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Analysis of Response of a Guyed FM Radio Broadcasting Tower Subjected to a Lightning Strike

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***Abstract*—This paper reports the results of computer simulations of a telecommunication tower located in a high flash density region and subjected to lightning strikes. This study is a response to lightning incidents which occurred within a few erected guyed towers in several locations in the region, and which resulted in severe damage to the low-voltage (LV) communication equipment connected to the tower. The aim is to elucidate the possible rea ons that led to such damage and recommend protection measures to improve lightning performance. Using a realistic geometric representation of the tower, frequency-domain computations are carried out using frequencies representative of the typical lightning current, taking into account the propagation phenomena along the tower. A partial element equivalent circuit (PEEC) approach is used to compute the ground potential rise (GPR) at the surface of conductors and inductively-induced potentials and currents on adjacent LV communication cable. The results show that, depending on the shape of the lightning current, large potential differences in excess of the maximum withstand level of the insulation may occur between the cable core and cable sheath. Mitigating measures to reduce both the induced overvoltages and to improve grounding are suggested.**

Keywords- Lightning, radio broadcasting tower, ground potential rise; frequency domain; ground surface potential, induced overvoltage, grounding.

I. INTRODUCTION

Lightning flashes to telecommunication towers can cause damage to both the tower structure and adjacent low-voltage systems, resulting in service interruption and economic loss. Direct strikes to structures can cause physical damage due to lightning current effects, and sparks caused by induced overvoltages, and/or failure of electronic systems due to lightning electromagnetic pulse (LEMP). Injury to living beings by electric shock due to step and touch voltages resulting from resistive and inductive coupling is also a possible consequence of the lightning flash. The IEC international standards [1- 3] provide general principles, and requirements for protection measures of structures and internal electronic systems within structures.

In remote suburban regions in Indonesia, with difficult terrain and/or limited transport resources, guyed towers are frequently used by indigenous communities to support local radio broadcasting stations. As opposed to general commercial radio, radio stations in these areas are purposed as basic means of communication for information sharing such as social events and job scheduling information at palm oil plantations. The region has a tropical climate and lies on the equator. It is considered as having one of the highest keraunic levels, where about 270 thunderstorm-days are recorded per year [4]. The average isokeraunic level [5] in the period between 1991 and 2006 was 37.6–50 in Sumatra Island. In southern Kalimantan, the isokeraunic number was in the range 50-100. According to Hidayat and Ishii [6], the maximum ground flash density in Java Island is about 16 flashes per km^2 with measured lightning currents having 26 kA median amplitudes. Figure 1 shows the isokeraunic map for Indonesia between 1991 and 2006 [5]. Between 2009 and 2014, local FM radio broadcasting stations were installed in various suburban places, indicated by light blue dots in Figure 1. During this period, six lightning strikes were reported. The locations of struck towers are indicated by dark blue dots in Figure 1. In these cases, some reports indicated that all radio equipment was damaged, with burning of the PCB module in the FM amplifier, and melting of the connector from coaxial cable to the antenna. Generally, commercial radio stations use a three-leg self-supporting tower (SST) to support the antenna, but for economic reasons, three-leg guyed towers are used instead.

Previous studies investigating the impact of lightning strike on telecommunication towers mostly studies focused on self-supporting towers. Potential hazards due to GPR, overvoltage transients, and induced effects in SST and its neighborhood was investigated, with report of damages in electronics and radio base station caused by lightning strike [7, 8]. In [9], the results of simulation of lightning strike to a GSM Base transceiver station (BTS) using field theory in the frequency domain were reported. Recently, the authors of [10] investigated the transient behavior of a bridge and transient potential in its vicinity using the electromagnetic field theory approach.

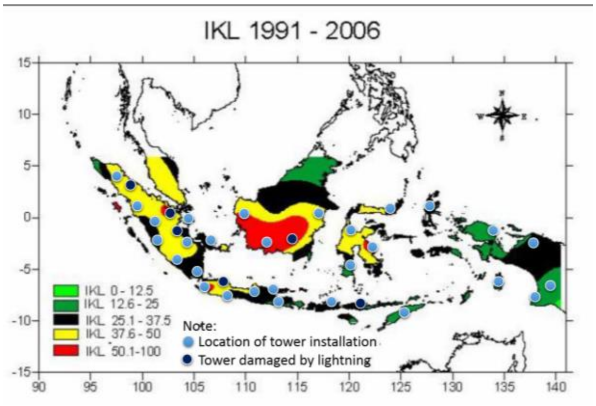


Figure 1. Lightning isokeraunic level in Indonesia adapted from [2]

The aim of this paper is investigate the impact of lightning strike to a guyed tower in the frequency domain. The XGSA_FD module of the XGS Lab package [11] is used for the computation. It is based on a hybrid approach involving the solution of Helmholtz electromagnetic field equations, and a partial equivalent circuit model for computing the distributions of currents, potentials and leakage currents. Hybrid methods may be used at low frequency [12] and at high frequency [13], and are very useful for an engineering purpose because they are accurate and flexible, and can allow an easy way to consider additional external parameters such as electromotive forces, currents, and impedances. In this work, computations are performed at each equivalent frequency of positive, negative and subsequent lightning current, taking into account the frequency dependence of soil parameters. Nonlinear effects, such as soil ionization and other thermal effects are neglected.

II. Modelling Of Tower Structure And Low-Voltage Radio Equipment

A. Structure

The guyed tower is modeled using AutoCAD 2016 and shown in Figure 2. Each component of the tower (wire, pole, brace, anchor...) is represented by a cylindrical conductor whose cross-section is determined such that it dissipates an equivalent power as that of the actual cross-section of the tower metalwork. The tower geometry is a uniform triangular prism of 50m height and 50cm base, with a lattice construction. It consists of two stacks of 5m-height each and ten stacks of 4m-height each. The bottom five stacks are supported by 3 sets of 5 stranded inner guy-wires made of 10mm diameter stainless steel wire, attached to each top corner of the stack and ground-anchored at a distance of 7 m from the tower center. The upper ten stacks are supported by 3 sets of 7 guy-wires of similar size and material, with anchors at 17 m from the center. A total of 36 guy-wires support the entire structure and it is designed to meet the load requirements.

B. Lightning protection system

The lightning protection system (LPS) of the structure consists of a 1-m lightning copper rod of 20 mm diameter, a copper down lead conductor of 16mm diameter placed inside a PVC duct and bonded to the tower at the top, and a 10-m diameter horizontal grounding ring made of 16 mm-diameter copper wire, buried at 1m depth. The tower and LPS are bonded to the tower ground using thermal bonding.

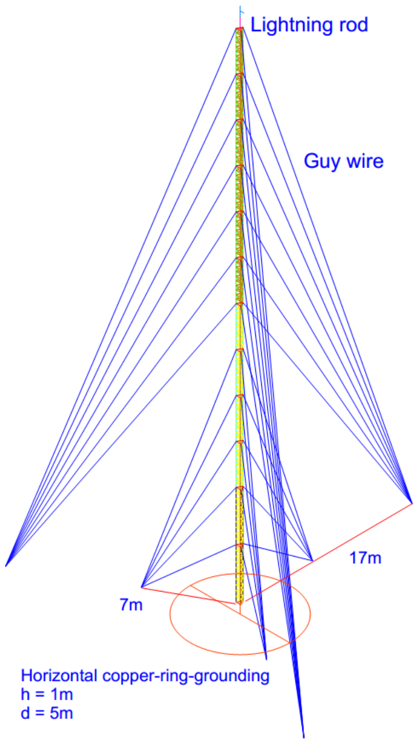


Figure 2. AutoCAD model of the three-leg guyed tower

C. LV radio equipment and connecting cable

The LV radio equipment of the local FM radio broadcast station is shown in Figure 3, it consists of:

- Low Voltage (LV) electronics: consisting of a computer, audio mixer, speakers, audio processor, and FM transmitter (1000W, 40V, 25A).
- Coaxial Cable and antennas: the LDF5-50A Heliax-7/8" 50 Ω coaxial cable type used in the local FM station, and the type of antenna is OMB 2.5 kW Broadband Vertical Dipole FM Antenna +7dB shown in Fig. 4.

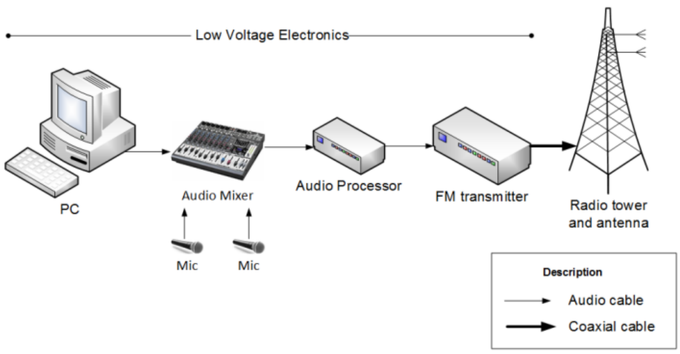


Figure 3. Local FM broadcast station diagram

Starting from a distance of 2.7 m below the tower top, an array of four vertical antennas are installed along the tower at distance intervals of 2.4 m, on the same side of the tower. These antennas are fixed onto the tower by insulating brackets, and connected to the coaxial cable through a non-conducting splitter box mounted at mid-point of the antenna array.

Figure 4. Vertical dipole antenna used in local FM broadcast station

III. SIMULATION STUDIES

For this study, a direct strike to the air-termination system of the tower LPS is assumed. The lightning strike is modelled by injecting an impulse current at the top of the tower. Three different current shapes simulating positive, negative and subsequent strokes are considered. The waveshape parameters are as specified in the standards [1] and their magnitudes are median values of peak current taken from the data recorded in the region [6]. These are: (a) first positive stroke represented by a 26 kA, 10/350 µs impulse; (b) first negative stroke represented by a 13 kA, 1/200 µs impulse; and (c) subsequent stroke represented by a 6.5 kA, 0.25/100 µs impulse.

A uniform soil resistivity of 80 Ωm is assumed as the basis for this study, based on the data reported in [12]. However, to examine the effect of possible variable soil conditions from one tower location to another, computations were also carried out for a range of soil resistivity values. For frequency domain computations, the equivalent frequency of a standard lightning impulse having risetime T_1 is determined as follows [14]:

$$f_{eq} = \frac{1}{4T_1} \quad (1)$$

The magnitudes and corresponding frequencies of the three lightning currents are shown in Table I. The equivalence between pulse and sinusoidal wave form means that, the maximum values of touch and step voltages or magnetic and electric field of the two wave forms are similar [13].

TABLE I. EQUIVALENT FREQUENCIES FOR IMPULSE CURRENTS

T_1/T_2 (µs)	I (kA)	f (kHz)
10/350	26	25
1/200	13	250
0.25/100	6.5	1000

IV. COMPUTATION RESULTS

A. Ground potential rise at the tower

Table II shows the ground potential rise at the point of injection for three different soil resistivity values. As can be seen from the table, the GPR increases with soil resistivity. For resistivity values equal or less than 1000 Ωm, the highest GPR magnitudes occur at the 1 MHz frequency representing the first negative stroke having the least current magnitude, whereas the lowest GPR magnitudes occur at the 25 kHz frequency associated the first positive stroke having the highest current magnitude. This may be explained by the higher impedance value of the tower at the 1 MHz frequency compared with the 25-kHz and 250-kHz frequencies. At these frequencies, the predominance of inductive effects causes an increase in GPR with soil resistivity. For the 1 MHz frequency, the tower GPR decreases with resistivity due to increased predominance of capacitive effects at high frequencies.

TABLE II. GPR AT THE POINT OF INJECTION FOR DIFFERENT SOIL RESISTIVITIES

	Ground potential rise at tower (kV)		
ρ (Ωm)	**25 kHz**	**250 kHz**	**1000 kHz**
80	298.40	825.21	2213.42
100	311.11	835.91	2201.33
200	371.14	890.51	2122.36
300	371.14	954.26	2041.90
500	594.70	1095.26	1883.60
800	859.16	1291.73	1669.31
1000	1042.85	1397.22	1548.57
5000	4676.52	2006.59	757.19

B. Induced voltages on LV coaxial cable and antennae

To compute the induced voltages on the low voltage coaxial cable running along the tower height, the cable was simulated by a simplistic representation of two adjacent vertical conductors running parallel to the tower, with the conductor closer to the tower representing the cable sheath, and the other conductor representing the core. Future simulations will investigate a more realistic representation of the cable. Figure 5 shows the two conductors and the antenna at the uppermost location on the tower.

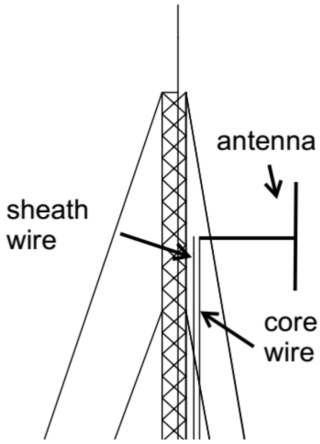


Figure 5 Close view of the tower showing conductors representing the coaxial cable and uppermost antenna

The GPR on the tower metal, and the voltages induced on the cable sheath and the cable core were computed at different points along the tower height. Figure 6 shows the results obtained for the three equivalent frequencies. The induced potentials in the LV cable are of the same order as the tower potential at the 250 KHz and 1 MHz frequencies, and decrease with decreasing tower height. For the 25 kHz frequency, the induced potentials show a slower decrease with height. A negative height means that the observation point is on the metal below ground. Figure 7 shows the potential difference between the cable core and sheath along the coaxial cable above ground, which can be taken as the prospective stress voltage on the cable insulation. At the 25 kHz frequency, the stress voltage induced on the cable would exceed the insulation withstand voltage of the cable of 8 kV specified by the manufacturer all along the cable. The tolerated impulse stress on the insulation is normally higher than the DC limit, and the overvoltages generated along the cable are likely to cause damage only at the weak points such as cable joints and connection boxes. Additional protective measures including installation of surge protective devices (SPD) should be added at these locations.

The induced potentials on the dipole antennae were obtained by modelling the antennae according to their actual geometrical dimensions and heights on the tower. Figure 8 shows the induced voltage and the tower GPR at the uppermost antenna location, where the highest induced potentials are expected. The induced potential values are close to the tower GPR values and their variation with soil resistivity is consistent with the findings obtained in section IV-A.

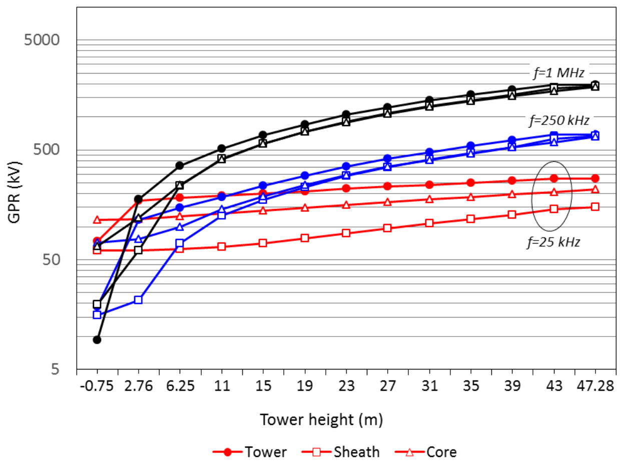


Fig. 6 Tower potentials and induced potentials along adjacent LV coaxial cable, ρ= 80 Ωm

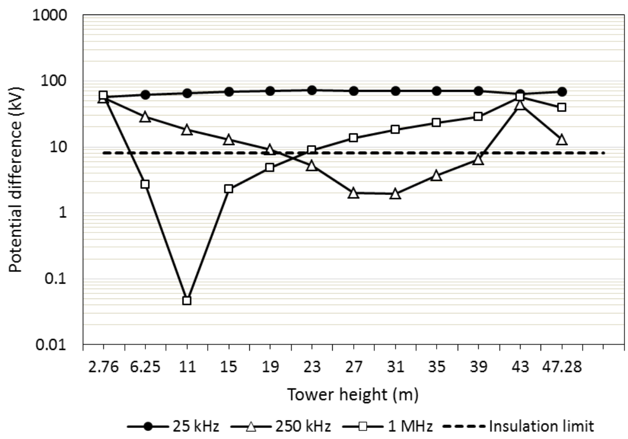


Fig. 7 Prospective potential stress on LV coaxial cable

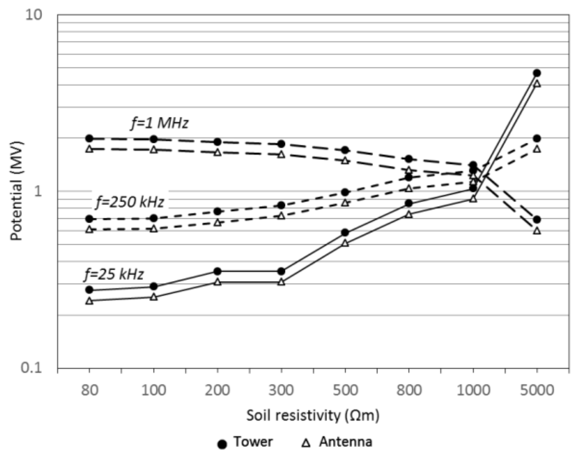
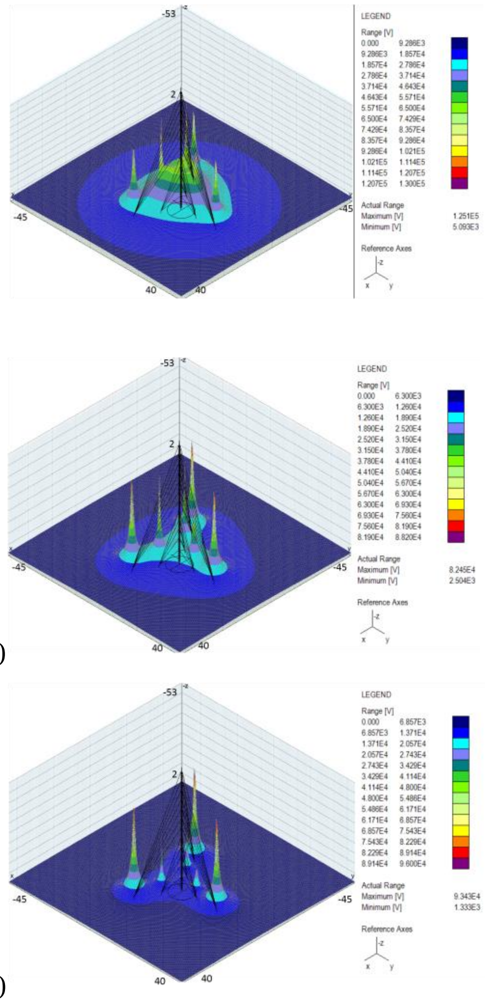


Fig. 8 Potential rise at tower and uppermost antenna

C. Ground surface potential distribution

The ground surface potential distribution around the tower is useful for assessing the safety risk associated with step and touch voltages. The 3D contours of tower and ground surface potentials are shown in Figures 9a-c at 25 kHz, 250 kHz and 1MHz respectively, for a soil resistivity ρ = 80 Ωm. The tower structure and guy wires are superimposed on the contours to help interpret the potential distribution. For all equivalent frequencies, high values potentials are produced by the lightning strike at the guy wire anchors, with maximum amplitudes of about 125 kV, 82.4 kV and 93.4 kV for the 25-kHz, 250-kHz and 1-MHz frequencies respectively. The figure also shows that the ground surface potentials have sharp gradients in the immediate vicinity of the anchors, indicating the possibility of existence of touch- and step-potential hazards, for which the risk needs to be evaluated. Grounding reinforcement in the form of surface chipping and/or buried ground electrodes may be required at both anchor locations and the tower base to control the safety voltages during lightning strikes.



(a) (b) (c)

Fig.9 3D representation of surface potentials 25 kHz (b) 250 kHz (c) 1 MHz

V. Conclusion

The results of a computer simulation of a telecommunication tower located in a high flash density region and subjected to lightning strikes were presented. The tower was modelled based on actual geometric dimensions of the tower, and frequency-domain computations within the spectrum of the lightning current were carried out. The results showed that large potentials are induced on both the LV coaxial cable and the broadcasting antennae, with the highest potentials observed with the 1 MHz frequency representing the subsequent stroke. Also, and depending on the shape of the lightning current, large potential differences in excess of the insulation withstand level may occur between the cable core and cable sheath. Mitigating measures to reduce both the induced overvoltages and to improve grounding should be applied and are summarized as follows:

- Installation of surge protective devices at the cable joints and connection boxes both on the tower and on the ground where the electronic equipment is located.
- Bonding of down lead conductor to the tower at multiple points.
- Improvement of grounding near the anchors points of guy wires to control step and touch voltages.

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