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Experimental and Analytical Studies on Lightning Surge Response of 500kV Transmission Tower

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I. Introduction

- The prediction of lightning performance is very important for the insulation design of 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.

Background of this study

- The experimental studies using scale models, as well as the theoretical studies, clearly show that the surge response of a transmission tower depends on the angle and direction of current injection.
- However, this has not yet been fully verified for actual transmission towers.
- Furthermore, the surge response generated by a vertical lightning stroke was not estimated in the previous studies.

Main subjects of this study

1. This paper presents experimental and analytical studies on the lightning surge response of a 500kV transmission tower without overhead lines.
2. To consider the influences of the angle and direction of current injection, the lightning surge response is measured for different current wire arrangements.
3. The experimental results are compared with the results calculated using the finite-difference time-domain (FDTD) method.
4. Furthermore, the surge response under a vertical lightning stroke is estimated by numerical electromagnetic field analysis.

II. Experiment on Lightning Surge Response of Transmission Tower

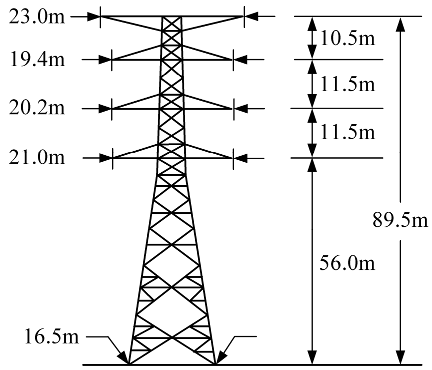
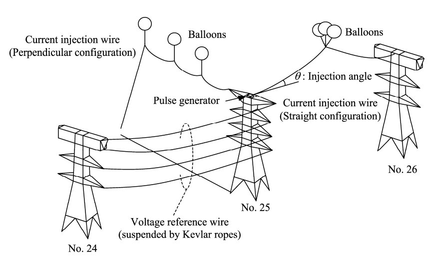


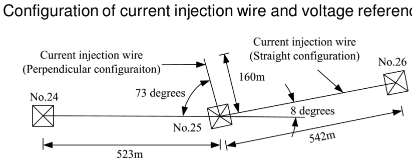
Fig. 1. Structure of the No. 25 tower.

- 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.

Measuring Wires Setup



(a) Configuration of current injection wire and voltage reference wires



(b) Arrangement of current injection wire and voltage reference wires

Fig. 2. Measuring setup of tower surge response.

- In this measurement, the direct method is adopted.
- The voltage reference wires are strung from No. 24 tower to No. 25 tower.
- In the straight configuration, the current injection wire is strung from No. 26 to No. 25 tower.
- In the perpendicular configuration, the current injection wire is set almost perpendicular to the voltage reference wires on the horizontal plane.

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Measuring Equipment Setup

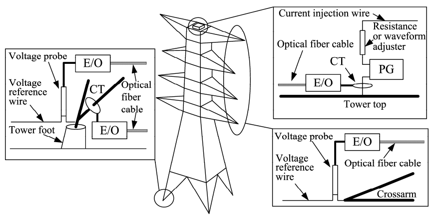

Fig. 3. Setup of measuring equipment on the tower.

TABLE I
Specifications of Measuring Equipment

	Equipment	Frequency	Sensitivity
Injection current sensor	Pearson 411	1Hz-20MHz	0.05V/A (with 50Ω)
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 LC334A	DC-500MHz	Max: 500MS/s 8bit/word

- All waveforms are measured simultaneously using electro-optical (E/O) and optical-electro (O/E) system.

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Calculation Method of Step Response and Surge Response

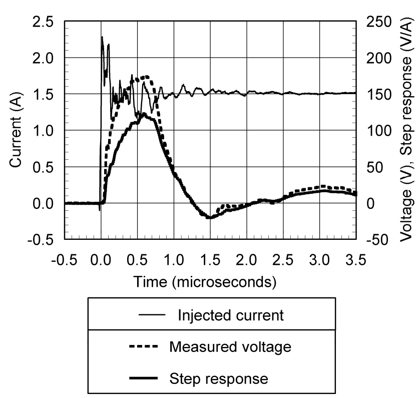

Fig. 4. Typical measured voltage and injection current waveforms and ideal step response.

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

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

Calculation of surge response Z_{Tf}:

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

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Experimental Results
1) Step Response of Transmission Tower

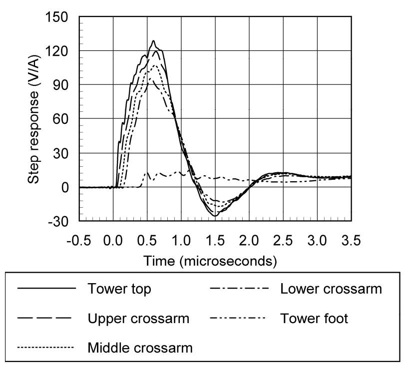

Fig. 5. Step response of each part of the tower (angle of current injection: 0 degrees, position of current injection wire: straight configuration)

- The measured results at the tower top is approximately 130V/A.
- This result is almost the same as the previous measured results with a similar configuration.
- The measured propagation velocity inside the tower is approximately 90% of the speed of light.

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Experimental Results
Effect of Current Injection Wire Angle

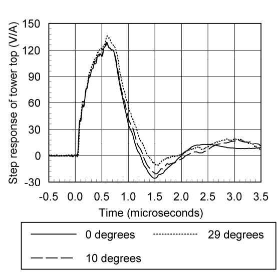

Fig. 6. Variation of step response at tower top with angles of current injection in straight configuration.

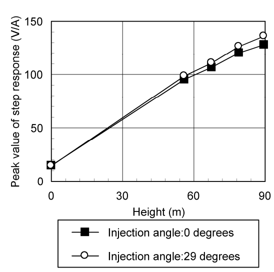

Fig. 7. Peak value of step response at each part of tower in straight configuration.

- The observed peak value of the tower surge impedance increases with the angle of current injection.
- From this, the injection angle of the return stroke should be considered in the estimation of the tower surge response.

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Experimental Results
2) Influence of Direction of Current Injection Wire

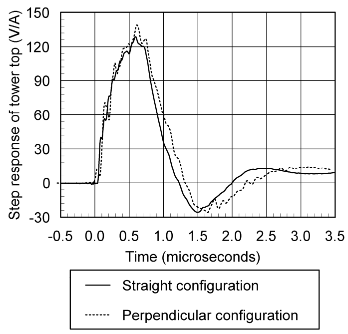

Fig. 8. Comparison of step response between straight configuration and perpendicular configuration (angle of current injection: 0 degrees).

- The observed peak value in the perpendicular configuration is higher than that in the straight configuration.
- From this, the direction of injection current should be considered in the estimation of the tower surge response.

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Experimental Results
3) Influence of Rise Time of Lightning Impulse Current

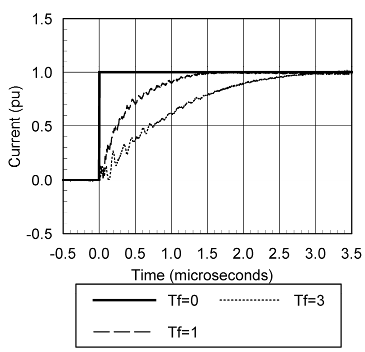

Fig. 9. Injected current waveforms with rise times (T_f) of 0, 1, and 3µs.

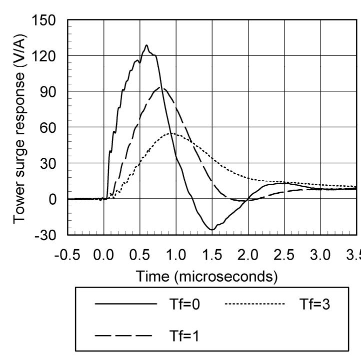

Fig. 10. Tower surge responses at tower top corresponding to rise times (T_f) of 0, 1, and 3µs (angle of current injection: 0 degrees, position of current injection wire: straight configuration)

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III. Analysis of Lightning Surge Response of Transmission Tower

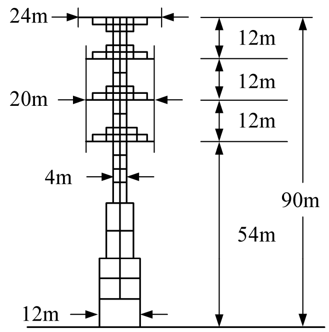

Fig. 11. Side view of a model tower simulating the 500kV double-circuit tower shown in Fig. 1 using the FDTD method.

- Analysis of the tower surge response is performed by the FDTD method.
- The FDTD method used in this paper is formulated in an orthogonal coordinate system.

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Configuration of Wires

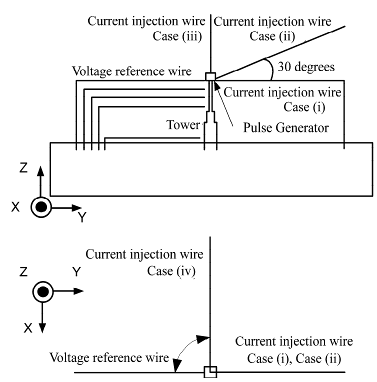

Fig. 12. Configurations of current injection wire and horizontal voltage reference wires used in the FDTD simulation.

The following arrangements are considered:

- Case (i): The current injection wire is kept horizontal along the Y-axis.
- Case (ii): The current injection wire is stretched upward at an angle of 30 degrees to the horizontal on the YZ-plane.
- Case (iii): The current injection wire is kept vertical along the Z-axis.
- Case (iv): The current injection wire is kept horizontal along the X-axis.

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FDTD Calculated Results of Surge Response

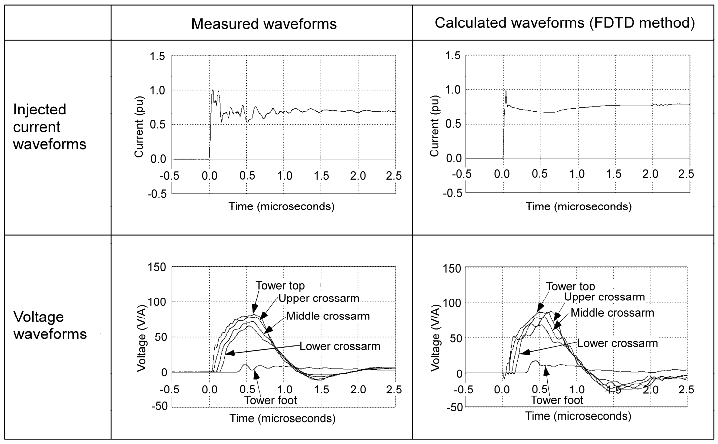

Fig. 13. Measured and calculated waveforms of injected current and voltage at various parts of transmission tower (case number: Case (i))

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Comparison between Measurement and Calculation

TABLE II Measured and Calculated Tower Surge Responses (Unit: V/A)

Case		Voltage of crossarms			
		Tower top	Upper arm	Middle arm	Lower arm
(i)	Measured results	128	120	106	95
	Calculated results	130	129	118	101
(ii)	Measured results	136	126	111	99
	Calculated results	141	141	129	108
(iii)	Measured results	–	–	–	–
	Calculated results	167	163	150	127
(iv)	Measured results	141	133	117	104
	Calculated results	146	144	135	115

- The case of vertical current injection (Case (iii)) is approximately 30% higher than the case of horizontal current injection (Case (i)).
- These results are of significance in modeling the tower surge response.

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IV. Conclusions

1. The measured surge response using the actual transmission tower, as well as that using the scale model, depends on the configuration of the current injection wire.
2. The peak value of the measured waveforms decreases in inverse proportion to the rise time of the lightning current waveform.
3. The measured current propagation velocity inside the tower was approximately 90% of the speed of light.

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IV. Conclusions (cont.)

4. The measured results were followed by FDTD method. The calculated surge responses agreed with the measured surge responses.
5. The surge response in the case of vertical current injection was approximately 30% higher than that in the case of horizontal current injection. These results are a significant factor in modeling the surge response of a transmission tower under an actual lightning stroke.