs for the positive cloud-to-ground lightning and 3.29 μs for the negative cloud-to-ground lightning, respectively. Also, in the positive and negative cloud-to-ground lightning discharges, the zero-to-zero crossing times in the wave tail of magnetic fields are significantly longer than those of the electric fields.

요 약

낙뢰뿐만 아니라 유도뢰에 의해서 발생되는 과도과전압에 대한 첨단전자장비의 보호대책이 중요 과제 중의 하나로 대두되었다. 본 논문에서는 낙뢰에 의해 발생된 수직전계와 수평자계를 측정하고 분석하였다. 낙뢰에 의해 발생한 전계와 자계 파형은 최초 피크 다음에 이어지는 수 개의 후속 피크들을 가지며, 이들 피크값은 시간의 경과와 더불어 감소하는 형상으로 나타났다. 원거리 낙뢰에 의해 방사된 전계파형은 자계 파형과 거의 흡사하였다. 낙뢰에 의해서 발생한 전계 파형의 10~90 % 상승시간은 정극성은 4.65 μs, 부극성에서는 3.29 μs이었으며, 또한 정·부극성의 낙뢰 모두 자계의 파미(波尾)부분의 영점교차시간은 전계 파형에 비해서 훨씬 길게 나타났다.

I. Introduction

The injurious effects of lightning discharge in atmosphere are very severe. Especially cloud-to-ground lightnings injure human body and bring about malfunction of small sized electronic circuits such as semiconductor de-

「이 연구는 1997년도 인하대학교 연구비 지원에 의하여 수행되었음.」
인하대학교 전기공학과(Dept. of Electrical Eng., Inha University)
· 논 문 번 호 : 980122-009
· 수정완료일자 : 1998년 3월 30일

vices, computer and control units, information systems, telecommunication facilities, and so on. In the view of lightning protection, it is very important to determine parameters of spatial electric and magnetic fields associated with lightning discharges. Therefore, this field has become an area of increasing public concern, and a lot of research concerning cloud-to-ground lightnings have been carried out by numerous workers in all over the world.[1]~[4]

In this study, the measuring systems of transient electric and magnetic fields were designed and fabricated with the object of analyzing the change of electric and magnetic field waveforms produced by lightning discharges. Thus the results of the statistical characteristics such as physical properties, the rise time of the electric and magnetic fields waveforms, the distribution of zero-to-zero crossing time associated with cloud-to-ground lightnings were reported.

The data described in this paper were measured at the seaside of Inchon from June 1995 to August 1996. All of the detected signals were not fine, but we report the only fine data.

Ⅱ. Theoretical Consideration of Electric and Magnetic Fields due to Cloud-to-Ground Lightnings

The thundercloud is made by the seperation and accumulation of the electric charges due to ascending air in atmosphere. Lightning discharges then are originated from insulation breakdown of the air, the electromagnetic waves corresponding to movement of electric charge or flowing current in air are radiated.

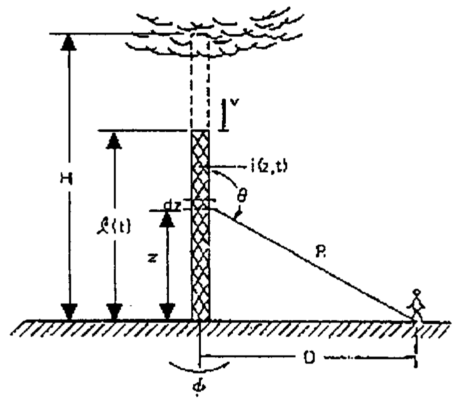


Fig. 1. Geometrical parameters used in calculating cloud-to-ground discharge.

The wave length of electromagnetic waves is longer than wave length of the return strokes flowing large current, otherwise it is shorter than that of shock wave during the producing new discharge channel. The geometrical and physical parameters were shown in Fig. 1 to express the ideal conduction channel and the electromagnetic fields produced by flowing current in the channel.

The vertical compoment of electric field and the horizontal component of magnetic field at a distance R away from the vertical channel of height H are given by[8],[11]

$$Ev(D,t)=\frac{1}{2\pi\varepsilon_0}\left[\int_0^H\int_0^t\frac{2-3\sin^2\theta}{R^3}i(z,\tau-R/c)d\tau dz+\int_0^H\frac{2-3\sin^2\theta}{cR^2}i(z,t-R/c)dz-\int_0^H\frac{\sin\theta}{c^2R}\frac{\partial}{\partial t}i(z,t-R/c)dz\right]a_z \qquad (1)$$

$$B_A(D,t)=\frac{\mu_0}{2\pi}\left[\int_0^H \frac{\sin\theta}{R^2}\, i(z,t-R/c)dz + \int_0^H \frac{\sin\theta}{cR}\frac{\partial}{\partial t}\, i(z,t-R/c)dz\right]a_\varphi \qquad (2)$$

where equations (1) and (2) are in cylindrical coordinates, ε_0, μ_0 and c are electric permittivity, permeability of vacuum and the light velocity, respectively.[5] Also, equation (1) gives the electrostatic component by the first term, induced component by the second term and radiation component by the third term. And equation (2) gives the induced component by the first term and radiation component by the second term. The electric field of low frequency bandwidth in short distance mainly presents electrostatic component of the first term in equation (1). The electric and magnetic fields produced by cloud-to-ground lightning discharges depend on the distance from the lightning stroke point to the measuring point. Generally, the electric and magnetic field waveforms have the zero crossing points and the shapes of them resemble closely each other when the distance from lightning stroke point to observation station is more than 50 km.[6],[11]

Ⅲ. Measuring System of Electric and Magnetic Fields

The hemisphere-type electric field sensor, whose diameter is 30 cm, was designed and fabricated to prevent a short circuit between the sensing electrode and earth plate by rainwater, ice and snow. The signal processing circuit including the amplification circuit and buffer circuit was installed within the shield box at the lower part of the sensor to reduce the electromagnetic noises due to magnetic field to be measured. The frequency bandwith of the electric field measuring system is in the range of 200 Hz~1.56 MHz and the sensitivity is 0.96 mV/V/m.[7]

The sensor of magnetic fields is made of loop-type coaxial cable to reduce the effects of electric field to be measured. It is necessary to intergrate the detected signal because the loop-type magnectic field sensor detects the time derivatives of signal to be measured. Accordingly, an active-type intergrating circuit was designed and the BNC connector was used in connection part for impedance matching. The frequency bandwith of magnetic field measuring system ranges from 270 Hz to 2.3 MHz and the sensitivity is 135 mV/μT.[8]

Fig. 2 shows a schematic diagram of the electric and magnetic field measuring system and the data recorder. In order to remove the effects of geographical feature and the earthing and neighboring metal structures for the fine data measurement, careful attentions were paid to the selection of the measuring site of electric and magnetic fields. Earthing

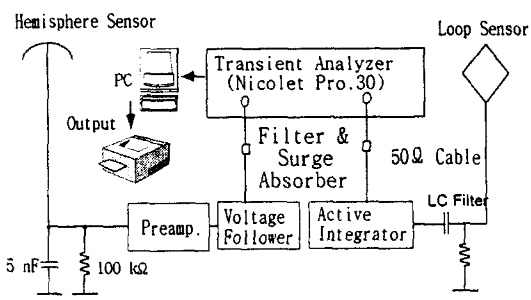


Fig. 2. Schematic diagram of electric and magnetic field sensors and data recorder.

rods were established, and copper plate of 900×1600 mm was covered at the bottom of earth. The data acquisition system(Nicolet Pro30) has the vertical resolution of 12 bit and the memory capacity of 512 kbytes per one event, and the sampling time could be adjusted in the range of 100 ns～500 μs.

Ⅳ. Results and Discussion

4-1 Parameters of the electric and magnetic field waveforms

The electric field waveforms radiated by cloud-to-ground lightning slightly differ from the magnetic field waveforms because of the dependence of distance from the lightning stroke point to measuring point as described in Sec. 2.

The characteristics of wave front in the electric and magnetic field waveforms associated with cloud-to-ground lightnings are divided into the initial slow part produced by the progress of last leader due to propagation on the ground with limited electric conductivity or sea and the fast transient part produced by lightning return strokes.[9] Also the fast transient part of wave front corresponds to change of lightning current.

The characteristics of wave tail are strongly dependent on the distance from the lightning stroke point to the measuring point. Genarally, the wave tail gives the droop waveform in proportion to the change of vertical components of electrostatic field after initial peak in several km. The electric and magnetic field waveforms are shown with the mixed waveform by radiated and induced components for the order of 50 km distance and with the radiated component only in long distance of more than 50 km.[10],[11] It is very effective to statistically analyze the electric and magnetic field waveforms produced by cloud-to-ground lightnings since those involve informations about lighting current as a radiation source. The electric and magnetic field waveforms, which are variable on the distance from lightning stroke point to detecting point, are characterized by parameters such as the rise time, the zero-crossing time and the overshoot to the inverse direction, and so on. Especially, the cloud-to-ground lightning location positioning system must detect the waveforms produced by cloud-to-ground lightning excluding intracloud discharges. In order to improve the detecting accuracy of the lightning location positioning system and to develop the effective lightning protection of power system, it is very important to analyze the characteristics of the electric and magnetic field waveforms produced by cloud-to-ground lightning in Korea.

Fig. 3 shows the definition of parameters such as a leader pulse of preceding discharge,

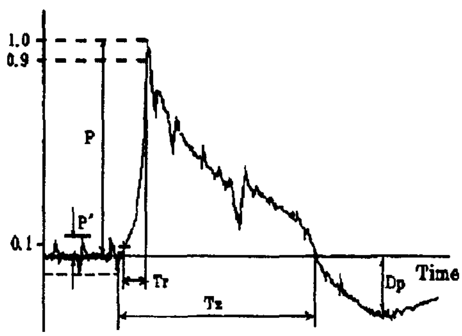


Fig. 3. Definition of parameters of the electric and magnetic field waveforms produced by cloud-to-ground lightning.

the rise time of wave front, the second peak value, the zero-to-zero crossing time, the depth of the dip after zero-crossing in the electric and magnetic field waveforms associated with cloud-to-ground lightnings. The 10 to 90 % rise time(T_r) of the electric and magnetic field waveforms is very useful since there is uncertainty in determining the virtual zero point of the waveform.

The zero-to-zero crossing time(T_z) presents the time interval from the origin point to the second zero crossing point. The depth of the dip(D_p) is presented the ratio of the second peak value in the opposite polarity relative to the first peak value.[12] T_z and D_p stand for the characteristics of wave tail. We analyzed the only data of the electric and magnetic field waveforms produced in long distance because the cloud-to-ground lightning is exactly distinguished from intracloud discharges, and Table 1 shows the typical discrimination criteria of the lightning return strokes used in the lightning location positioning system.

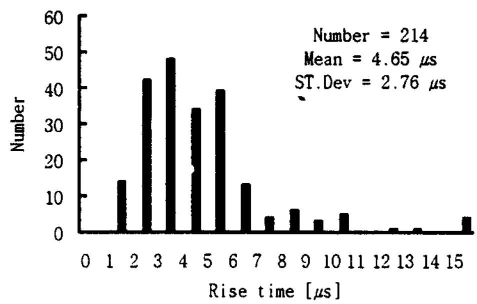
Three parameters(T_r, T_z, D_p) characterizing the fine structure of electric and magnetic field waveforms from the first return strokes are statisticlly examined in this paper. In order to remove the distortion caused by propagation and by the effect of the induced field, the electric and magnetic field waveforms produced by cloud-to-ground lightnings in the case of existing the zero crossing point were analyzed.

Table 1. Discrimination criteria of lightning return strokes from electric and magnetic field waveforms.

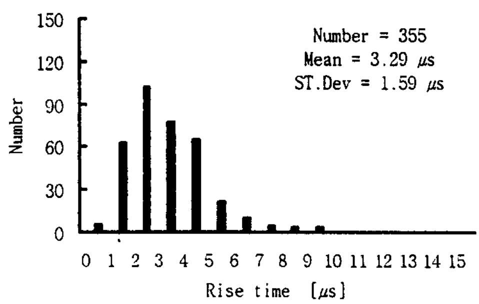
Parameter \ Polarity	Positive	Negative
Rise time [μs]	$T_r<32$	$T_r<32$
Zero crossing time [μs]	Tz>6	Tz>6
Peak value of the preliminary breakdown	P′<0.23P	P′<0.2P
Peak value for the inverse direction after zero crossing	$D_p<P$	$D_p<P$

4-2 Rise time

The statistical distributions of the rise time in the electric field waveforms produced by cloud-to-ground lightnings were shown in Fig. 4.



(a) Positive

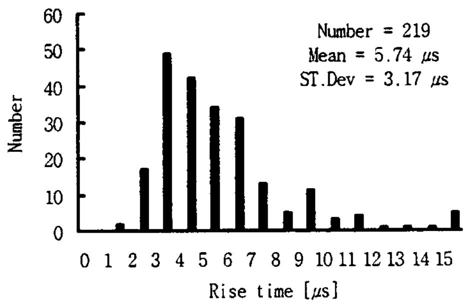


(b) Negative

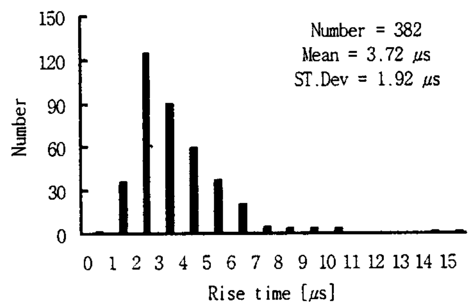
Fig. 4. The rise time of the electric field waveforms.

The mean value of the rise time for the positive electric field waveforms is 4.65 μs and the standard deviation is 2.76 μs. Most of the rise times for the negative lightning return strokes are concentrated in the time range of 2~5 μs. The mean value of the rise time for the negative is 3.29 μs and the standard deviation is 1.59 μs. Accordingly, it was known that the progress velocity of the positive lightning return strokes is slower than that of the negative lightning return strokes.

The rise time of the magnetic field waveforms radiated from lightning return strokes gives the dependence of polarity like the electric field waveforms as shown in Fig. 5.



(a) Positive



(b) Negative

Fig. 5. The rise time of the magnetic field waveforms.

Most of the rise times of magnetic field waveforms for the negative polarity are chiefly concentrated in the time range of 2~7 μs. The mean value of the rise time of the negative magnetic field waveforms is 3.72 μs and it is slightly longer than that of the electric field waveforms. And the standard deviation is about 1.92 μs. The mean value of the rise time of the positive magnetic field is longer than that of the electric field waveforms too. And the mean value of the rise time is 5.74 μs and the standard deviation is 3.17 μs.

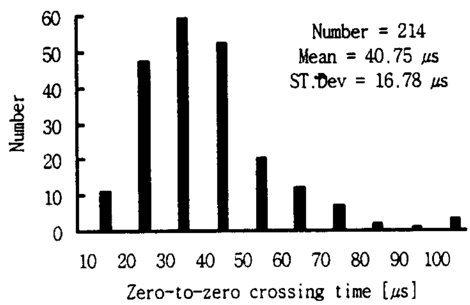
As a result, it was found that the rise time of the wave front in the electric field waveforms produced by lightning return strokes is shorter than that for the magnetic field waveforms up to about 20 [%] for both polarities. The front part of the electric and magnectic field waveforms is constituted of the slow part produced by attachment of preliminary breakdown leader and the fast part around the peak value. The 10 to 90 % rise time is substantially the same as rise tme of the slow part, because the deviation of the fast transition part is less than 1μs. Therefore the nature of the 10 to 90 % rise time is characterized by the attachment process of lightning return strokes, and the dispersion of the 10 to 90 % rise time originates from discharge process of the preceding leaders. The rise time of the electric and magnectic field waveforms produced by lightning return strokes is a critical parameter in the area of analysis of lightning phenomena. Also in the view of engineering issue, the rise time is very important factor in design of lightning protection devices because it is directly influenced on the response characteristics of lightning protection devices against the very fast transient overvoltages.

4-3 Zero-to-zero crossing time

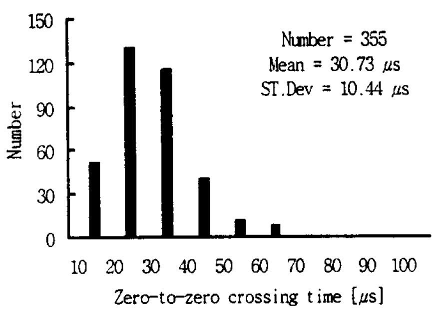
The zero-to-zero crossing time(Tz) is the time interval between the beginning point of the waveform and the crossing point to zero after the first peak, and it is applied to evaluate the energy quantity transmited by lightning strokes to ground in relation to the duration of lightning return strokes. Also it has a strong dependence of the distance from the lightning stroke point to observatory.

As shown in Fig. 6, the mean value of the positive zero-to-zero crossing time for the electric field waveforms is 40.75 μs and the standard deviation is 16.78 μs. On the other hand, the mean zero-to-zero crossing time in the negative polarity is 30.73 μs and the standard deviation is 10.44 μs. The mean zero-to-crossing time of the positive electric field waveforms is much longer than that of the negative.

The mean value of the positive zero-to-zero crossing time of the magnetic field waveforms as shown in Fig. 7 is 54.37 μs and the standard deviation is 20.46 μs. And the mean zero-to-zero crossing time of the negative magnetic

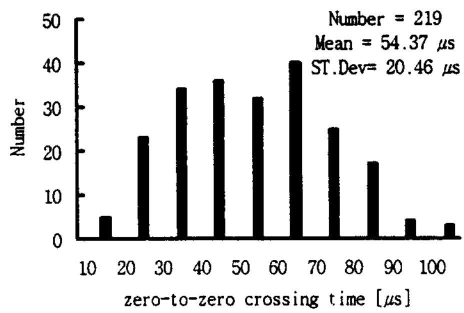


(a) Positive

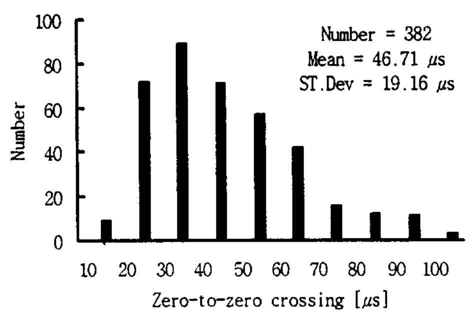


(b) Negative

Fig. 6. Zero-to-zero crossing time of the electric field waveforms.



(a) Positive



(b) Negative

Fig. 7. Zero-to-zero crossing time of the magnetic field waveforms.

field waveforms is 46.71 μs and the standard deviation is 19.16 μs.

The positive zero-to-zero crossing times for both electric and magnectic field waveforms are longer than the negative zero-to-zero crossing times and wider dispersions in the histograms. The difference might be because of the long duration current among the positive cloud-to-ground lightning.[13] Also the zero-to-zero crossing times of the electric field waveforms for both polarities are mainly concentrated before and after the mean value whereas those of the magnectic field waveforms are widely distributed.

The mean values of the zero-to-zero crossing times of the electric and magnetic field waveforms obtained in this work are slightly shorter than other researcher's data.[13] It was inferred that the difference might be caused by the following factors such as the distance from the lightning stroke point to the observatory, the geographical and seasonal effects, and so on.

4-4 Depth of the dip

The depth of the dip, which presents the ratio of the second peak value in the opposite polarity to the first peak value, shows the characteristics of the wave tail. The depth of the dip for the cloud-to-ground lightnings at long distance is deeper than that at close distance, because it is changed by the distance from the lightning stroke point to the measuring point.

Fig. 8 and 9 show the depths of the dip for the electric and magnetic field waveform produced by lightning return strokes.

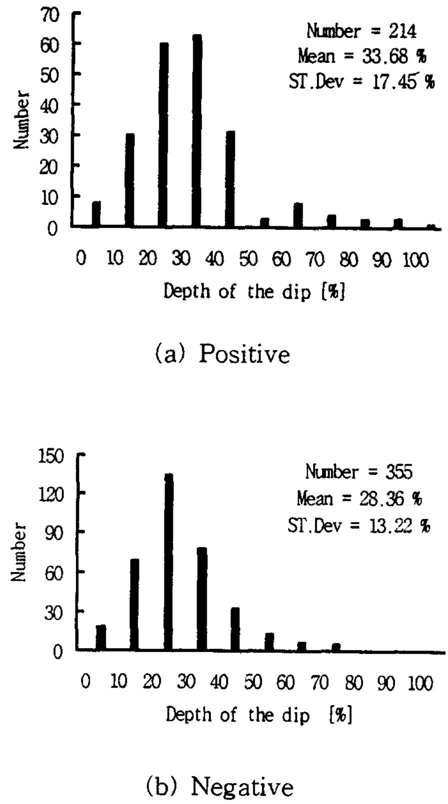
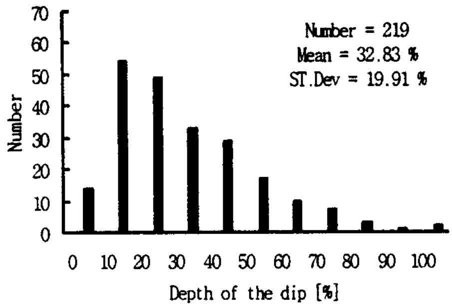
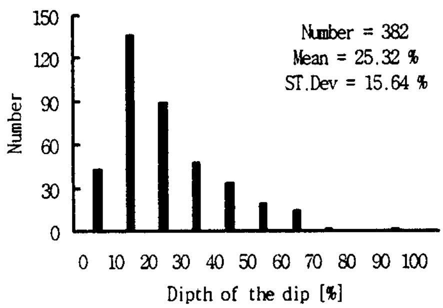


Fig. 8. Depth of the dip of the electric field waveforms.

The mean depth of the dip for the positive electric field waveforms is 33.68 % and the standard deviation is 17.45 %. Also, the mean depth of the dip for the negative polarity is 28.36 % and the standard deviation is 13.22 %. The depths of the dip for the positive electric field waveform are distributed before and after 20 to 50 %. The mean depth of the dip for the positive magnetic field waveforms is 32.83 % and the standard deviation is 19.91 %. Also, the mean depth of the dip for the negative polarity is 25.32 % and the standard deviation is 15.64 %.



(a) Positive



(b) Negative

Fig. 9. Depth of the dip of the magnetic field waveforms.

The positive depths of the dip for both electric and magnetic fields are deeper than the negative depths of the dip. And the depths of the dip of the electric fields for both the positive and negative polarties are deeper than those of the magnetic fields. The trend can be explained by the irregularity of lightning discharges.

V. Conclusion

The electric and magnetic field waveforms associated with cloud-to-ground lightnings are dependent on the geographical and seasonal effects and the distance from the lightning stroke point to the measuring point. In summer, a lot of the negative cloud-to-ground were occured. The rise times of the positive electric and magnetic field waveforms are longer than those of the negative, and the mean rise time of the magnetic fields are longer than that of the electric fields. The zero-to-zero crossing times of the electric fields for both positive and negative polarities are shorter than those of the magnetic fields. The rise time and the zero-to-zero crossing time are very useful data in determination of the response time and the energy capacity on lightning arresters, protection facilities, respectively. The positive depths of the dip of the electric and magnetic fields are deeper than the negative depths of the dip. The results of the statistical distribution for the rise time, the zero-to-zero crossing time and the depth of the dip obtained in this work will provide the valuable informations on the design of surge protectors and lightning protection devices.

References

[1] C. Leteinturier, J. Hamelin and C. Weidman, "Correlation of Lightning Current and Electric Field Derivative," *8th International Zurich Symposium and Technical Exhibition on Electromagnetic Compatibility*, pp. 405~410, 1989.

[2] P. R. Krehbiel, M. Brook, and R. A. McCroy, "An Analysis of the Charge Structure of Lightning Discharges to Ground," *J. Geo. Res.*, vol. 84, no. C5, pp. 2432~

2443, 1979. 5.

[3] M. A. Uman, Lightning, Dover Publications Inc. New York, 1982, pp. 1~65.

[4] P. W. Casper, "The LPATS Time of Arrival Lightning Positioning System : Critical Performance Aspects," *20th ICLP*, pp. 1~12, 1990.

[5] Bok-H. Lee and Kyoung-O. Lee, "Characteristics of the Electric and Magnetic Field Waveforms Radiated by Lightning Discharges," *J. KEES*, vol. 7, no. 4, pp. 300~309, 1996.

[6] W. Beasley, M. A. Uman, and P. L. Rustan, "Electric Fields Proceeding Cloud-to-ground Lightning Flashes," *J. Goe., Res.*, vol. 87, no. C7, pp. 4883~4902, 1982.

[7] Bok-H. Lee, Chang-H. Ahn and Mun-N. Joo, "Characteristics of the Electric Fields Associated with Lightning Discharges," *Trans. KIEE*, vol. 45, no. 10, pp. 1467~1472, 1996.

[8] Bok-H. Lee, Kyoung-O. Lee and Bong-C. Ha, "Characteristics of Radiation Magnetic Field Waveforms Produced by Lightning Discharges," *Trans. KIEE*, vol. 45, no. 9, pp. 1318~1323, 1996.

[9] C. D. Weidman, E. P. Krider, "The Fine Structure of Lightning Return Stroke Wave Forms," *J. Geo. Res.*, vol. 83, no. C12, pp. 6239~6247, 1978.

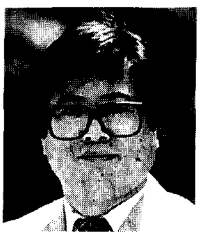
[10] M. A. Uman, "Lightning Return Stroke Electric and Magnetic Fields," *J. Geophys. Res.*, vol. 90, no. D4, pp. 6121~6130, 1985.

[11] M. A. Uman and E. P Krider, "A Review of Natural Lightning : Expermental Data and Modeling," *IEEE Trans.*, vol. EMC-24, no. 2, pp. 79~105, 1982.

[12] Bok-H. Lee, M. Ishii and J. Hojo, "Characterization and Evaluation of the Electric Fields Produced by Lightning Return Strokes," Proc. of 4th Annual Conf. of Power & Energy Society, *IEE of Japan*, pp. 70~73, 1993.

[13] M. Ishii and J. Hojo, "Statistics on Fine Structure of Cloud-to-Ground Lightning Field Waveforms," *J. Geo., Res.*, vol. 94, no. D11, pp. 267~274,

이 복 희



1954년 6월 29일생

1980년 2월 : 인하대학교 공과대학 전기공학과(공학사)

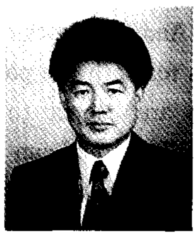
1987년 2월 : 동 대학원 전기공학과 (공학박사)

1988년 4월~1989년 9월 : 일본 동경대 생산기술연구소 객원연구원

1990년 3월~현재 : 인하대학교 공과대학 전기공학과 부교수

[주 관심분야] EMI /EMC, 전자계 측정 및 해석, 뇌방전 현상, 고전압 및 기체절연재료, 과도접지임피던스 해석

안 창 환



1959년 11월 4일생

1983년 2월 : 원광대학교 공과대학 전기공학과(공학사)

1991년 2월 : 인하대학교 대학원 전기공학과(공학석사)

1995년 3월~현재 : 인하대학교 대학원 전기공학과 박사과정

[주 관심분야] EMI /EMC, 뇌방전 현상, 전력계통운용, 고전압 현상론, GIS 성능해석