Paper Number: 09GM0030, IEEE PES General Meeting 2009, July 28, 2009

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Experimental Study on Lightning Surge Response of 500kV Transmission Tower with Overhead Lines

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I. Introduction

- The prediction of lightning performance is very important for the insulation design of electric power and telecommunication systems.
- Lightning surge phenomena are determined by many parameters.
- In particular, the tower surge response is a significant parameter for determining the lightning performance of transmission lines.

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Background of this study

- A number of experimental and theoretical studies on the tower surge response have been carried out.
- Most of these studies used freestanding structures such as scale models or actual transmission towers.
- However, the surge response of towers with overhead lines is a significant parameter for the estimation of the lightning performance of transmission systems.
- It is necessary to investigate the surge response of towers with ground wires and phase wires experimentally and theoretically.

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Main subjects of this study

1. This paper presents the measurement of the lightning surge response of a 500kV transmission tower with overhead lines.
2. The effects of the direction of the injection current on the measured results are investigated.
3. Furthermore, the characteristics of current flowing into the ground wires and the tower are investigated to estimate the surge response of a tower with overhead lines.
4. On the basis of these results, the tower surge impedance is estimated.

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II. Measuring Method of Tower Surge Response

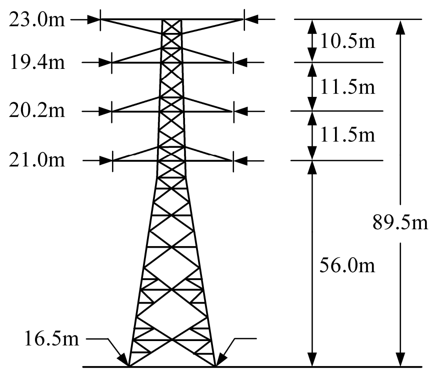

Fig. 1. Structure of the No. 25 tower.

- The measured tower has a 500kV double-circuit transmission line and is 89.5m high.
- The steady-state resistance of the No. 25 tower foot is 6.5Ω.
- This tower is equipped with 3 ground wires and phase wires with 4 subconductors.

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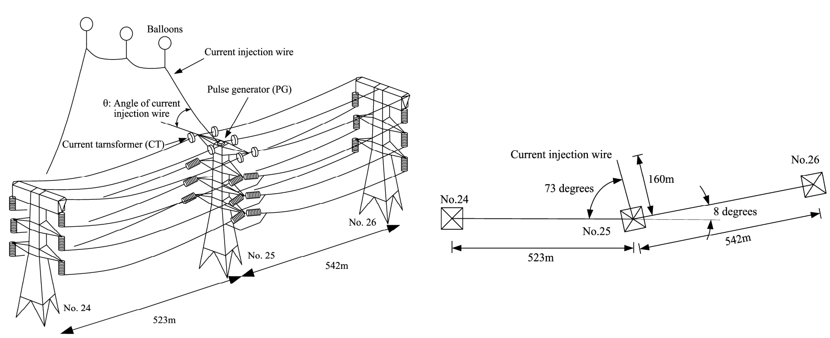
Current Injection Wire and Transmission Lines Setup



(a) Configuration of transmission line and current injection wire

(b) Arrangement of transmission line and current injection wire

Fig. 2. Setup for measurement of tower surge response.

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Measuring Equipment Setup

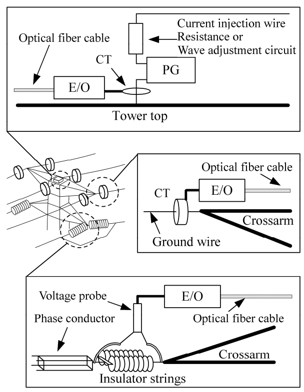

Fig. 3. Setup of measuring equipment on the tower.

TABLE I
Specifications of Measuring Equipment

	Equipment	Frequency	Sensitivity
Injection current sensor	Pearson 411	1Hz-20MHz	0.05V/A (with 50Ω)
GW current sensor	Pearson 3525	5Hz-15MHz	0.05V/A (with 50Ω)
Tower foot current sensor	Sankosha	1kHz-3MHz	0.1V/A (with 50Ω)
Voltage sensor	Tektronix P5100	DC-250MHz	100:1
E/O-O/E	Sony Tektronix A6904S	DC-100MHz	Max: ±50V
Recording equipment	Lecroy LC554DL	DC-500MHz	Max: 2GS/s 8bit/word

All waveforms are measured simultaneously using E/O-O/E system.

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III. Calculation Method of Step Response and Surge Response

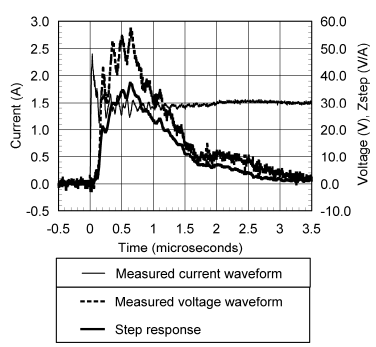

Fig. 4. Typical measured voltage and injection current waveforms and ideal step response.

Calculation of the ideal step response $Z_{step}(t)$:

$$Z_{step}(t) = L^{-1}\left[\frac{1}{s}\cdot\frac{L\{V(t)\}}{L\{I(t)\}}\right](\mathrm{V/A})$$

Calculation of surge response Z_{Tf}:

$$Z_{Tf} = \frac{V(t)}{I_P}(\mathrm{V/A})$$

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IV. Measuring Conditions of Tower Surge Response

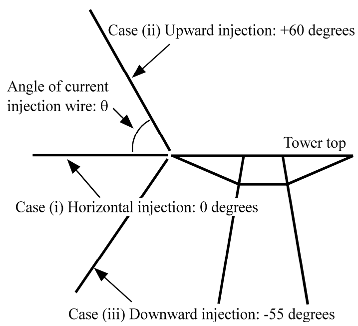

Fig. 5. Angle of current injection wire.

- Case (i): The current injection wire is kept horizontal.
- Case (ii): The current injection wire is stretched upward at an angle of 60 degrees to the horizontal.
- Case (iii): The current injection wire is stretched downward at an angle of -55 degrees.

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V. Measured Results of Tower Surge Response

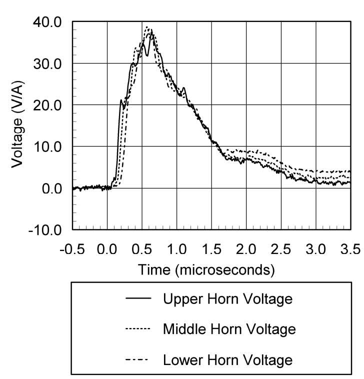

Fig. 6. Step response of voltages across insulator strings (case number: Case (i), angle of current injection wire: 0 degrees)

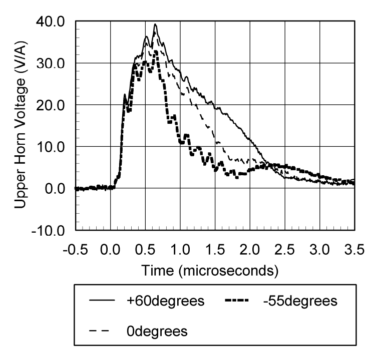

Fig. 7. Comparison of upper horn voltages for various angles of current injection wire.

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Effect of Current Injection Angle

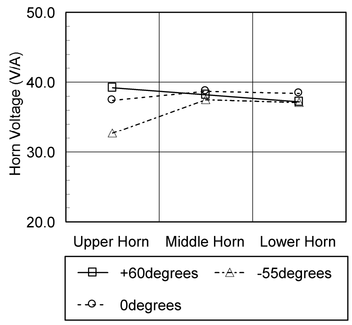

Fig. 8. Comparison of peak voltage at each arcing horn.

- The direction of the injection current has a significant effect on the upper horn voltage.
- For middle and lower horn voltages, the direction has a slight effect.
- The difference among the horn voltages due to the direction of the injection current is approximately 5%.
- These results are expressed as follows:

$$V_T(K-C) = \text{constant}$$

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Measured Results of Propagation Velocity inside Tower

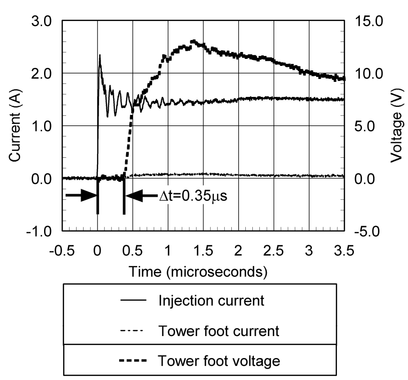

Fig. 9. Measured results of injection current, tower foot current and tower foot voltage (case number: Case (i), angle of current injection wire: 0 degrees).

- Propagation velocity inside the tower: 85%(=89.5m/0.35μs/300m/μs) to 90%(=94.5m/0.35μs/300m/μs) of the speed of light.
- However, the propagation velocity inside the tower was considered to be the speed of light.
- These discrepancies should be examined in a future study.

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Effect of Rise Time of Lightning Impulse Current

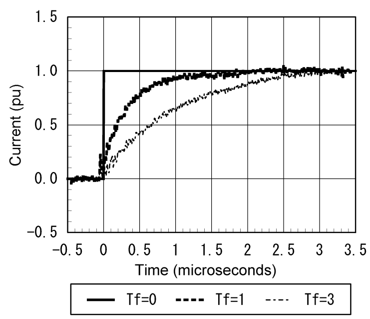

Fig. 10. Injection current waveforms with rise times (T_f) of 0, 1, and 3µs.

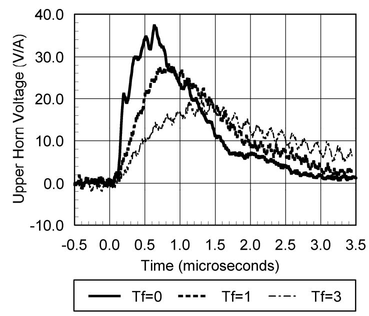

Fig. 11. Measured voltage waveforms across upper insulator strings corresponding to rise times (T_f) of 0, 1, and 3µs (case number: Case (i), angle of current injection wire: 0 degrees).

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Characteristics of Current Flowing into Ground Wires

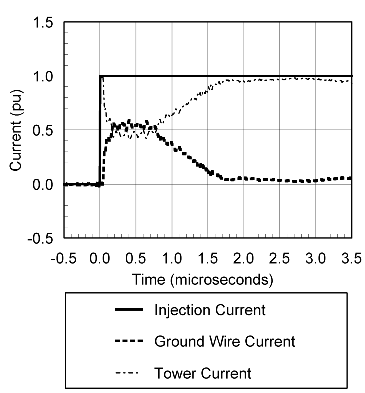

Fig. 12. Current waveforms flowing into the ground wires and the tower (case number: Case (i), angle of current injection wire: 0 degrees).

- The current flowing into the ground wires is almost constant until approximately t=0.7µs.
- From this, the surge impedance of the ground wires is almost constant until the reflection current from the tower foot reaches the tower top.
- After the reflection current reaches the tower top, the tower current increases to the injection current.
- From this, the equivalent impedance (input impedance) of the tower decreases due to the reflection wave from the tower foot.

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Effect of Current Injection Angle

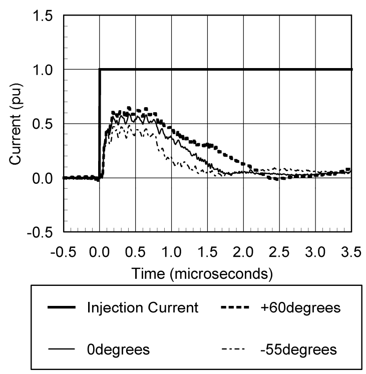

Fig. 13. Results of the ground wire current for various angles of current injection wire.

- The ground wire current increases in proportion to the current injection angle.
- However, for the measured cases, the ground wire current is almost constant until approximately t=0.7μs.
- From this, the tower surge impedance varies with the angle of the injection.
- These phenomena are important for the modeling of the towers under actual lightning surge.

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VI. Evaluation of Tower Surge Impedance

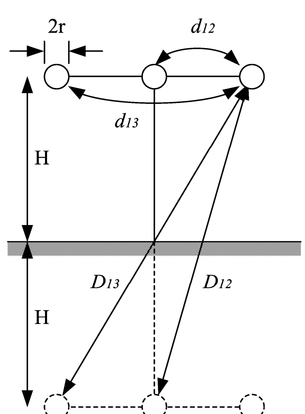

Fig. 14. Arrangement of ground wires.

$$\text{Self-surge impedance}: Z_{ii} = 60 \ln \frac{2H}{r} (\Omega)$$

$$\text{Mutual surge impedance}: Z_{ij} = 60 \ln \frac{D_{ij}}{d_{ij}} (\Omega)$$

The total surge impedance Z_g of the ground wires is given as follows:

$$Z_g = \frac{Z_{11}^2 + Z_{11} \cdot Z_{13} - 2Z_{12}^2}{3Z_{11} - 4Z_{12} + Z_{13}} (\Omega)$$

The total surge impedance of the combined ground wires is approximately 296Ω.

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Equivalent Circuit

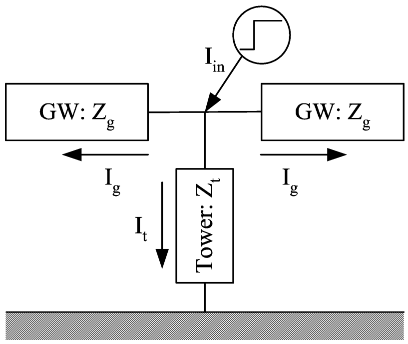

Fig. 15. Equivalent circuit of No. 25 tower with ground wires.

- In TEM mode, the relationship between the currents flowing into the ground wire and the tower is summarized as follows:

$$I_{in} = 2I_g + I_t$$
$$V_T = Z_t \cdot I_t = Z_g \cdot I_g$$

- The tower surge impedance is estimated as follows:

$$Z_t = Z_g \cdot \frac{I_g}{I_t} (\Omega)$$

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Estimated Results of Tower Surge Impedance

Table II Estimated Results of the Tower Surge Impedance

Case Number	2Ig (pu)	It (pu)	Zg (Ω)	Zt (Ω)
Case (i): Angle 0degrees	0.55	0.45	296	181
Case (ii): Angle +60degrees	0.6	0.4	296	222
Case (iii): Angle -55degrees	0.4	0.6	296	99

- From the table, the tower surge impedance depends on the direction of the injection current.
- However, these results are obtained experimentally and the assumption used in the calculation is realized on TEM mode.
- Detailed study of these experiment results will be carried out in a future study.

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VII. Conclusions

1. The measured peak voltages across the insulator strings at each crossarm were almost the same and independent of the angle of the current injection wire. However, the width of the voltage waveforms depended on the direction of the injection current.
2. The propagation velocity inside the tower was 85-90% of the speed of light.

VII. Conclusions (cont.)

3. The peak value of the measured waveforms decreased in inverse proportion to the rise time of the lightning current waveform.
4. The current flowing into the ground wires depended on the direction of the injection current. The tower surge impedance depends on the angle of the current injection wire if the surge impedance of the ground wires is constant.

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VII. Conclusions (cont.)

5. The tower surge impedance depends on the direction of the injection current. In the determination of the tower surge impedance under actual lightning conditions, the influence of the lightning path angle should be considered.

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