Revised Tower Earthing Design in High-Voltage Transmission Network for High-Frequency Lightning Condition

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Abstract. Tower earthing system for transmission grid is designed to protect the working personnel and equipment, as well as to maintain the quality of supply during fault. The existing tower earthing system for towers in TNB’s grid is catered for normal power frequency (low-frequency) fault conditions. This earthing design is found to be inapt for transient nature of lightning condition to a certain extent, which involves a high-frequency domain. The current earthing practice of installing the electrodes radially in 60m straight horizontal lines under the ground, in order to achieve the specified impedance value of less than 10 Ω, was deemed ineffective in reducing the high-frequency impedance. This paper introduces a new earthing design that produces low impedance value at the high-frequency domain, without compromising the performance of low-frequency impedance. The performance of this new earthing design, as well as the existing design, are simulated for various soil resistivity values at varying frequency. The proposed concentrated earthing design is found to possess low tower footing resistance (TFR) value at both low and high-frequency. A good earthing design should have a fine balance between compact and radial electrodes under the ground.

1. Introduction
Grid network is the backbone for high-voltage power transmission in most countries. Yet, transmission lines are physically exposed and, therefore, are affected by weather conditions particularly lightning activities. Tenaga Nasional Berhad (TNB), as the electric utility company in Malaysia, addressed its concern regarding transmission line tripping due to lightning [1–2]. It was reported that more than 36% of transmission line tripping in Malaysia are related to adverse weather [3]. This is consistent with the tripping records which indicates that the biggest factor of the transmission line tripping in TNB is due to lightning. There have been instances where tripping from lightning activity occurred on transmission lines with TFR values below the TNB-specified limits.

During a lightning strike, the high-voltage transmission system is subjected to a very large current with a fast rise-time. Lightning strike to tall structures, such as transmission towers, can produce voltages so high that insulation fails and electrical equipment might be damaged. Thus, high-voltage transmission systems require lightning protection and insulation co-ordination schemes to protect personnel and equipment from danger and damage. A fundamental factor that determines the effectiveness of these schemes is a good connection to earth and this includes the earthing system. A good design of earthing system limits the step and touch voltages to be within the values permitted by national and international standards at low and high-frequency. The design also has to comply with the accepted values for line lightning performance.
With this in mind, this project was carried out to better understand the dynamic and performance of transmission tower earthing system under low and high-frequency. This knowledge is crucial in reducing tripping occurrence on the transmission lines due to lightning. In this paper, a concentrated tower earthing designs were investigated. The designs were modelled and simulated using the Current Distribution, Electromagnetic, Grounding and Soil Structure Analysis (CDEGS) software. The dynamics of impedance of the tower earthing designs at different frequency were evaluated. The tower earthing design that gives small impedance value at both low and high-frequency is proposed.

2. Research Methodology

2.1. Data collection and measurements
Soil resistivity (SR) measurements were performed at the selected towers of different voltage level as this study is based on the actual conditions at site. The measured SR raw data was then analyzed using RESAP module in CDEGS software to determine the number of soil layers, its thickness, and the resistivity of each layer. For ease of comparison, SR value of 500 \( \Omega \cdot m \) is regularly used in this simulation, which is the starting range of SR for hard soil [4].

2.2. Modelling and simulations
The existing tower earthing design of the selected towers were modeled in MALZ module in CDEGS software. The actual SR values were used as a basis to determine the uniform SR. The impedances of tower earthing system for various frequencies ranging from 100 Hz to 1 MHz were determined. Similarly, a new tower earthing design was modelled and its performance was simulated to determine the impedance over a range of frequencies. In this simulation, the horizontal electrodes used were 12 mm in diameter, while the vertical electrodes were 16 mm in diameter, similar to the size in actual installation. It is important to note that as the transmission tower earthing design is a rather extensive combination of steel and copper of up to 600 m in length underground, the effect of soil ionization is minimum [5]. For that reason, ionization effect is omitted in the simulation as the induced electric field during lightning activity is assumed to be inadequate to ionize the surrounding soil.

3. Results and analysis
By taking the SR value and existing tower earthing design, the TFR at low-frequency and high-frequency can be simulated. Figure 1 shows existing earthing designs for transmission tower. In TNB’s guideline, design (a) is constructed during tower erection phase. In this design, diagonal electrodes are connected between the tower legs to form an X, and a 9-meters-rod is planted in the middle. If the measured TFR value is above the TNB-specified limit of 10 \( \Omega \), the grounding system is extended into design (b), in which, 60-meters-counterpoises are laid horizontally on the opposite side, along the traverse of the transmission line. If the TFR value is still above the limit, design (c) is implemented, with a total of four 60-meters-counterpoises, one for each tower legs.

Figure 1. A schematic of (a) basic grounding X-method, (b) Counterpoise1, and (c) Counterpoise2
In CDEGS simulation, this practice yields the intended low TFR of $<10\ \Omega$ when measured using earth tester meter at 128 Hz on $500\ \Omega\ \cdot\ m$ soil. However, in the 1 MHz range (lightning frequency), the TFR is alarmingly well above the specified limit, as shown in Figure 2.

![Figure 2. The corresponding TFR values at different frequency for existing earthing design at SR of $500\ \Omega\ \cdot\ m$](image)

The long stretch of counterpoise in the earthing system introduces inductive effect within the grounding system. The inductance will increase the impedance value at high-frequency significantly [6-7]. A good earthing design should minimize frequency-dependent inductive behaviour by making the grounding design more compact, in such a way that does not compromise the performance at low-frequency. Hence, the horizontal counterpoises are shortened to 25 meters, the effective length of horizontal grounding electrode during lightning transient condition [8-9]. The shorter counterpoises compliment the introduction of diamond and square electrode arrangements, as illustrated in Figure 3.

![Figure 3. A schematic of new proposed tower earthing design; (a) Stage 1, (b) Stage 2, and (c) Stage 3 earthing](image)

The proposed tower earthing design also comes in three stages. The first stage consist of X-method and diamond electrode arrangement. If the measured TFR value is above $10\ \Omega$, square electrode and radial counterpoises of 25 meters are added, as illustrated in Stage2 design. The third stage design consist
of additional crow-foot counterpoises at each tower legs and ground rods. The simulated TFR values at different frequency for the proposed tower earthing design at SR of 500 Ω.m are shown in Figure 4.

![Figure 4](image.png)

**Figure 4.** The corresponding TFR values at different frequency for proposed earthing design at SR of 500 Ω.m

As expected from the new design, the TFR values for low and high-frequency are relatively low, as compared to existing design. The TFR values of Counterpoise1 and Counterpoise2 can be seen increasing starting from frequency 10 kHz, the start of lightning frequency spectrum. The values at 1 MHz for the existing tower earthing design are simulated to be 22.5 Ω and 16.9 Ω for Counterpoise1 and Counterpoise2 design respectively. Whereas, for the newly proposed tower earthing designs, the TFR value can be seen to be constant up until 100 kHz and increase slightly thereafter. The impedance values at 1 MHz for the new design is 11 Ω, 10 Ω, and 8 Ω with respect to the stages. As explained earlier, with shorter counterpoises, and compact design, the inductance effect on the grounding system is reduced. At low-frequency, the reduction in TFR value is not obvious. But, at high-frequency, at which the inductance’s influence is significant, the TFR value for the new design is half the value of existing design. In the case of SR value at 500 Ω.m, Stage2 design is enough to maintain the TFR value below 10 Ω.

However, there is a limitation to this newly proposed design, similar to the limitation for existing earthing design. Stage1 design can be implemented for SR value up to 500 Ω.m, Stage2 up to 700 Ω.m, while Stage3 is applicable for soil of SR value up to 900 Ω.m. Beyond this SR value, extension of earthing electrodes is not economically feasible. Alternative methods of tower grounding such as the usage of earth enhancement compound (EEC), or tower lightning arrester (TLA), should be adopted for soil beyond 900 Ω.m.

### 4. Conclusion

As evidenced from the simulation result, the current practice of laying the earthing electrodes in a straight horizontal line under the ground, was indeed not effective in reducing the high-frequency impedance. A good earthing design should minimize frequency-dependent inductive behaviour by introducing compact earthing design with shorter counterpoises. A new tower earthing design is proposed which comes in three stages to suite the condition of soil at site. From the simulation performance using CDEGS, the full-fledged new design yields low TFR value at low and high-frequency up to SR value of 900 Ω.m.
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