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Estimation of Damage Rate of Electronic Watt-Hour Meters Caused by Transient Magnetic Field due to Direct Lightning Strokes to Distribution Line

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***Abstract*—In Japan, the introduction of smart meters into distribution systems has recently been accelerating. Since smart meters are low-voltage electronic equipment, they are considered to be vulnerable to disturbances such as lightning surge. In this study, we first experimentally examined the lighting failure of smart meters caused by a transient magnetic field. Then, we calculated the lightning damage rate of a smart meter due to a magnetic field by lightning surge analysis. To improve the lightning performance of smart meters, it is effective to ensure a suitable relationship between the bus conductor and the processing unit inside the smart meter.**

Keywords- electronic watt hour meter; distribution line; transient magnetic field; failure rate calculation

I. INTRODUCTION

In Japan, the introduction of smart meters into distribution systems has recently been accelerating [1]. Smart meters, installed in customer's houses, are highly functional electronic watt-hour meters (WHMs) with communication and switching functions. Smart meters are very important for achieving a future smart society.

However, since WHMs consist of electronic circuits operating at a low voltage, they are considered to be vulnerable to disturbances such as lightning surge. Thus, we have examined the failure of WHMs. In previous studies [2], we showed that the failure mechanisms of WHMs can be classified into the following three factors.

(i) Sparkover from line to line by lightning overvoltage

(ii) Burnout of power wire on printed circuit board by excess lightning current energy

(iii) Breakdown of processing unit caused by magnetic field generated by lightning current flowing through WHM.

However, the current Japanese test standard for WHMs only includes a lightning impulse voltage test and does not consider the lightning current energy and transient magnetic field. Therefore, to ensure the reliable supply of electricity in future distribution systems, it is important to consider lightning protection measures for WHMs.

In this study, we examined the lightning performance of WHMs with a metering function equivalent to that of the smart meters. We first experimentally examined the lightning performance of WHMs against transient magnetic field. Then, we calculated the lightning damage rate of WHMs due to direct lightning strokes to the distribution line.

II. OVERVIEW OF WHMS USED IN THIS STUDY

A. Circuit configuration of WHMs

Fig. 1 shows the circuit configuration of one of the WHMs used in this study. This WHM is a single-phase three-wire system and generally used in homes in Japan. There are six terminals in the WHM. The three terminals on the left (1s, 2s, 3s) are connected to the power supply, and the three terminals on the right (1L, 2L, 3L) are connected to the load. Inside the

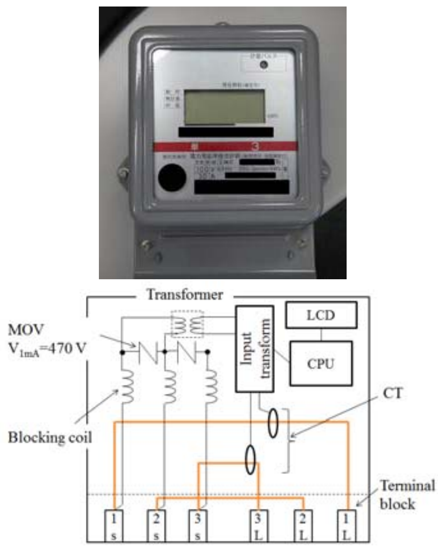


Fig. 1 Circuit configuration of electronic watt hour meter.

WHM, metal oxide varistors (MOVs, V_{1mA}=470 V) are installed between each phase (between 1s and 2s and between 2s and 3s) to suppress lightning overvoltage.

B. *Structure of WHM*

Fig. 2 shows the detailed structure of the two types of WHM (hereafter referred to as type A and type B) investigated in this study. The positional relationship between the processing unit and the WHM bus conductor is very different in type A and type B WHMs. Note that the 2s-2L bus is not shown in Fig. 2, because it is located inside the terminal blocks of the WHMs.

III. Failure Aspects of WHMs by Transient Magnetic Field

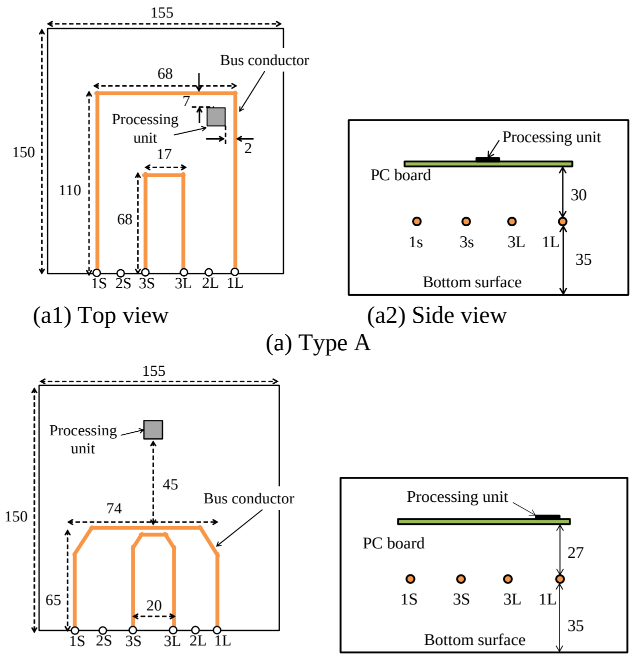
In this section, through the results of a lightning impulse test, we experimentally examined the failure of WHMs caused by a transient magnetic field.

A. *Experimental setup*

In this study, a lightning impulse current was directly injected into the bus conductor of each WHM using the 12 MV impulse generator (IG) in Shiobara testing yard of CRIEPI. Fig. 3 shows the equivalent circuit of the IG and the injection current waveform (wavefront duration: 0.5 µs, wavetail duration: 11 µs). Table 1 show the main test cases examined in this study. From the experimental results, we obtained the minimum failure value and its derivative *dI*/*dt*.

B. *Experimental results*

Table 2 shows the minimum values of the injected lightning impulse current when the WHM failed. The failure current of the type A WHM is much higher than that of the type B WHM. This is due to the positional relationship between the processing unit and the bus conductor inside the WHMs. In the type B WHM, since the processing unit is located inside the 1s-1L bus conductor, the processing unit is susceptible to a



(a1) Top view (a2) Side view

(a) Type A

(b1) Top view (b2) Side view

(b) Type B

Fig. 2 Layout of electronic WHMs used in this study. (unit in figures: mm).

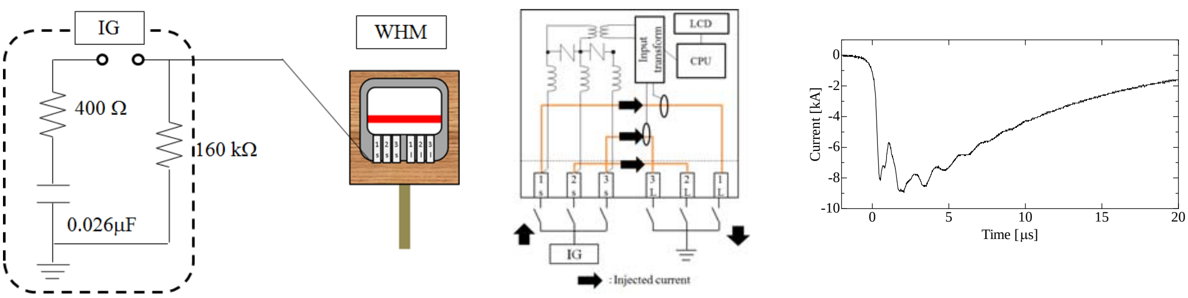
Table 1 Experimental circuit configurations.

Case No.	Injection phase	Grounding phase
Case I	1s, 2s, 3,	1L, 2L, 3L
Case II	1s	1L
Case III	2s	2L
Case IV	3s	3L

Table 2 Minimum failure currents of each WHM.

Case No.	Failure current [kA] (*dI*/*dt* [kA/µs])	
	Type A	Type B
Case I	18.7* kA<	9.1 kA (26.0 kA/µs)
Case II	18.2 kA (43.2 kA/µs)	3.1 kA (7.6 kA/µs)
Case III	18.7 kA*<	18.7* kA <
Case IV	18.7 kA*<	18.7* kA<

*18.7 kA: Maximum output current of IG



(a) Equivalent circuit of 12 MV IG (b) Test circuit (c) Injected current waveform

Fig. 3 Equivalent circuit of impulse generator and arrangement of test circuit.

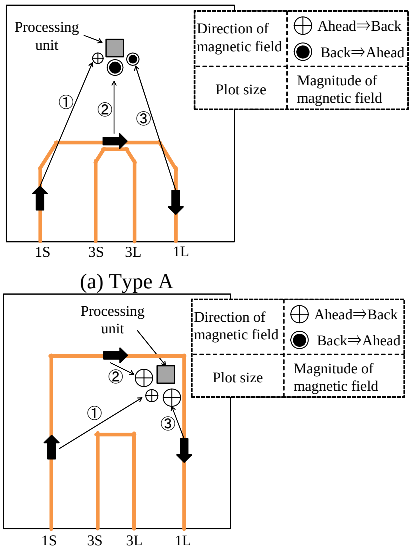


Fig. 4 Direction of magnetic field around processing unit when lightning current is injected to 1s -1L bus conductor.

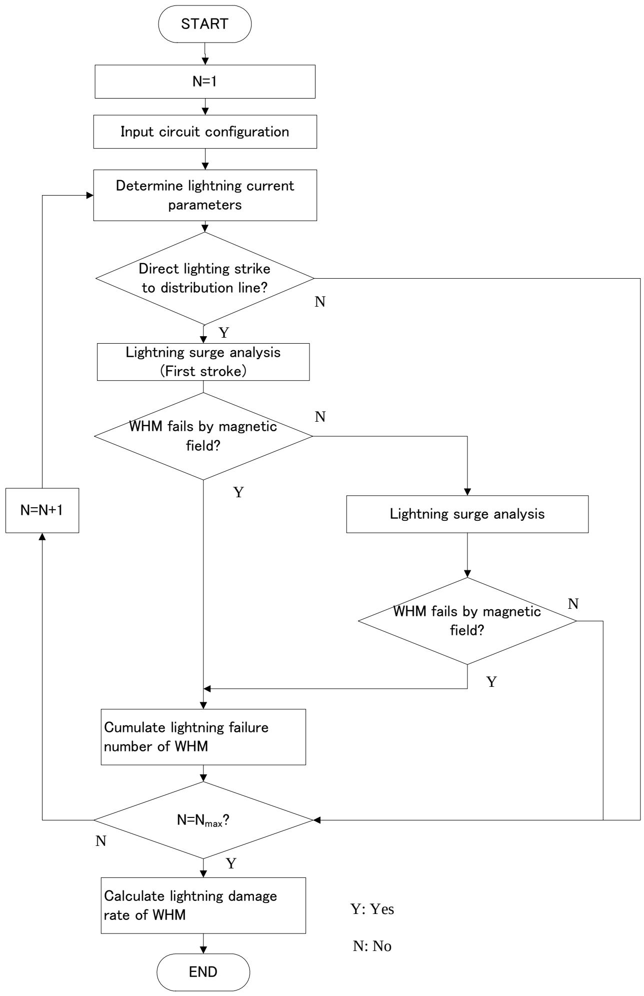


Fig. 5 Method of calculating lightning damage rate of WHM due to transient magnetic field.

transient magnetic field generated by the lightning current (Fig. 4(b)) and overvoltage induced around the processing unit. On the other hand, in the type A WHM, the processing unit is located outside of the bus conductor and there is a considerable distance between the processing unit and the bus conductor (Fig. 4(a)), meaning that the induced voltage around the processing unit is smaller than that in the type A WHM.

From these results, to improve the lightning performance of WHMs against a transient magnetic field, it was clarified that separating the bus conductor and the processing unit is effective.

IV. CALCULATION METHOD FOR DAMAGE RATE OF WHM BY TRANSIENT MAGNETIC FIELD

In the previous section, we experimentally determined the failure current of WHMs caused by a transient magnetic field. In this section, on the basis of the experimental results, we show the calculation method for the damage rate of WHM when a lightning stroke directly hits distribution lines. Fig. 5 shows a flow of the calculation of the damage rate of the WHM. This flow consists of the following A~C parts:

Part A: Decision of lighting surge analysis model

Part B: Decision of lighting current parameter and lightning strike point

Part C: Lightning surge analysis and damage rate calculation

In the following, we describe these parts in detail.

A. Part A: Decision of lighting surge analysis model

Fig. 6 shows the arrangement of the distribution line in this study. In this study, the distribution line (three-phase three-wire system, total route length: 1 km) is present in a unit area (area: 1 km square). In addition, a pole transformer is mounted on

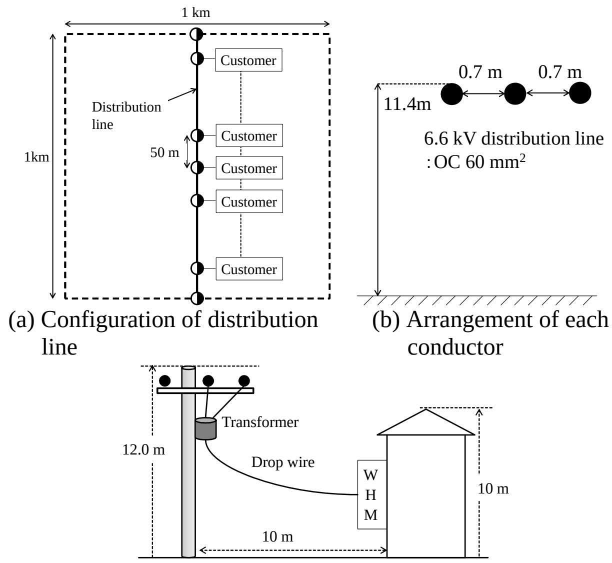


Fig. 6 Arrangement of distribution line used in this study.

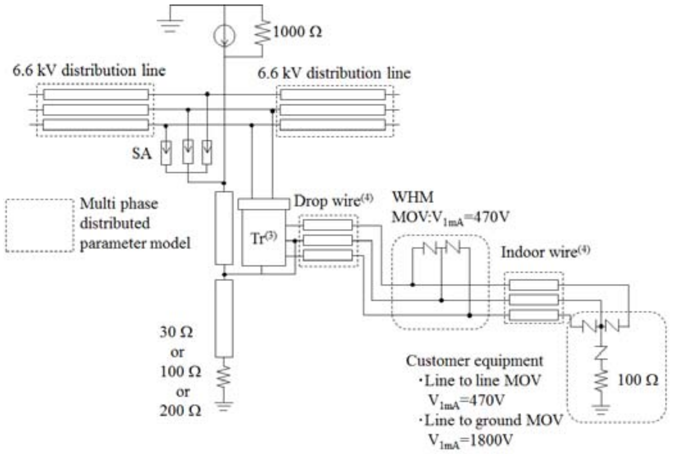


Fig. 7 Lightning surge analysis model of distribution line and customer equipment.

each reinforced concrete pole, and the secondary side of the pole transformer is connected to the WHM through a drop wire.

Fig. 7 shows the lightning surge analysis model of the distribution line and customer equipment. The WHM is simply modeled by MOVs (V_{1mA}=470 V). The pole transformer is modeled in accordance with [3], and the drop wire and indoor wire are modeled in accordance with [4]. The customer equipment is modeled by MOVs (line to line: V_{1mA}= 270 V, line to ground: V_{1mA}= 1800 V). The other analysis conditions are given in Table 3.

B. Part B: Decision of lighting current parameter

In this paper, the lightning current waveform is modeled by a ramp waveform, and the damage rates of the WHM in the case of negative lightning flashes are investigated. Table 4 shows the statistics of negative first strokes and subsequent strokes obtained by Berger et al. [5]. In the analysis, the correlation between the current peak and the wavefront duration is taken into account. In the case of negative first strokes, the correlation coefficient between the current peak value and the wavefront duration is 0.37, and for the subsequent strokes, the correlation coefficient is 0.28 [5]. The wavetail duration is fixed to 70 μs.

Table 3 Calculation parameters used in this study.

Item	Parameter
Distribution line	
6.6 kV distribution line	Cu-OC 60 mm^2
Span length	50 m
Drop wire, Indoor wire	DV3.2 mm, VVF2.0 mm[4]
Drop wire, Indoor wire length	10 m
Distributed parameter model	Constant frequency Calculated frequency：100 kHz
Ground resistivity	100 Ωm
Reinforced concrete pole	
Surge impedance	250 Ω
Propagation velocity	300 m/μs
Ground resistance	30/100/200 Ω
Pole transformer	Proposed model in [3]
Other	
Lightning current waveform	Ramp wave
Lightning path impedance	1000 Ω

Table 4 Negative return stroke current parameter obtained by Berger.

		95 % value	50 % value	5 % value
First stroke	Peak [kA]	14	30	80
	Front duration [μs]	1.8	5.5	18
Subsequent stroke	Peak [kA]	4.6	12	30
	Front duration [μs]	0.22	1.1	4.5

In this paper, the occurrence frequency of direct lightning strokes to the distribution line is calculated by the following procedure. First, the lightning strike point in the calculation area (Fig. 6(a)) is determined by the Monte Carlo method. From the current peak value of the first stroke determined above, the critical distance is evaluated by (1) and (2), which is based on the electrogeometrical model in Fig. 8 [6].

$$r_S = r_c = 10 I^{0.65} \tag{1}$$

$$r_G = 0.9 r_S \tag{2}$$

Here,

r_d, r_c [m]: Striking distance to the distribution line and customer house

r_g [m]: Striking distance to the ground

I [kA]: Lightning peak current

H_d [m]: Height of distribution line

H_c [m]: Height of customer house

C. Part C: Lightning surge analysis and damage rate calculation

In the case that a lightning flash becomes a direct lightning stroke to the distribution line, we carry out surge analysis and calculate the lightning current flowing through the bus conductor of the WHM by XTAP, which is a transient analysis program developed by CRIEPI [7]. When the wavefront

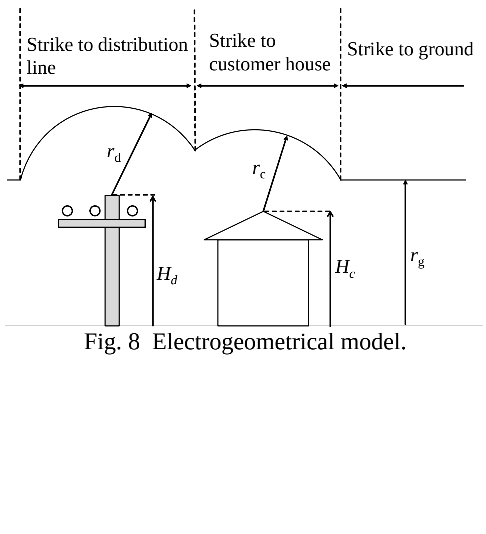


Fig. 8 Electrogeometrical model.

steepness *dI/dt* of the lightning current flowing through the 1s-1L bus conductor exceeds the threshold value shown in Table 2, we judge that the WHM fails as a result of the transient magnetic field. At this time, the multiplicity in the flash is assumed to be 2, and if a fault is not caused by the first stroke, we carry out the calculation for the subsequent stroke to determine whether a fault occurs.

On the basis of the above calculation results, we finally calculate the damage rate of the WHM by a transient magnetic field. In this paper, the damage rate of the WHM is defined as the annual damage frequency per WHM, which is represented by the following formula:

$$P = \frac{F}{N} * \frac{1}{S} * GFD \tag{3}$$

Here,

P: Damage rate of WHM [number/unit/year]

F: Number of instances of damage of WHM [number]

N: Number of calculation [number]

S: Number of WHMs in calculation area [unit/ km^2]

GFD: Ground flash density [number/km^2/year]

In this paper, *N* is set to 3000, and *GFD* is assumed to be 1.

V. Calculation Results

A. *Lightning current flowing through bus conductor*

Fig. 9 shows the cumulative frequency distribution of the lightning current flowing through the 1s-1L bus conductor of the WHM in the case that the grounding resistance of the pole transformer is 30 Ω. According to this figure, although the current peak of the first stroke is larger than that of the subsequent stroke, the current wavefront steepness of the subsequent stroke is larger than that of the first stroke. Since the induced overvoltage is proportional to the wavefront steepness, the damage rate of the WHM due to the magnetic field of the subsequent stroke is larger than that of the first stroke.

Fig. 10 shows the relationship between the lightning current flowing to the 1s-1L bus conductor and grounding resistance of the pole transformer. The lightning current increases as the grounding resistance of the distribution line increases.

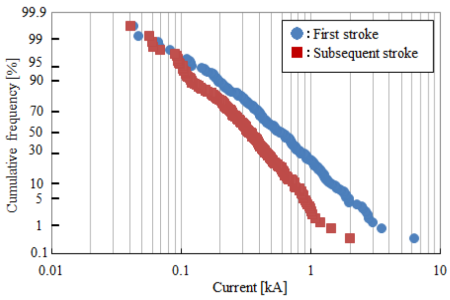
B. *Lightning damage rate of WHM due to magnetic field*

From the results of the lightning surge analysis, we calculated the damage rate of the WHM by a transient magnetic field when lightning directly hits the distribution line. Fig. 11 shows the calculation results for the damage rate of the type B WHM due to magnetic field. The magnetic damage rate associated with the subsequent stroke is higher than that associated with the first stroke. Also, the higher the grounding resistance of the pole transformer, the higher the damage rate.

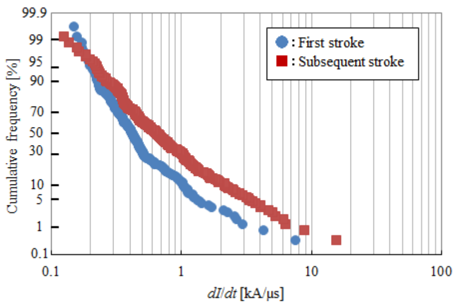
VI. Conclusion

In this paper, to consider the effectiveness lightning protection measures of smart meters, we investigated the lightning performance of WHMs against a transient magnetic field. The main results are shown below.

(1) When a lightning current flows into the bus conductors of the WHM, induced voltage generates around the processing unit. This voltage depends on the structure

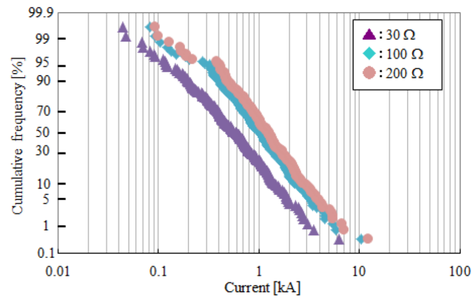


(a) Peak value

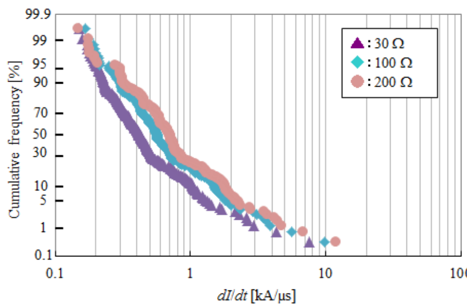


(b) *dI/dt*

Fig. 9 Relationship between the lightning current parameter and current flowing into 1s- 1L bus conductor (grounding resistance of distribution line: 30 Ω).



(a) Peak value



(b) *dI/dt*

Fig. 10 Relationship between the grounding resistance of pole transformer and current flowing into 1s- 1L bus conductor (first stroke).

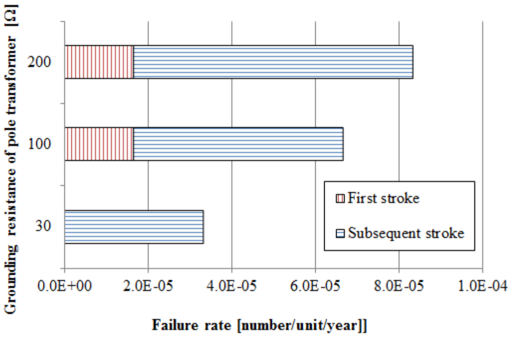


Fig. 11 Calculation result of magnetic failure rate of type B WHM.

of the WHM, and decreasing this voltage improves the lightning performance of WHMs.

(2) From the results of lightning surge analysis, we calculated the damage rate of a WHM by a transient magnetic field when lightning directly hits the distribution line. The magnetic failure rate associated with the subsequent stroke is higher than that associated with the first stroke. Also, the higher the grounding resistance of the distribution line, the higher the damage rate.

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