The Measurement and Analysis of Surge Characteristics using Miniature Model of Air Insulated Substation

T. Watanabe, *nonmember,* K. Fukui, *nonmember,* H. Motoyama, *Member, IEEE,* T. Noda, *Member, IEEE*

Abstract-- This paper describes a new approach of the lightning surge analysis for an air-insulated substation (AIS). The lightning impulse withstand voltage (LIWV) level of electric power facilities in substations and power stations is determined by the lightning overvoltage. This is calculated by the lightning surge analysis using an electromagnetic transients program like EMTP (Electromagnetic Transients Program). The proposed approach for the lightning surge analysis of the AIS employs the multi-phase constants parameter model (M-CP model) line. It is theoretically difficult to apply the conventional model using multiphase lines when the length of the bus conductor is short. The proposed approach demonstrates high accuracy by comparing the experimental results and the finite-difference time-domain (FDTD) method. From the examinations, it is also clearly shown that the LIWV of a present AIS could be reduced, if the proposed approach for the lightning surge analysis and high performance metal-oxide surge arresters are applied to the AIS.

Keywords: EMTP, air-insulated substation, lightning over-voltage, multiphase distributed-parameter line, surge impedance

I. INTRODUCTION

The lightning impulse withstand voltage (LIWV) level of electric power facilities in substations and power stations is determined by lightning overvoltage.[1] Therefore, the development of an accurate lightning surge analysis method is important to estimate the appropriate LIWV level in substations and power stations. In general, the lightning overvoltage is estimated by electromagnetic transients program like EMTP (Electromagnetic Transients Program). A multi-phase constant parameter model (M-CP model) considering the structure of gas-insulated bus (GIB) is applied to the lightning surge analysis for a gas-insulated substation (GIS).

In the lightning surge analysis for an air-insulated substation (AIS), the bus and conductor are modeled as multiphase lines.[2] It is difficult to apply the overhead transmission line model to air-insulated bus (AIB) assuming that the line length is infinite, because the length of AIB is short. Therefore, AIB is modeled by the conventional model in which a single-phase constant parameter model (S-CP model) is used because of its simplicity. The S-CP model disregards the mutual coupling among bus conductors because of ignorance of the structure of the AIB. Estimated lightning overvoltage using the S-CP model is higher than the actual lightning overvoltage incoming into a substation and a power station. Therefore, it is possible to reduce the LIWV of a present AIS.

From these viewpoints, a possibility of the reduction of the LIWV for an AIS is examined in this paper. A new approach of the lightning analysis for an AIS using the M-CP model is proposed. The proposed approach is compared with the experimental results by using a miniature model of the AIS and the calculated results by using a finite-difference time-domain (FDTD) method. This paper also confirms the validity of the model using multiphase lines [2] for the first time.

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II. IMPROVEMENT OF PRECISION OF ANALYSIS MODEL

A. *Modeling of Air Insulated Bus*

In the lightning surge analysis for an AIS, AIB is modeled by the S-CP model (surge impedance: 350Ω, propagation velocity: $3*10^8$m/s) ignoring the mutual coupling among bus conductors and the structure of the real bus position. These parameters, in Japan, are typical values regardless of a voltage class, bus size, and so on. Therefore, the calculated results of the S-CP model might not fully simulate the actual lightning surge level in the AIS.

For these reasons, a new model for an AIB using the M-CP model is investigated. In the proposed model, actual positions and electrical characteristics of three phase aluminum pipe bus (Alp-bus) are considered. The multiphase constant parameter of the Alp-bus obtained from the Line Constants program which is auxiliary program of EMTP is applied to the EMTP surge analysis. Figure 1 shows the typical configuration of the AIB.

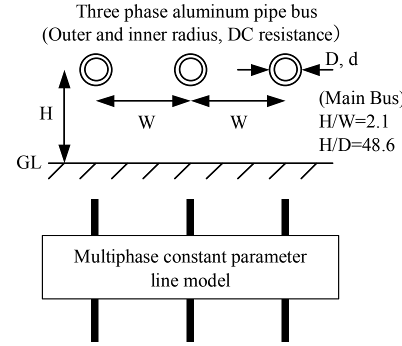


Fig. 1. Modeling of bus conductors using multiphase distributed-parameter line

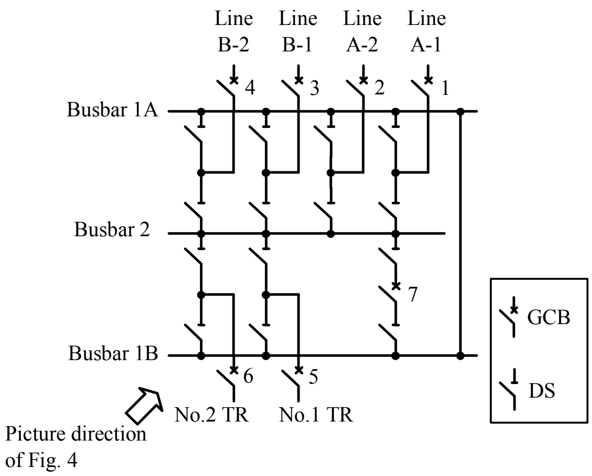


Fig. 2. Model Circuit

B. Lightning Surge Analysis

Figure 2 shows a model circuit of an AIS. This circuit is a typical configuration of an AIS. The lightning overvoltage of this circuit is estimated by using EMTP (ATP/Watcom) in two models: (i) Three phase Alp-bus is modeled by the S-CP model ignoring the real characteristics, (ii) Three phase Alp-bus is modeled by the M-CP model considering the real characteristics. Figure 3 shows the result comparison between the S-CP model and the M-CP model at the lightning surge injection phase. The lightning surge is generated by the back-flashover at the nearest transmission line tower. The lightning stroke parameters used in this analysis are given below:

Peak Current = 150kA
Time to Crest = 1μs
Half Time = 70μs

In the case of Fig. 3, the injection point is the nearest tower of Line B-2, and Line B-2 and No. 1 Transformer (TR) are connected. In addition, all disconnecting switches (DS) on busbar 2 are close and those on busbar 1A and 1B are open. The waveform of Fig.3 shows the voltage at the open circuit breaker on Line A-1.

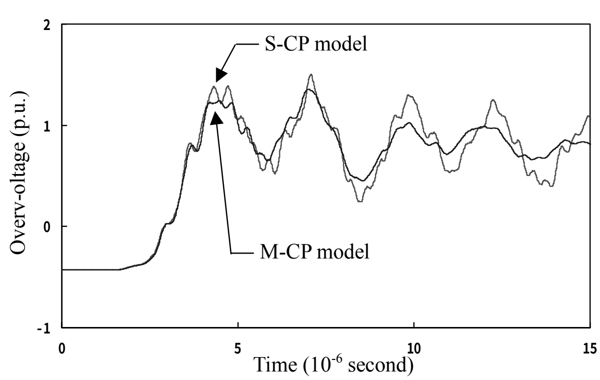


Fig. 3. Lightning surge voltage waveforms calculated by EMTP

The comparison shows that the calculated peak value of the S-CP model is higher than that of the M-CP model, and the dumping of the waveform of the S-CP model is slower than that of the M-CP model. This fact indicates that the line constants of the S-CP model are different from the real line constants of the AIB, because the real characteristics of the bus structures are not considered.

In the circuit of the AIS shown in Fig. 2, the overvoltages are compared at the open gas circuit breaker (GCB) points. Table 1 shows that overvoltages of the S-CP model are higher than those of the M-CP model in every point. Moreover, the results show that the LIWV of GCB can be reduced, if high performance metal-oxide surge arresters using zinc oxide element that improves the discharging capability are applied to the AIS. Therefore, the appropriate insulation co-ordination makes it possible to reduce the LIWV of an existing AIS.

TABLE 1. OVERVOLTAGE REDUCTION AT OPEN GCB

GCB	M-CP model	M-CP model + High performance SA
1	-9%	-24%
2	-5%	-12%
3	-6%	-15%
4	-9%	-22%
5	-6%	-15%
6	-3%	-16%
7	-6%	-25%

(Difference from S-CP model)

III. EXPERIMENT AT MINIATURE MODEL

In order to check the validity of the proposed approach, the comparison between the calculated and experimental results is carried out. The experiment is conducted on the 1/10 scale model of the AIS. Figure 4 shows the experimental setup of the AIS. The AIB is modeled by aluminum pipes. Table 2 shows the specifications of the measuring equipment.

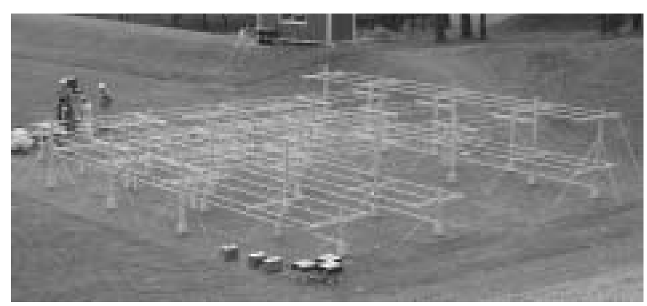


Fig. 4. 1/10 scale model of AIS

TABLE 2. SPECIFICATIONS OF MEASURING EQUIPMENT

Equipment	Manufacturer, Type	Specification
Voltage probe	Tektronix, P5100	DC~250MHz, Sensitivity: 100:1
Pulse generator	Velonex, Type360	Rise time: 20ns, Pulse width: 50ns~3ms, Maximum voltage: 2500V
Optical converter (E/O, O/E)	Sony-Tektronix, A6904S	DC~100MHz, Length: 200m, Input: ±50V~±0.2V, Output: ±1V
Digital storage oscilloscope	Lecroy, LC544DL	DC~500MHz, Sampling: 2GS/s

The calculated results by EMTP and FDTD method are compared with the measured results to confirm the validity of the proposed approach.

A. Applied Method of Pulse Voltage

A pulse generator (PG) is installed at the one end of the AIB. Applied voltage waveform is a step waveform with the rise time of 20ns. This rise time is equivalent to the lightning surge waveform with about 200ns in the actual lightning surge incoming into the AIS. This is equivalent to the surge waveform generated by the backflashover at the nearest tower. Figure 5 shows the voltage source circuit in this experiment.

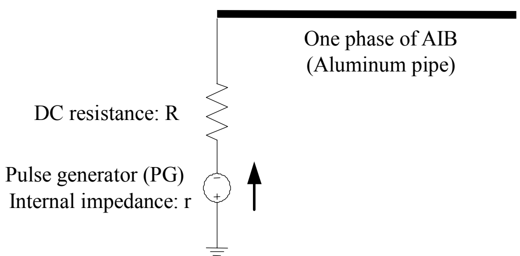


Fig. 5. Voltage source circuit

B. Measurement Method of Voltage

Figure 6 shows the voltage measurement circuit. In order to minimize the effect of the induction of measurement auxiliary wire, the wire is vertically led downward from the aluminum pipe to the ground. The voltage probe with high resistance and low capacitance is inserted between the measurement wire and the ground. The voltage probe and digital storage oscilloscope (DSO) are connected through the optical converter (E/O-O/E) to reduce the influence of electromagnetic noise.

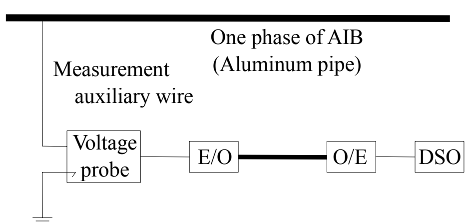


Fig. 6. Voltage measurement circuit

C. Voltage Measuring Points

Some measurement cases which can be made by combinations of main bus and branch bus (transmission line and transformer line) are carried out. Figure 7 shows an example case. Voltage waveforms are measured at five points in this experiment (voltage injection point, 1/4 length of AIB, middle point of AIB, 3/4 length of AIB, and transformer point).

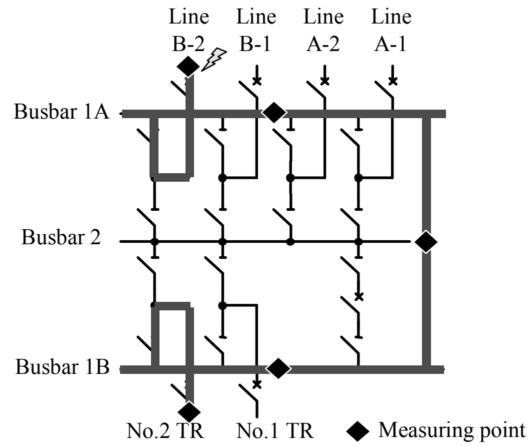


Fig. 7. Example case

D. Measurement of surge impedance of Alp-Bus

The measured surge impedance of the simple Alp-bus is compared with the theoretical one in order to check the validity of this experiment. The surge impedance of Alp-bus of the experimental circuit is measured by the voltage drop method.

In the circuit of Fig. 8, self and mutual surge impedances of the bus conductors are determined by equations (1) and (2) based on the experimental results.

Self-surge impedance: $$Z_o = \frac{V_2}{V_1 - V_2} \cdot R \qquad (1)$$

Mutual surge impedance: $$Z_m = \frac{V_3}{V_2} \cdot Zo \qquad (2)$$

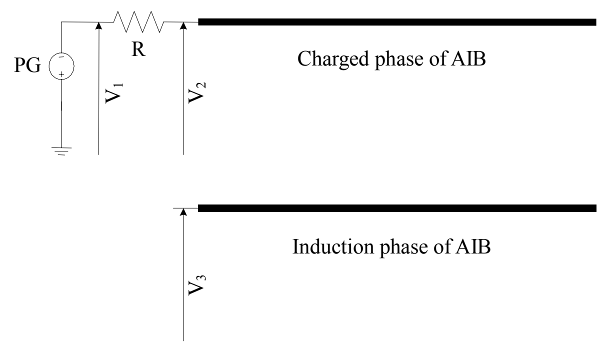


Fig. 8. Circuit of voltage drop method

The theoretical surge impedance of bus conductor is obtained from equations (3) and (4), when the configuration is shown in Fig. 9. [3]

Self-surge impedance: $$Z_o = 60 \ln \frac{2h_i}{r_i} \qquad (3)$$

Mutual surge impedance: $$Z_m = 60 \ln \frac{D_{ij}}{d_{ij}} \qquad (4)$$

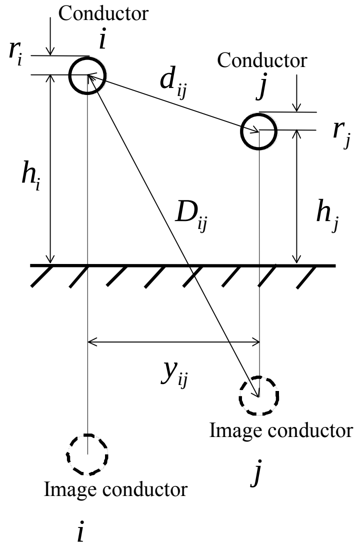


Fig. 9. Configuration of conductors

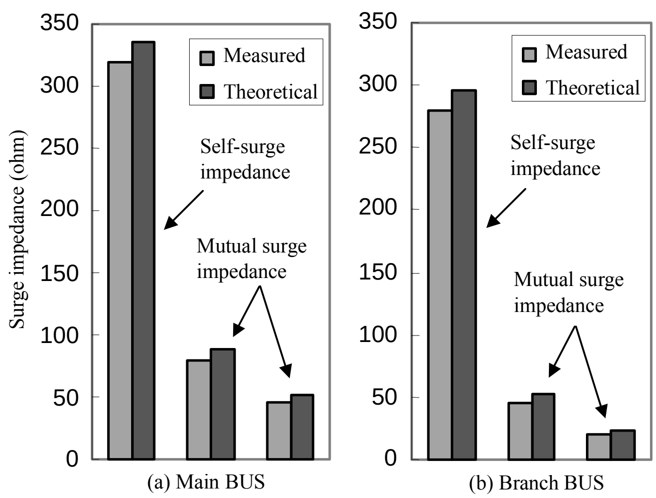


Fig. 10. Measured and theoretical values of surge impedance of conductors

A comparison of the measurement result and the theoretical value is shown in Fig. 10. The self-surge impedance obtained from the measurement is lower than the theoretical value by about 5%. The mutual surge impedance obtained form the measurement is lower than the theoretical value by about 10%. This difference may be derived from measurement error because some influence of measurement auxiliary wire and leakage resistance between the conductor and the supporting structure on the ground cannot be eliminated.

The measured and the theoretical values of the surge impedance of a bus conductor are lower than the standard surge impedance of 350Ω used in the S-CP model. In this fact, the estimated lightning overvoltage in the conventional model is higher than that in actual lightning fault. Therefore, it is suggested that the M-CP model is the best model for accurate lighting surge analysis for an AIS.

E. Analysis by FDTD Method

FDTD method[4][5] is one of the numerical electromagnetic analyzing algorithm and is based on Maxwell's equation. This method directly calculates the electrical and magnetic fields of cubic cells by discretizing the Maxwell's equation of electromagnetic field. It can analyze the electromagnetic transient phenomenon in a three-dimensional structure like bus conductors.

Inputting the configurations and electrical characteristics of the miniature model, the electromagnetic field for every derivative of time and space are calculated, and the voltage at each part is derived. FDTD calculation time, however, is very long (several hours), and it is impossible to analyze an electric circuit including lumped elements such as resistance, inductance, capacitance and arrester.

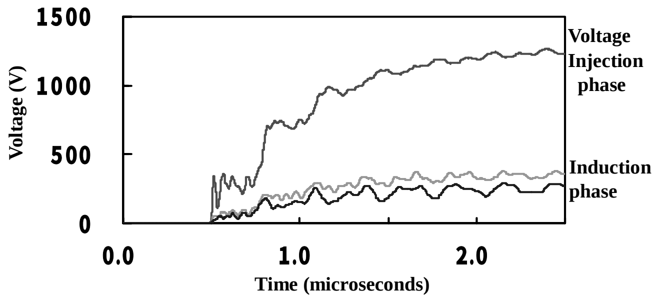
On the other hand, EMTP can calculate transient phenomenon in an electric circuit easily. EMTP replaces the electrical characteristics, such as surge impedance and propagation characteristic, to an electric circuit, and calculates transient phenomenon in a time domain. Its calculation time is very short (several seconds).

Then, the calculation results of these two analyses are compared with the experimental result in order to evaluate the difference between EMTP and FDTD method.

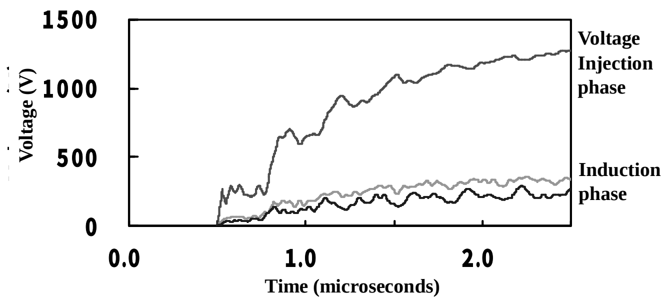
F. Comparison of Experimental Results and Calculated Results

Figure 11 and 12 show examples of measurement and calculated waveforms by FDTD method and proposed EMTP model. The comparison reveals following results:

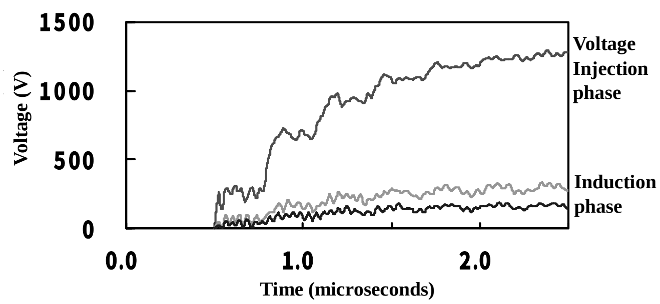
1. The calculation results (peak value and reflection time) are almost equal to the experimental results. Thus, the surge characteristic of the AIS can be determined accurately in analysis.
2. By considering the mutual coupling among bus conductors in the numerical analysis, it is possible to estimate an accurate injection voltage and induction phase voltages.
3. There is no remarkable difference between the analysis results of FDTD method and those of EMTP. Therefore, the proposed model has sufficient accuracy in practical use.



(a) Experimental result

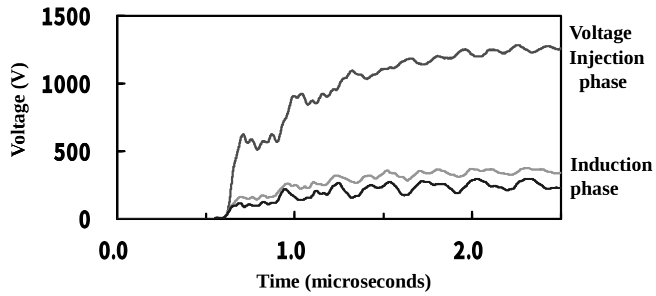


(b) Calculated result by FDTD method

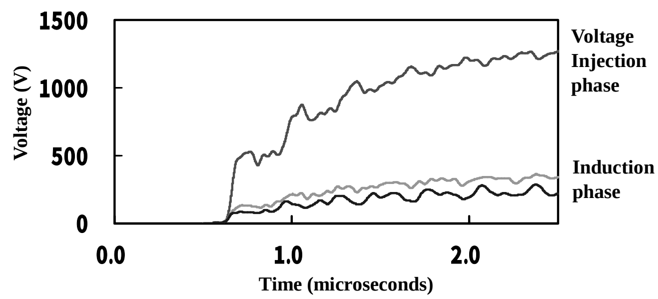


(c) Calculated result by EMTP

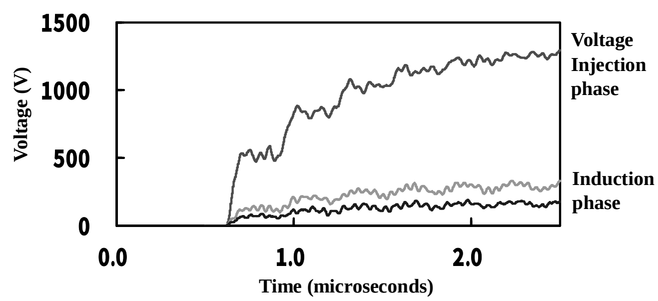
Fig. 11. Experimental and calculated results (Voltage applied point)



(a) Experimental result



(b) Calculated result by FDTD method



(c) Calculated result by EMTP

Fig. 12. Experimental and calculated results (Transformer point)

IV. Conclusions

The comparison between the calculation and the experiment can lead to the following conclusions;

(1) The estimated overvoltage in the single-phase constant parameter model is higher than the one in the multiphase constant parameter model. Thus, the lightning impulse withstand voltage level of a present air-insulated substation (AIS) can be reduced, if the proposed approach for the lightning surge analysis is applied. Then, the combination of the proposed model and high performance metal-oxide surge arresters can reduce LIWV level further.

(2) The result in the multiphase constant parameter model corresponds to the experimental and the finite-difference time-domain (FDTD) method results well. This result shows that the lightning overvoltage in air insulated bus conductors is lower than the one obtained in the conventional single-phase constant parameter model and that the multiphase constant parameter model is the best model for the accurate lighting surge analysis in an AIS.

(3) The surge impedance of a bus conductor used in the single-phase constant parameter model is higher than the real one. In order to calculate the lightning overvoltage accurately, it is necessary to consider the mutual coupling, the real position, and material characteristics of the air-insulated bus.

V. References

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VI. BIOGRAPHIES

Tatsuya Watanabe was born in Gifu, Japan, on February 14, 1972. He received his Bachelor's and Master's degrees in electrical engineering from Nagoya Institute of Technology, Japan, in 1994 and 1996, respectively. He joined Chubu Electric Power Corporation Inc. in 1996. Presently, he is mainly engaged in the design and analysis of substations. Mr. Watanabe is a Member of IEE of Japan.

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