Characteristics of Lightning Overvoltages Coming in Low-Voltage Power Distribution Systems

Bok-Hee Lee*, Dong-Moon Lee*, Su-Bong Lee*, Dong-Cheol Jeong*, Jae-Bok Lee and Sung-Ho Myung****

Abstract - The importance of improving the quality of electric power is being strongly raised, owing to an increasing use of sensitive and small-sized electronic devices and systems. The transient overvoltages on low-voltage power distribution systems are induced by direct or indirect lightning return strokes. These can cause damage and/or malfunction of the utility systems for home automation, office automation, factory automation, medical automation, etc. The behaviors of lightning overvoltages transferred through the transformer to the low-voltage distribution systems using a Marx generator were experimentally investigated. Furthermore, the coupling mechanisms of lightning overvoltages transferred to the low-voltage systems were clearly illustrated through a theoretical simulation using a Pspice program. The overvoltages in low-voltage ac power systems are rarely limited by the application of the surge arrester to the primary side of the distribution transformer. A superior surge protection scheme is to install surge protection devices at the service entrance switchboard and/or at the load devices in TN power systems.

Keywords: Lightning overvoltages, Distribution transformer, Low-voltage ac power systems, Surge protection devices

1. Introduction

Due to the increasing importance of improving the quality of electric power, particular attention to the lightning overvoltages in low-voltage power distribution systems and utility companies has been drawn by research centers. Lightning is an unavoidable natural phenomenon, which has a strong affect on low-voltage power distribution systems. Numerous surveys of lightning overvoltages have been conducted in various environments [1-5]. In particular, there have been many studies of lightning overvoltages in relation to computer data systems as well as to signal/communication systems. However, the answers to numerous questions concerning lightning overvoltages in low-voltage power distribution systems remain unknown. One of the phenomena that should be more deeply investigated is related to the lightning overvoltages transferred through transformers to low-voltage power distribution systems. Direct or indirect lightning overvoltages are induced in the primary high-voltage power lines of the distribution transformer, and the lightning overvoltages propagate through step-down distribution transformers to the secondary low-voltage power lines. Normally lightning overvoltages are originated from several various mechanisms and can cause damage or upset to electronic circuits and systems. Any damage or temporary malfunction of computerized information/communication systems can cause serious disturbances to industrial, military, financial, business and social activities. The four types of lightning overvoltages in low-voltage power distribution systems are as follows; lightning surges transferred through the transformer from high-voltage systems, overvoltages caused by direct lightning flashes to low-voltage distribution systems, induced overvoltages in low-voltage distribution systems, and overvoltages caused by flashes of lightning to protection systems [6]. The accurate analysis of the characteristics of lightning overvoltages in low-voltage power distribution systems is a critical and important process in developing and validating survival of microelectronic devices and systems.

In general, lightning overvoltage protection of electric power networks is now often examined based on data related to theoretical simulation of responses to lightning and switching surges. However, because most line elements of electric power networks cannot be easily modeled, it is very difficult to obtain the correct simulation for the lightning or switching surges appearing on the low-voltage power distribution systems. In the standard 61643-1 published in 1998 [7], protection from the low-voltage side of the distribution transformer to the outlets in buildings was considered, as well as direct lightning to the buildings with lightning structures. Special protection against lightning overvoltages transferred from high-voltage distribution

* school of Electrical and Computer Engineering, Inha University #253, Yonghyun-dong, Nam-ku, Inchon, 402-751, KOREA (bhlee@inha.ac.kr, g2021074@inhavision.inha.ac.kr, dcjeong2000@korea.com)
** Korea Electrotechnology Research Institute
Received: April 1, 2003 ; Accepted: July 31, 2003

systems is currently under consideration [6].

Therefore, this work was oriented on the analysis of the characteristics of lightning overvoltages transferred through transformers from high-voltage distribution systems to low-voltage power distribution systems, in order to propose guidelines for effective installation and design of surge protection devices (SPDs) against lightning or other transient overvoltages. When the 1.2/40μs impulse voltage was applied to the primary side terminals of the distribution transformer, the impulse voltages transferred through the transformer to the low-voltage power lines were measured and calculated. The characteristics of propagation of lightning overvoltages in low-voltage power distribution systems associated with the types of system grounding were also examined.

2. Experimental setup

Possible lightning stroke locations on overhead lines and an example of typical application of lightning surge arresters on overhead lines have been illustrated in Fig. 1. It is advantageous that the high-voltage surge arresters be connected at the primary side of the transformer and the low-voltage surge protective devices be installed at the secondary side of the transformer, or at the service entrance of the building and at the equipment side. Sometimes the SPDs for low-voltage circuits at the secondary side of the transformer and at the service entrance are omitted. Lightning may strike either high-voltage distribution systems or low-voltage distribution systems.

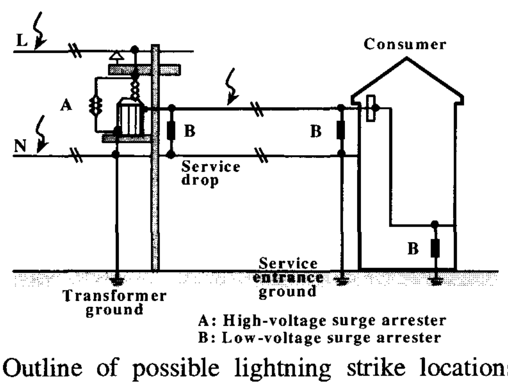


Fig. 1 Outline of possible lightning strike locations and typical application of low-voltage surge protection devices

The experiments were carried out using the test circuits of a 22.9kV/220V distribution transformer. A Marx generator, which has the equivalent circuit as shown in Fig. 2, supplied the test voltage and its maximum output voltage was 400kV. The applied voltage measurement was made by a special electric field probe designed for laboratory surge research and the high cutoff frequency of the electric field probe was 290 MHz [8].

The electric field probe was placed near the point to be measured and the CT was placed around the ground resistor. The test impulse voltage had a rise time of 1.2μs and the time to decline to half of the peak value was about 40μs as shown in Fig. 3. In the case of direct flashes to the high-voltage distribution systems, the lightning overvoltages transferred through the transformer to the secondary side were measured. Additionally, when direct lightning struck the low-voltage distribution systems, lightning overvoltages through the main panel board with earth leakage breaker /overcurrent circuit breaker and watthour meter were observed at the equipment side for four types of system grounding.

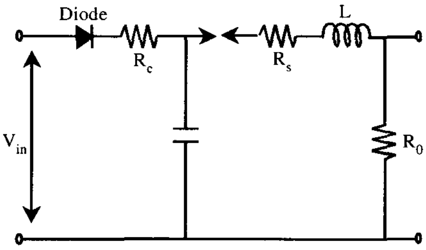


Fig. 2 Equivalent circuit of the impulse voltage generator

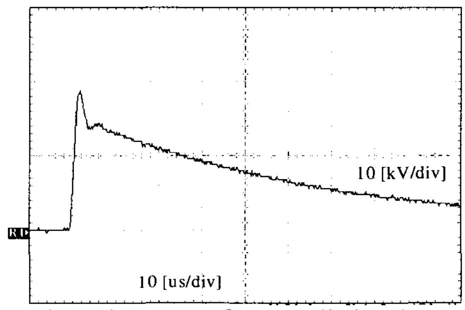


Fig. 3 Impulse voltage waveform applied at the test circuits

3. Results and discussion

There are two main ways that low-voltage side overvoltages can be conducted by lightning stroke to the primary conductor of the distribution transformer. Lightning overvoltages might appear at the secondary side with either the conduction mechanism created by ground current flowing through the neutral conductor or the electromagnetic coupling through the transformer. If the lightning has struck the primary phase conductor of the distribution transformer, the lightning current flows into the neutral conductor through the surge arrester. Thus, a lightning stroke to the phase conductor is similar to the neutral conductor, and the lightning current flows through the transformer ground and the service entrance ground. Initially, a larger portion of the lightning currents may flow into the transformer ground because the path is shorter and the inductance is less than the path to the service entrance ground. Inductivity effects subside after a few microseconds for surges with long wave tails and the lightning currents then divide according to relative ground resistances [9]. Therefore, the low-side surge problem surrounding the conduction mode voltages elevated by the lightning currents flowing through the neutral conductor to the ground is significantly acute when the service ground resistances are much less than the transformer ground resistances, and it is directly related to the system grounding. The purpose of this work was intended to obtain the information about the propagation of lightning overvoltages from the primary side to the secondary side in distribution transformers due to the electromagnetic coupling through the transformer.

3.1 Transfer characteristics of lightning surges in the distribution transformers

The test voltage at the primary side of the distribution transformer of 10kVA was applied between the hot line and ground conductors. The impulse voltages transferred to the secondary side were measured between the hot line and neutral line (differential mode) and between the hot line and ground conductor (common mode), with the test transformer ground resistance at 5Ω. The experiments were conducted in the cases that a surge arrester was either installed at the primary side of the transformer or not. Fig. 4 shows the outline of measurement circuits used in this work. The grounding electrode conductors in the primary and secondary sides of distribution transformers are generally solidly bonded. This bonding plays an important role in prevention of lightning overvoltages that could break down the insulation between the primary and secondary conductors of the transformer.

In the case that a surge arrester was not installed at the primary side of test distribution transformers, the typical waveforms of the applied voltage, open-circuit impulse differential mode and common mode voltages transferred to the secondary side and the ground current have been shown in Fig. 5. The waveform of the lightning overvoltage is changed when it propagates through the distribution transformer, and the transformer does not block lightning overvoltages. [10]

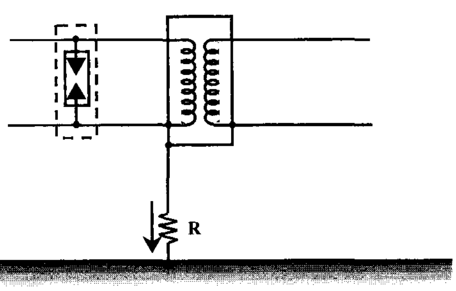
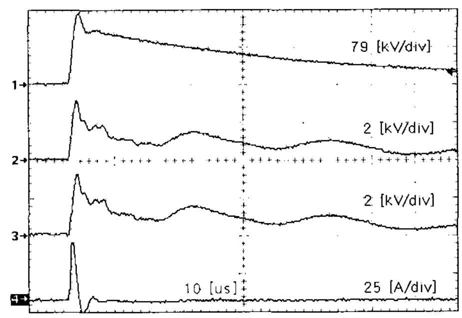


Fig. 4 Measurement circuits associated with the installation method of surge arrester at the primary side of distribution transformers.

The open-circuit voltages appearing across the secondary conductor of the transformer have high frequency oscillations due to the natural frequency of the circuit and damped component that is essentially the resistive and inductive voltage drop. As well, the ground current consists of the displacement current component determined by a value of dV/dt. Each transformer conductor has circuit elements such as series resistance, self-inductance and mutual inductance, interwinding capacitance and parasitic capacitance to ground. Lightning overvoltages are transferred through step-down transformers to the low-voltage side by parasitic capacitance between the primary and secondary conductors. In a word, the lightning overvoltage across the low-voltage side with respect to the input surge voltage with a large rate of change may be greater than the amplitude expected on the basis of the ratio of turns in the primary and secondary transformer conductors.



1: Applied voltage 2: Common mode voltage
3: Differential mode voltage 4: Ground current

Fig. 5 Typical waveforms of the applied voltage, the open-circuit voltages transferred to the secondary side and the ground current of distribution transformers without a surge arrester.

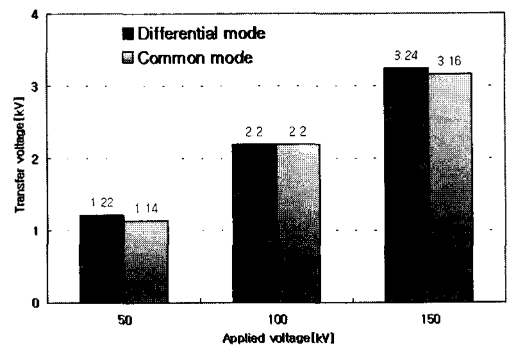
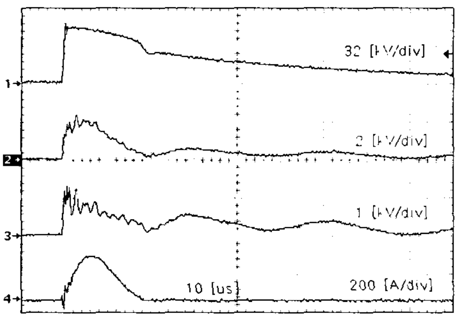


Fig. 6 Comparison of the common mode and differential mode voltages transferred to the low-voltage side in open-circuits.

The impulse voltages transferred to the secondary side of the transformer are linearly increased when the applied voltage increases as shown in Fig. 6. An incident lightning overvoltage at the primary lines of the distribution transformer is essentially coupled through the transformer by the parasitic capacitance between the primary and secondary conductors. This coupling is independent of the capacity and ratio of turns in both the primary and secondary conductors of the distribution transformer [11].



1: Applied voltage 2: Common mode voltage
3: Differential mode voltage 4: Ground current

Fig. 7 Waveforms of the applied voltage, the impulse voltages transferred to the secondary side and the ground current in the instance that a surge arrester has been installed at the primary side of the transformer.

In addition, measurements were taken in the test circuit that has a surge arrester connected between the hot line and ground conductors. Fig. 7 shows the incident impulse voltage, the impulse voltages transferred to the secondary side and the ground current. The incident impulse current is shunted around the transformer primary winding by the surge arrester.

Compared to the test circuit without a surge arrester, the lightning overvoltage transferred to the secondary side of the transformer was decreased and the ground current was significantly increased because the surge arrester limits the incident impulse voltage at the primary conductor. Therefore, the common mode voltage at the secondary side was larger than the differential mode voltage as shown in Fig. 8, and the voltages transferred to the low-voltage side were linearly increased with an increase in the ground current owing to the potential rise of the transformer ground. The lightning overvoltages transferred to the low-voltage side through the transformer are nearly independent of whether a surge arrester is installed or not. In other words, the application of a surge arrester to the distribution transformer does not substantially limit the low-voltage side surges in residential indoor wiring systems. An excellent method of protection of electronic circuits from lightning surges coming through low-voltage ac power systems is to install SPDs such as ZnO varistors at the service entrance as well as at the equipment. In addition, because the majority of transient overvoltages entering the low-voltage power distribution systems are essentially induced by direct or indirect lightning as mentioned above, it is effective that the SPDs for low-voltage power lines are tested by lightning surges with short time duration rather than performing the withstand capability test against rectangular current waves.

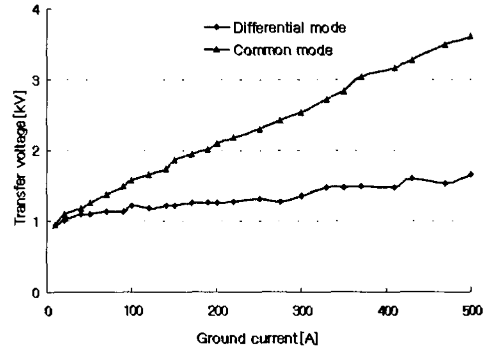


Fig. 8 Characteristics of the transferred voltage versus the ground current in the case that the surge arrester was installed at the primary side of the transformer.

3.2 The parameters characterizing the distribution transformer

The theoretical simulation was intended to determine the parameters of the test transformers and to analyze the characteristics of the impulse voltages transferred through the transformer to the low-voltage side. The calculations of the impulse voltages transferred to the low-voltage side in this simulation were carried out using the Pspice circuit analysis software on a desktop computer. The equivalent circuit for calculating the lightning overvoltage transferred to a secondary conductor of the transformer is illustrated in Fig. 9.

Fig. 10 shows the waveforms of the incident and transferred voltages for the transformer obtained by measurement and simulation. The simulation result is very similar to the measured impulse voltage waveform. In particular, the measured waveform of the impulse voltage transferred to the secondary conductor in the test distribution transformer is in good agreement with the simulated result.

The waveform of the impulse voltage transferred to the secondary conductor through a step-down transformer to the low-voltage side is characterized as follows: There are

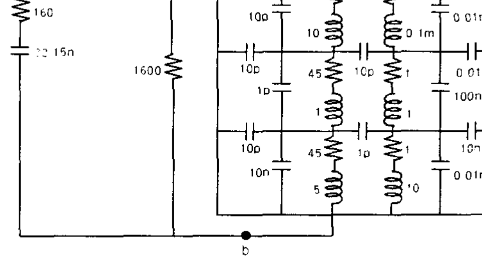
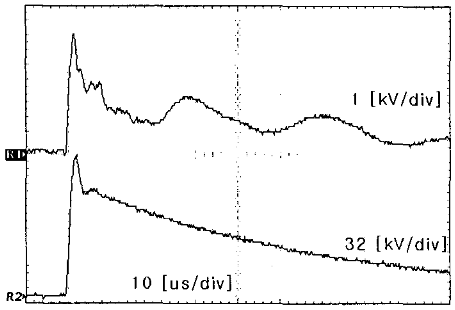
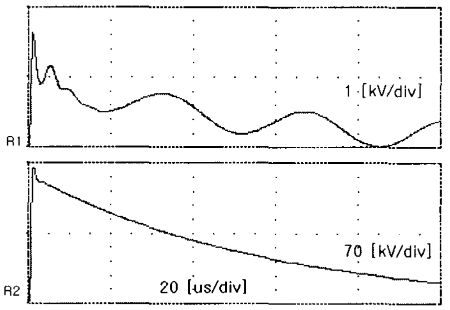


Fig. 9 The equivalent circuit of distribution transformer



(a) Measured waveform



(b) Simulated waveform

R1: Voltage transferred to the secondary side

R2: Incident voltage

Fig. 10 Waveforms of the incident and transferred voltages obtained by experiment and simulation

four mechanisms for coupling a surge voltage through a transformer: parasitic capacitance between the primary and secondary conductors, parasitic capacitance between each conductor and ground, mutual inductance, and oscillations in each of the primary and secondary conductors [11]. The amplitude of impulse voltage transferred to the secondary conductor of the transformer is principally determined by the parasitic capacitance between the primary and secondary conductors. Moreover, the series resistance of the secondary conductor and the parasitic capacitance between the secondary conductor and ground characterizes the decay and oscillation components just after the peak of the impulse voltage. The amplitude of large oscillation components on the wave tail of the transferred voltage is mainly determined by the series resistance of the primary conductor, and the oscillation is formed by the natural frequency associated with the parasitic inductance of the primary conductor and the parasitic capacitance between the primary conductor and the ground.

3.3 The effect of surge protective devices on the transferred voltage for the secondary side according to types of system grounding

There are several types of power system groundings. The TN systems have one point directly grounded, the exposed-conductive-parts of the installation being connected to that point by protective conductors and are divided into three types according to the arrangement of neutral and protective conductors, as follows; TN-S systems: in which throughout the system, a separate protective conductor is used; TN-C-S system: in which neutral and protective functions are combined in a single conductor in a part of the system; TN-C system: in which neutral and protective functions are combined in a single conductor throughout the system. The TT system has one point directly grounded, the exposed-conductive-parts of the installation being connected to ground electrodes electrically independent of the ground electrodes of the power system. The IT system has all live parts isolated from the ground or one point connected to the ground through impedance of the exposed-conductive-parts of the electrical installation being grounded independently or collectively or to the system grounding [12].

The high-voltage distribution systems are TN systems, but a large number of customer's facilities in Korea consist of the TT system. The experimental conditions composed as shown in Fig. 11 are intended to simulate the measurement circuits for various system groundings. R1 is the test distribution transformer ground resistance and R2 is the service entrance ground resistance. The values of R1 and R2 are 5Ω. In the IT system, switches S1, S2 and S3 are open and switch S4 is closed. The circuit is the TT system in which only the S1 and S4 switches are closed. In the TN-S system, the S1 and S2 switches are closed and the S3 and S4 switches are open. In the TN-C system, the S1 and S3 switches are closed and the S2 and S4 switches are open.

The test voltage was applied between the hot and ground conductors, between the neutral and ground conductors and between the bundle of hot and neutral conductors and the ground conductors at the low-voltage side of the distribution transformer. The differential mode and common mode voltages at the distance of 30m from the entrance service switchboard were measured.

Examples for waveforms of the applied voltage, the differential mode and common mode voltages transferred to the low-voltage side, the ground currents flowing into

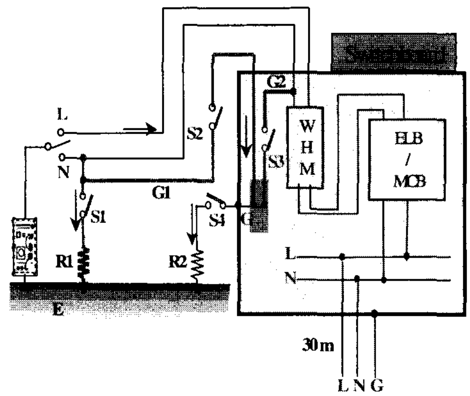
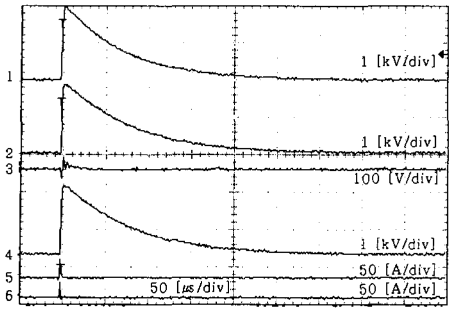
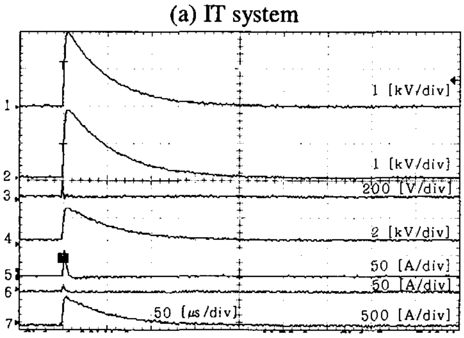


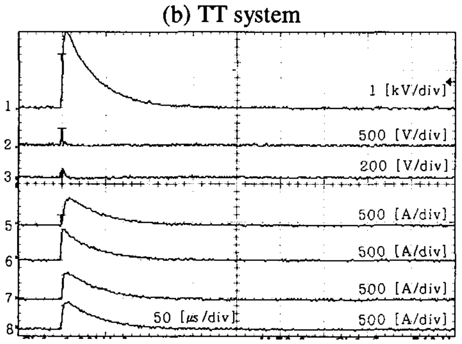
Fig. 11 Measurement circuit associated with types of system grounding



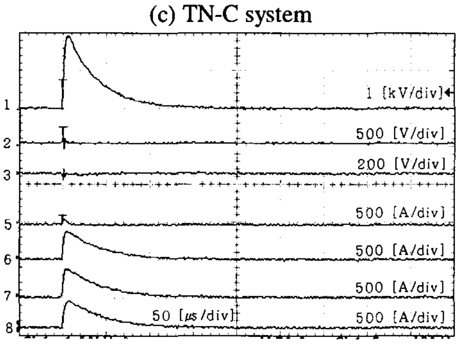
(a) IT system



(b) TT system



(c) TN-C system



(d) TN-S system

1: Applied voltage 2: Line-to-ground voltage
3: Line-to-neutral voltage 4: Neutral-to-ground voltage
5: Current flowing through the bundle of live and neutral conductors
6: Entrance service ground current
7: Transformer ground current
8: Current flowing through the G1 or G2 ground conductor.

Fig. 12 Waveforms of the test voltage, voltages between each conductor and currents flowing through each circuit according to types of system groundings, when the lightning surge voltage was applied between the hot and neutral conductors and the ground conductor.

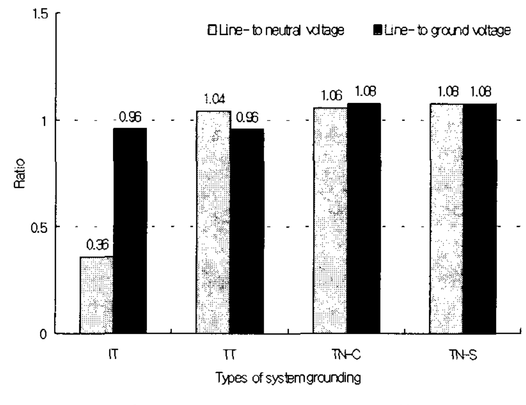
both the two ground resistances and the currents flowing through ground G1 and/or G2 lines according to types of system groundings have been illustrated in Fig. 12 in the case that the test voltage was applied between the bundle of hot and neutral conductors and the ground conductors.

Fig. 13 illustrates the line-to-neutral voltages and the line-to-ground voltages according to the incursion paths of lightning surge voltage and they are in the ratios of the line-to-neutral voltages to the incident voltage and the line-to-ground voltages to the incident voltage. When the lightning surge voltage is invaded with common mode on the ac power lines, that is, when direct lightning strikes the overhead power lines, only the line-to-neutral voltage in the IT system is about a third of the incident voltage, and the line-to-neutral and line-to-ground voltages are approximately equal to the incident voltage in TT, TN-S and TN-C systems as shown in Fig. 13 (a).

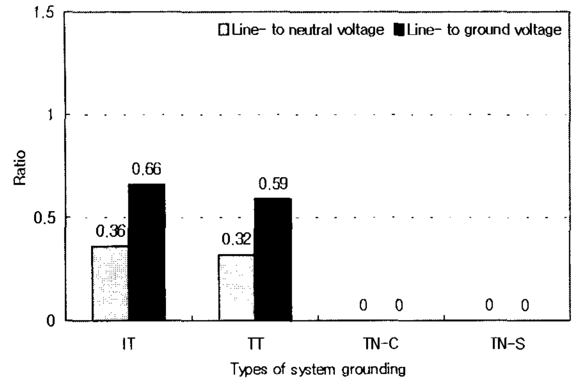
The line-to-ground voltages are raised by the potential rise due to the entrance service ground resistance. Thus, the line-to-ground voltages in the IT and TT power systems are usually larger than the line-to-neutral voltages. As a result, the separate installation of the transformer ground and service entrance ground is ineffective in surge protection.

The application of the test voltage between the neutral line and ground conductors is used to simulate the surge incursion from the grounding systems. The line-to-neutral and line-to-ground voltages were zero in the TN systems, and were relatively low in the IT and TT systems. Also, the test voltage applied between the bundle of hot line and neutral line and the ground conductor presents the induced surge voltage on the power lines produced by indirect lightning, and most frequently this induced surge voltage appears in low-voltage power distribution systems. In this case, the line to-ground voltages in the IT and TT systems were above 90% of the applied voltage, but the line-to-neutral voltages did not appear in all grounding systems.

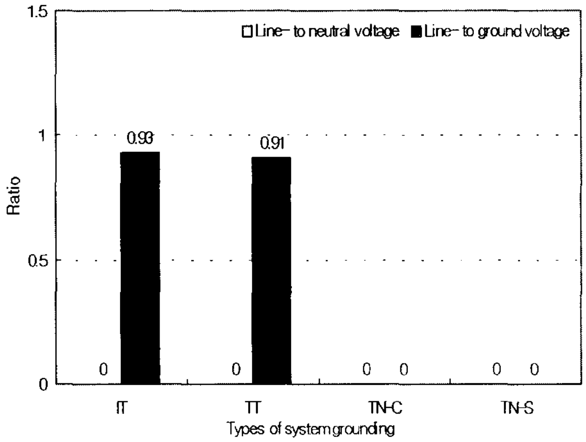
In the case that an additional ground at the service entrance in the TN systems is installed, the incident current is shared into both the grounding conductors of the trans-



(a) In case that the test voltage was applied between the line and ground conductors



(b) In case that the test voltage was applied between the neutral and ground conductors



(c) In case that the test voltage was applied between the bundle of line and neutral conductors and the ground conductors

Fig. 13 Voltages between each conductor according to the incursion paths of lightning surge voltage.

former ground and service entrance ground. Provided that the service entrance ground resistance is significantly low, a large portion of the incident surge current to flow in the neutral line of the service drop can produce low-voltage side surge. The surge problem in low-voltage distribution systems is essentially the same as the transformer ground [10]. In general, it is very difficult to limit the common mode surge voltages. Thus it is known that the TN systems are very effective in protecting the induced lightning surges and lightning surges coming from grounding systems after lightning rod or tower strokes.

4. Conclusion

The behaviors of lightning overvoltages transferred through transformers to low-voltage distribution systems were experimentally investigated. As a consequence, the equivalent circuit of a distribution transformer was proposed, and the measured waveforms of lightning impulse voltages transferred to the secondary side of the transformer are in good agreement with the simulation results. Transient overvoltages, which are induced in the high-voltage power lines of distribution systems by direct or indirect lightning, are easily transferred through the transformer to the low-voltage power lines. It was found that the lightning overvoltage is mainly coupled by the interwinding parasitic capacitance of the distribution transformer.

The surge arrester installed at the primary side of the distribution transformer does not essentially limit the secondary side surge voltages. Therefore, an effective surge protection of electronic devices is to place SPDs for low-voltage at the service entrance and/or at the equipment, and it is beneficial that the SPDs for low-voltage circuits be tested with lightning surges. In addition, the TN systems in protecting electronic circuits and systems from lightning overvoltages entering through ac power lines are more effective than the IT and TT systems. Finally, from these results, we can estimate a proper protection method of information technology equipment against lightning surges injected from the low-voltage ac power lines and grounding conductors.

References

[1] Alexander Piantini, Caius V. S. Malagodi, "Voltage surges transferred to the secondary of distribution transformers", High Voltage Engineering Symposium, 22-27 August 1999 Conference Publication No. 467, IEE, 1999.

[2] C. K. Roy, J. R. Biswas, "Studies on impulse behaviour of a transformer winding with simulated faults by analogue modeling". IEEE Trans., Vol. 141, No. 5, September 1994.

[3] B. Richter, "Surge protective Devices for Low-Voltage Power Distribution Systems, - The New IEC - Standard and First Experience with It", Proc. 23rd ICLP, Paper No.7C-1, pp. 764~767, 1998.

[4] R. C. Dugan and S. D. Smith, "Low-Voltage-Side Current-Surge Phenomena in Single-Phase Distribution Transformer Systems", IEEE Trans. on Power Delivery, Vol. 3, No. 2, pp. 637~647, 1988.

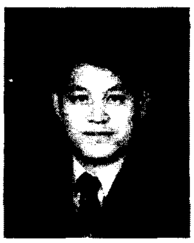
[5] G. L. Goedde, R. C. Dugan and L. D. Rowe, "Full Scale Lightning Surge Tests of Distribution Transformers and Secondary Systems", IEEE Trans. on Power Delivery, Vol. 7, No. 3, pp. 1592~1598, 1992.

[6] IEC 61643-12, "Surge protective devices connected to low-voltage power distribution systems - Part 12: Selection and application principles", First edition, 2002-02, pp. 113~117.

[7] IEC 61643-1, "Surge protective devices connected to low-voltage power distribution systems - Part 1: Performance requirements and testing methods", First edi-

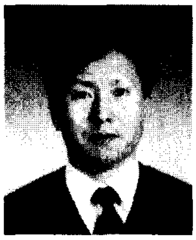
tion, 1998-02, pp.3 ~ 37.
[8] T. Kawamura and B. H. Lee, "Transient Impulse Breakdown of SF6 Gas in Inhomogeneous Electric Fields" Jpn. J. Phys. Vol. 30, Pt. 1, No. 8, pp. 4898 ~ 4904, 1999.
[9] Task Force Report, "Secondary (low-side) surge in distribution transformers", IEEE Trans., Vol. 7, No. 2, April 1992.
[10] M. B. Marz, S. R. Mendis, "Protecting load devices form the effects of low-side surges". IEEE Trans., Vol. 29, No. 6, November/December 1993.
[11] R. B. Standler, "Protection of Electronic Circuits from Overvoltages", John Wiley & Sons, Inc., First edition, New York, pp. 3 ~ 33, 1989.
[12] IEC 60364-3, "Electrical installation of buildings - Part 3: Assessment of general characteristics", Second edition, 1993-03, pp. 11 ~ 15.

Bok-Hee Lee
He was born in Korea on June 29, 1954. He received his B.S. degree in Electrical Engineering from Inha University in 1980, his M.S. degree in Electrical and Electronic Engineering from Hanyang University in 1993 and his Ph. D degree in Electrical Engineering from Inha University in 1987. He has been with the school of Electrical Engineering at Inha University, Inchon, Korea, where he became a Professor in 1999. During 1988 to 1989, he was a post-doctoral research fellow at the Institute of Industrial Science, University of Tokyo. From Apr. 1999 to Feb. 2000, he was a Visiting Professor at the University of Cincinnati. Since Oct. 2002, he has been the Director of the Research Center at Inha University. His research interests are in the areas of lightning, lightning protection, grounding system, surge protection, high voltage engineering and electromagnetic compatibility.
Tel: +82-32-860-7398, Fax: +82-32-863-5822,
http://hierc.inha.ac.kr



Dong-Moon Lee
He was born in Korea on April 20, 1958. He received his B.S. degree in Electrical Engineering from Inha University in 1987 and his M.S. degree in Electrical Engineering from Inha University in 2000. He has been working at Hanjin Heavy Industries in the area of lightning and high voltage engineering.
Tel. 032-860-7398, Fax. 032-863-5822.

Su-Bong Lee
He was born in Korea on April 13, 1979. He received his B.S. degree in Electrical Engineering from Kyungnam University in 1998 and his M.S. degree in Electrical Engineering from Inha University in 2003. His research interests are in the area of lightning, lightning protection, surge protection and high voltage engineering.
Tel: 032-860-7398, Fax: 032-863-5822,



Dong-Cheol Jeong
He was born in Korea on September 18, 1964. He received his B.S. degree in Electrical Engineering from Yeungnam University in 1989 and his M.S. degree in Electrical Engineering from Korea University in 2002. He has been working at Hanjin Heavy Industries & construction. His research interests are in the area of lightning and high voltage engineering.
Tel: 032-860-7398, Fax: 032-863-5822

Jae-Bok Lee
He was born in Korea on Aug. 17, 1962. He received his M.S. and Ph.D degrees in Electrical Engineering from Inha University in 1987 and 1999, respectively.
He has worked with the Korea Electrotechnology Research Institute as a Principal Researcher since 1987. His current research interests include lightning protection, grounding system and EMC.

Sung-Ho Myung
He was born in Korea on Mar. 20, 1959. He received his M.S. and Ph.D degrees in Electrical Engineering from Seoul National University in 1983 and 1996, respectively. He has worked with the Korea Electrotechnology Research Institute as a Director for the Electrical Environment & Transmission Group. His current research interests are design and analysis of electromagnetic fields.