

Article

Effect of Earthing Enhancing Compound (EEC) on Improving Tower Footing Resistance of a 500 kV Tower in a Rocky Area

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Citation: Nasir, N.A.F.M.; Kadir, M.Z.A.A.; Osman, M.; Abd Rahman, M.S.; Ungku Amirulddin, U.A.; Mohd Nasir, M.S.; Zaini, N.H.; Nik Ali, N.H. Effect of Earthing Enhancing Compound (EEC) on Improving Tower Footing Resistance of a 500 kV Tower in a Rocky Area. *Appl. Sci.* **2021**, *11*, 5623. <https://doi.org/10.3390/app11125623>

Academic Editor:
Luis Hernández-Callejo

Received: 20 May 2021
Accepted: 13 June 2021
Published: 18 June 2021

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Abstract: This paper presents a comparative analysis of different earthing designs' performances, with particular interest on the use of earthing enhancing compound (EEC) for a selected earthing design of 500 kV transmission towers in a rocky soil, using the SESCAD tool of the Current distribution, electromagnetic field grounding and soil structure analysis (CDEGS) software. The simulation included the interpretation of soil profile and comparison between designs A, B and C, which are currently used for the 500 kV tower footing resistance (TFR) improvement. Results showed each design had reduced the TFR by 66%, 54.7% and 63.2% for the towers T42, T48 and T50, respectively. In some cases, further improvement of TFR is required, especially in the rocky area where the soil resistivity (SR) value is of more than 500 Ω ·m. In this case, EEC was used in Design C, encasing both the vertical and horizontal electrodes, and it reduced the TFR further by 16% to 20%. The characteristics of the soil and earthing arrangement design play an important role in achieving a low TFR value, which is directly proportional to the backflashover occurrence and thus to the transmission line performance.

Keywords: earthing design; tower footing resistance (TFR); EEC; CDEGS

1. Introduction

Reducing the tower footing resistance (TFR) is the right option for increasing the performance of a transmission line. TFR coupled with soil resistivity (SR) is known to have a significant influence on the possibility of failure of a transmission line system [1]. In Peninsular Malaysia, Tenaga Nasional Berhad (TNB) has fixed the tower footing resistance to be less than or equal to 5 Ω for a 500 kV line [2]. Hence, an effective earthing design is needed to improve the performance of transmission lines and it is one of the best solutions for this issue. During the development of a transmission line, the TFR is one of the important parameters to be considered. The result of a TFR change depends on several factors, including the earthing structure and soil resistivity among others [3–7]. Typically, the structure of the earthing system has a relationship to the configuration or the tower footing shape. At present, round steel and profiled bar earth electrodes are buried at the base of each footing before the concrete foundation is mounted [8,9]. Moreover, earth electrodes and the tower footing are buried together during installation. In China, the

earthing structure was usually installed based on the location of the transmission tower and surrounding soil conditions. When the soil resistivity exceeds $100 \Omega \cdot \text{m}$, an additional earth electrode should be added, i.e., a rectangular or square horizontal electrode. However, if the soil resistivity is over $4000 \Omega \cdot \text{m}$, the use of a horizontal electrode along the tower and connection of an earth electrode to each tower are two measures found to be more effective and recommended [10–13]. Table 1 shows some of the current practices of earthing designs available and used in several Asian countries.

Table 1. Current practice of earthing design and arrangement in several Asian countries.

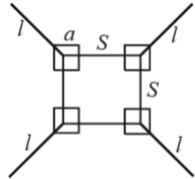
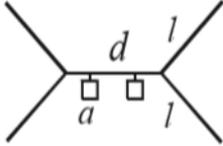
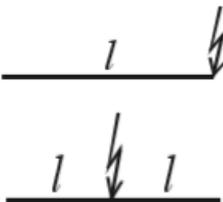
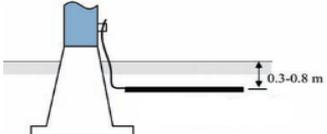
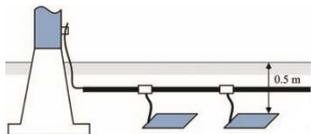
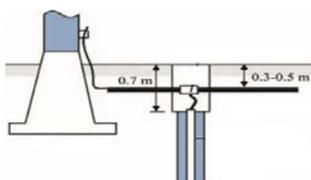
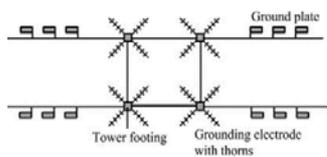
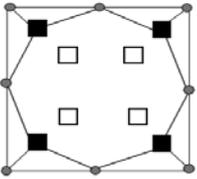
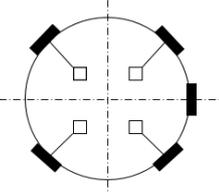
Countries	Earthing Design	References	Remarks
China		[11,12]	Earthing design of a steel tower: a: 4 m S: 8 to 10 m l: 0 to 50 m
			Radial earthing design of a reinforced concrete pole: a: 1.5 m d: 10 m l: 5 to 53 m
			Horizontal earth electrode with a lead wire connected at a terminal: l: 5 to 100 m Horizontal earth electrode with a lead wire connected in the middle: l: 5 to 60 m
Japan		[11]	Square-shaped earthing electrode with a horizontal earthing electrode.
			Horizontal earthing electrode with an earth plate.
			Horizontal earthing electrode with a combination of an earth rod and a filled low resistivity material.
			Earthing electrode with thorns and an earth plate.

Table 1. Cont.

Countries	Earthing Design	References	Remarks
Indonesia		[14]	Octagon shape
Thailand		[14]	Ring shape

Another method to reduce tower footing resistance is the counterpoise approach. It is perceived as practical and efficient for high voltage transmission earthing systems [15,16]. There are two types of counterpoises that have been widely used for towers located in high soil resistivity areas, such as rocky and sandy soils: the continuous and the radial type [3,4]. Other aspects important in earthing design include soil resistivity, number of soil layers and soil thickness in each layer [17,18].

Thus, a convenient way to reduce the value of soil resistivity and earthing resistance is to use an earthing enhancement compound (EEC), which has recently become popular in electric power systems, particularly for mitigating the issue of earthing systems [19,20] by replacing inappropriate soil content to minimise footing resistance caused by high cost and space constraints [21–23]. Hence, in this paper, we intended to present an improvement of an earthing system with different earthing designs and applications of EEC on a selected design to achieve the requirement limit for tower footing resistance of a 500 kV tower, i.e., less than or equal to 5 Ω . We also interpreted the soil structure and evaluated several earthing designs based on the soil resistivity measurements carried out on selected 500 kV towers.

2. Methodology

A comprehensive description concerning our study method is provided in this section. The outline of this study was divided into three stages: data collection; modelling and computation work; and results analysis. In Stage 1, measurement work and data collection on-site were undertaken using soil measurement equipment. The apparent resistance of the soil was measured for Towers T42, T48 and T50, which were chosen for the case study. This was followed by modelling and computation work in Stage 2, using the Current distribution, electromagnetic field, grounding and soil structure analysis (CDEGS) software, a platform to compute results based on the input from Stage 1. Finally, in Stage 3, results were analysed and discussed before the conclusion of all findings and contributions.

The analysis carried out included three modelling components: soil, earthing and EEC. The methods of all models included several phases in sequence. The modelling and simulations were all performed using the SESCAD tool for CDEGS. The CDEGS software was sufficiently powerful to interpret complex soil profiles from field measurement data and to design earthing systems [24]. The first step of this analysis was to use the RESAP module to determine the soil profile based on the real data from Peninsular Malaysia. Subsequently, the tower earthing structure was developed and evaluated using the MALT module based on the soil structure built in the first step. After the earthing structure was developed, the calculation of the EEC model followed. This section also provides a real case study demonstrating how a proper simulation of soil, earthing and EEC was

developed and analysed. The quantitative and qualitative analyses of the earthing system were determined based on the earthing resistance obtained under steady-state conditions.

2.1. Description of the Case Studies

The Grid Division of Tenaga Nasional Berhad Transmission (TNB) is responsible for the design, management and operation of the transmission systems comprising three different line voltages, i.e., 132 kV, 275 kV and 500 kV. Here, a 500 kV double circuit line, denoted as Line A–B, was selected for a case study, taking into consideration that the line is located in a lightning-prone area and critical for the national grid. Furthermore, this particular line was subsequently chosen based on the high number of interruptions on this line compared with other 500 kV lines in Malaysia [25–27]. Within this area, 30% of the line is under forestation and at a high altitude with a higher tower footing resistance caused by the high altitude soil profile [25,27]. Generally, 500 kV towers consist of a two earth wire design at the top with a height of around 46 to 67 m. For this analysis, the methodology of interpreting the soil profile characteristics was applied to a real case involving three towers on the 500 kV double-circuit line. Figure 1 shows the dimensions of a 500 kV transmission tower. In short, the study cases were as follows:

- a. Case study A: Modelling of soil profile interpretation.
 - i. Case A (1): Soil layer analysis
 - ii. Case A (2): Soil resistivity analysis
- b. Case study B: Simulation of tower footing resistance (TFR) with different earthing designs under steady state conditions, using CDEGS.
 - i. Case B (1): Effect of design analysis (Towers T42, T48 and T50)
 - ii. Case B (2): Effect of soil profile analysis
- c. Case study C: Simulation of tower footing resistance (TFR) with earthing Design C and encasement with EEC under steady state conditions, using CDEGS.

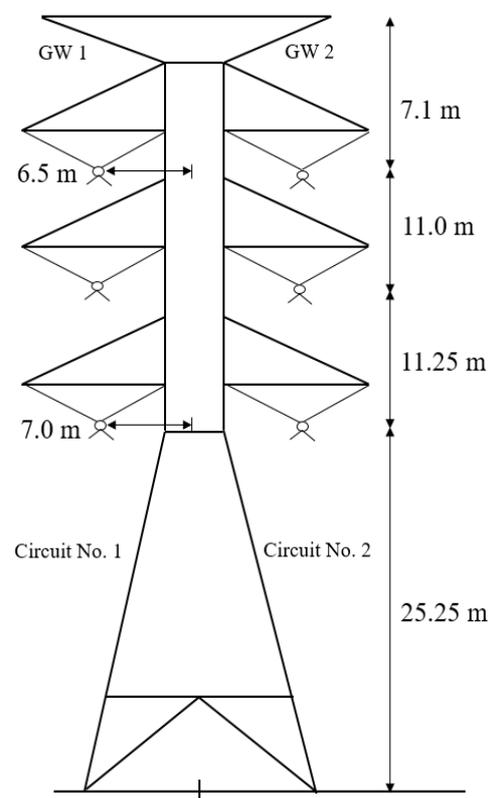


Figure 1. Structure of a tower for 500 kV line.

2.2. Soil Modelling

Soil modelling is a methodology designed to mathematically describe the local soil profile for the design of an earthing system. The soil is generally considered as uniform or homogenous, although, in reality, it is often multi-layered. This is due to the geological features—soil type differs from one location to another—and to the existence of bedrock or groundwater that results in a significant change in resistivity as a function of depth [28–30]. In this study, the analysis started with computation of the soil profile interpretation using the RESAP module of the CDEGS software. The RESAP computation module is sufficiently powerful to calculate the soil resistivity value coupled with the approximate thickness of the soil layers [31]. To interpret the exhaustive soil profile, an apparent resistance data collection from site measurements was used as input to RESAP and the analysis of the soil profile was achieved by applying a selected Wenner method during simulation [24]. In this study, three apparent resistances from a selected tower were used, and Table 2 shows the average of the apparent resistances for Towers T42, T48 and T50. These tests were carried out with various measurements at different locations to achieve the best possible indication of apparent resistance [32]. Figure 2 illustrates three measurements at different location areas for every tower. R1, R2 and R3 represent the first, second and third apparent resistance measurement positions (also known as traverses), respectively.

Table 2. Averages of apparent resistance (Ω) values.

Spacing, a (m)	Average Apparent Resistance (Ω)		
	T42	T48	T50
1	398.6	236.4	150.69
1.5	233.12	95.92	89.15
2	166.72	57.63	61.57
3	115.61	35.97	34.25
4.5	71.64	20.14	25.87
6	42.77	16.92	19.06
9	28.74	10.72	17.82
13.5	14.25	9	8.41
18	8.58	9.87	7.94

Measurements were successfully achieved using the Wenner method, which is the most widely used and easy method for measuring soil resistivity in an earthing system. The Wenner method is the simplest arrangement with four poles, denoted as C1, P1, P2 and C2, and a set of reading probes spaced during testing [33–36]. All electrodes are placed in one line and equally spaced from each other. The two outer electrodes, namely C1 and C2, are current electrodes and the two inner electrodes, P1 and P2, are potential electrodes. Figure 3 presents a schematic of the Wenner measurement method currently used by the power utility for on-site SR measurements.

2.3. Earthing Systems with Different Designs

A good earthing system design greatly improves the efficiency and performance of a transmission line [31,37]. Generally, the configuration of an earthing system is related to the footing shape. In a region of high soil resistivity, an additional earth electrode should be applied to the tower base. Within this section of the study, three earthing design arrangements, Designs A, B and C, were proposed to evaluate the performance of different earthing design arrangements. The models of the earthing designs were developed using SESCAD and they were implemented by the MALT module to compute the tower footing resistance. Figure 4 illustrates the default design with a 2×60 m counterpoise, denoted as Design A. In this design, the base of the tower was $15 \text{ m} \times 15 \text{ m}$, consisting of one vertically driven electrode at a depth of 9 m. The burial depth of the horizontal electrode was 0.5 m from the surface, and it was made of stranded copper with a radius of 6.35 mm (or 0.00635 m).

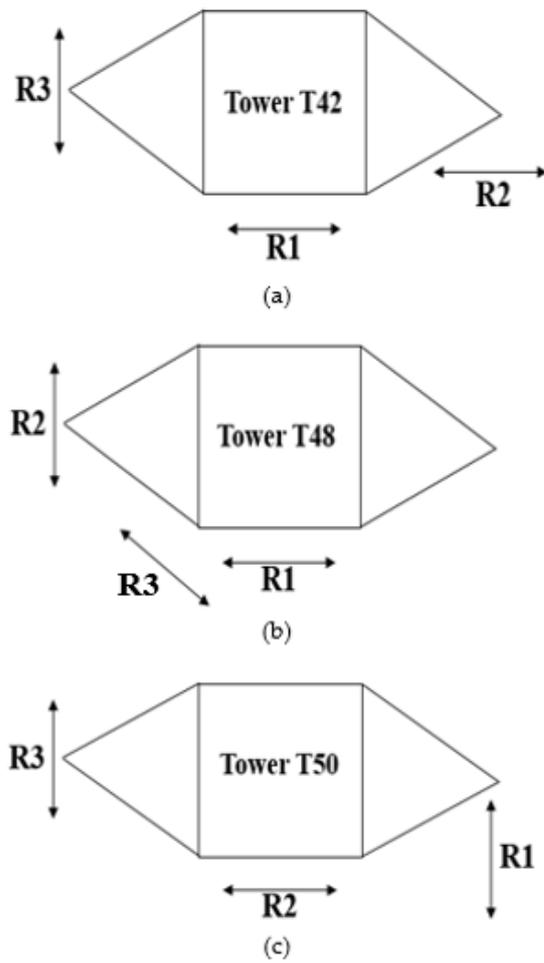


Figure 2. Top view: Apparent resistance measurements at the different location areas; (a) Tower T42; (b) Tower T48; (c) Tower T50.

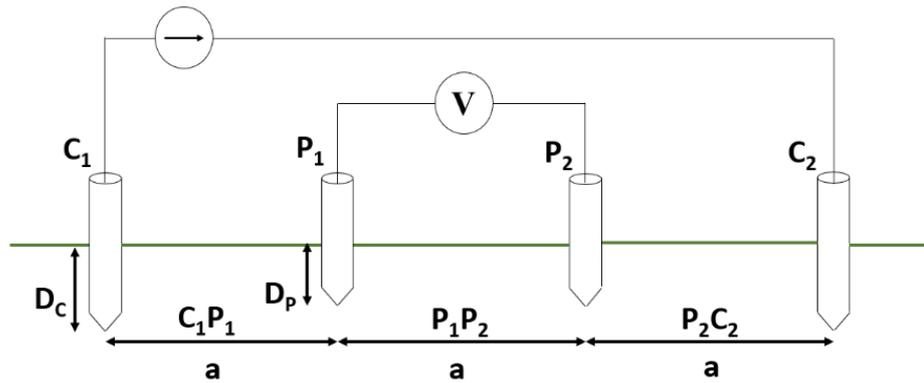


Figure 3. Wenner measurement method.

Design B was a combination of a radial and a ring, which was extended from the default of Design A. The base of the tower was also 15 m × 15 m, with 10 m stranded copper cable, extended horizontally from the tower leg, and 13 vertically driven electrodes. Similarly to Design A, the burial depth of the horizontal electrode was 0.5 m from the surface, and it was made of stranded copper with a radius of 6.35 mm (or 0.00635 m), as shown in Figure 5.

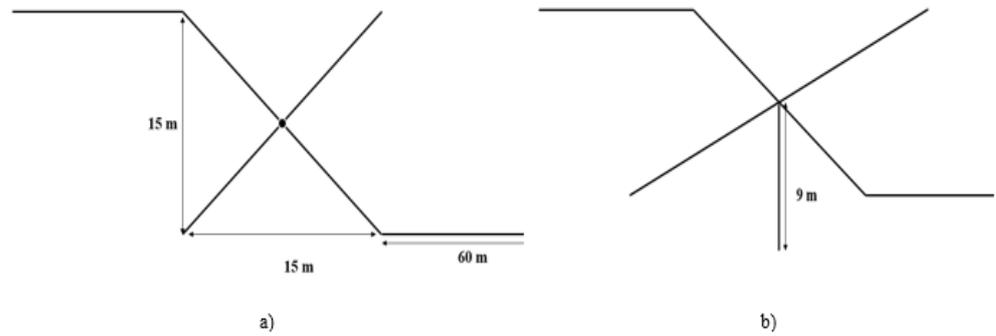


Figure 4. Design A: Default design with counterpoise; (a) top view; (b) 3D view.

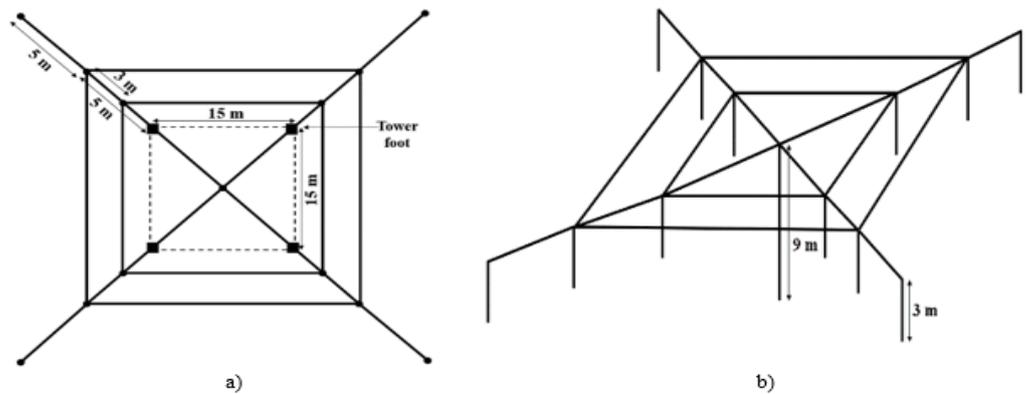


Figure 5. Design B: Radial and ring electrodes; (a) top view; (b) 3D view.

Lastly, Figure 6 illustrates the Design C, known as the diamond, with 4×60 m counterpoises installed additionally to the vertical electrodes. For this particular design, there were 28 vertically driven electrodes installed at a depth of 3 m, on top of a 9 m electrode that was initially installed based on the default design.

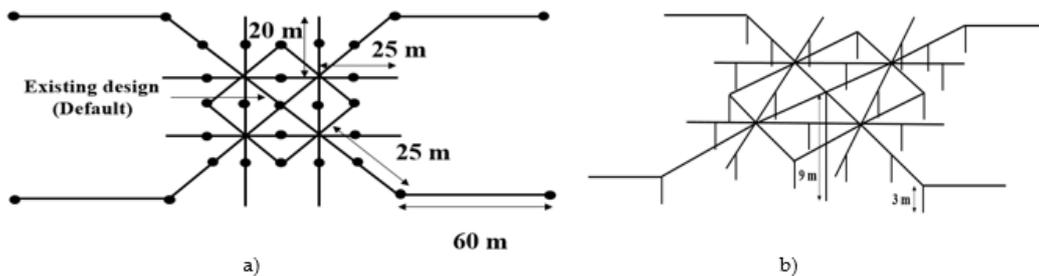


Figure 6. Design C: Diamond-style with counterpoise and vertical electrodes; (a) top view; (b) 3D view.

The analyses and discussions on the performance of the different earthing design arrangements (Design A, B and C) were considered and simulated using the CDEGS software approach.

2.4. Earthing Enhancing Compound (EEC)

The footing resistance has a linear relationship to soil resistivity. Soil resistivity is a fundamental parameter in the design of line earthing and is used to measure the fault current of the earth along a transmission line [38]. The effect of soil resistivity on earth impedance is generally greater compared with earthing electrode arrangements. It is an indicator of how much electric current is conducted, and it varies with soil type, moisture and temperature [39–41]. Previous studies showed that soil resistivity might be decreased

by increasing the salt content, moisture and temperature of soil [41–43]. Therefore, implementing the EEC approach to substitute for an unsuitable soil content surrounding the electrodes is a simple method to reduce tower footing impedance. After several years of research and development, EEC brand A (later denoted as EEC) was developed and has been used very effectively in many locations around the world. The EEC is referred to as an ultra-conductive material containing a soil resistivity reducing agent that provides extremely minimal resistance to the flow of electrical conductivity and thus significantly improves the efficiency of the earthing. EEC is made of environmentally friendly, robust components and contains no heavy metals nor other harmful materials [44]. In this part of our study, the test was conducted according to the manufacturer’s instructions, and the physical properties of EEC with prepared specimens were as in normal use, as shown in Table 3 [44]. Subsequently, the modelling of EEC in CDEGS was developed by adding a coating to the surrounding electrode. The thickness of the EEC is one of the variables that influence the electrode resistance, and all parameters used in this study were based on the actual earthing system arrangement and the properties of EEC. Figure 7 illustrates a cross-sectional view of the EEC that was modelled by the CDEGS software. There are three parameters required in for modelling: the borehole radius, R_{borehole} ; the earth electrode radius, $R_{\text{electrode}}$; and the thickness of the outer electrode, which represents the thickness of the EEC surrounding the electrode. It can be calculated by the following equation:

$$R_{\text{borehole}} - R_{\text{electrode}} = \text{EEC thickness}$$

Table 3. Physical properties of the EEC.

Properties	Unit	Values
Visual appearance	-	Dark tan (powdered)
Dry bulk density (average) at 47.7 N compaction force	g/cm ³	1.07
Resistivity (average) at 100% moisture content, EEC mixed with water (1:1 ratio by volume)	Ω·m	0.6
Wet bulk density (average) at 1:1 ratio by volume	g/cm ³	1.49
Conductivity (average) at 100% moisture content, EEC mixed with water (1:1 ratio by volume)	S/m	1.7

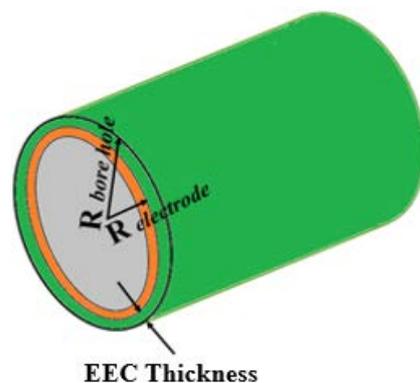


Figure 7. Cross-sectional view of the EEC modelled in the CDEGS software.

Table 3 indicates the soil resistivity parameter of the EEC, which was 0.6 Ω·m, and the thickness of the coating was 0.116698 m, as depicted in Table 4, and this was defined by selecting “Define | Coating types” on the characteristic menu in CDEGS. Table 4 shows also the details of EEC and its thickness required to fill a borehole.

Table 4. Details about the EEC required for modelling in CDEGS.

Parameter	Value
Radius of the borehole (m)	0.12
Radius of the electrode (m)	0.003302
EEC thickness (m)	0.116698

In practice, each bag of 25 kg of EEC was mixed with 15–20 L of water (depending upon the level of dryness of the site) so that it assumed a slurry form. Referring to Figure 6, this EEC slurry was poured to surround the borehole of a vertical electrode and to cover the horizontal electrode, then we filled the hole up back with the soil. Depending on the actual dimensions at the tower based, estimated 67 bags of 25 kg EEC were used for each tower.

3. Results and Discussion

In this section, we provide an analysis of the soil profile for the selected towers of a 500 kV line in Peninsular Malaysia. Furthermore, the computations of the tower footing impedance (TFI) and ground potential rise (GPR) curve, using the soil profiles, were compared between all the different designs.

3.1. Case Study A: Soil Profile Interpretation

In the quest to interpret the soil profiles, we inferred from the results that the soil profiles for each tower consisted of two, three and sometimes four layers with different values of soil resistivity. As indicated in Figure 8, the Tower T42 soil profile had two layers. The surface layer, referred to as air, had infinite resistivity and thickness. The first layer of the soil had a resistivity of 2240.443 Ω·m and a thickness of approximately 5.3335 m, while in case of the second layer, it was 842.7448 Ω·m and an infinite thickness.

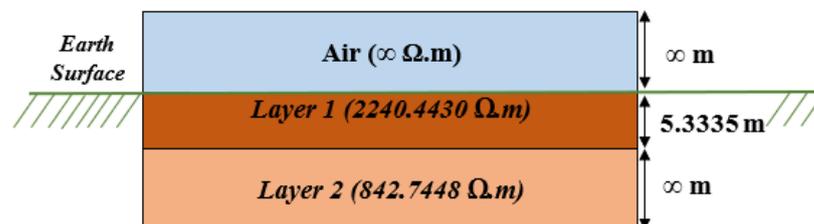


Figure 8. Soil profile interpretation for the Tower T42.

Figure 9 shows the soil structure for Tower T48, which was composed of three layers with different soil resistivity. Results indicated that the highest soil resistivity was recorded at the third layer with 2520.846 Ω·m and an infinite thickness. The first and second layer showed 2066.665 Ω·m and 535.7491 Ω·m and the thickness of 0.7022 m and 9.4521 m, respectively.

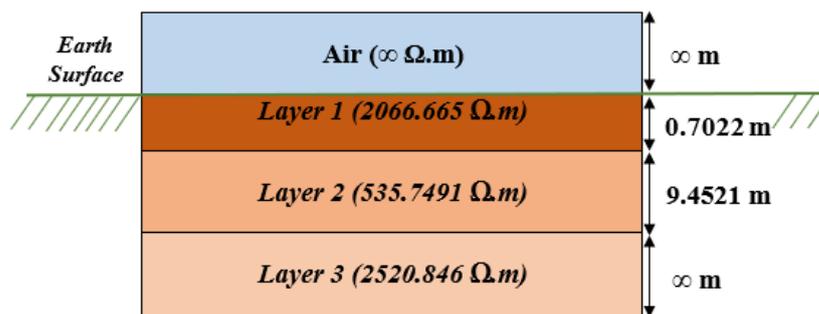


Figure 9. Soil profile interpretation for the Tower T48.

Figure 10 presents the four-layer soil profile for the Tower T50. Result indicated that the soil resistivity of the first layer was $1129.640 \Omega \cdot m$ and its thickness was 0.8880 m . The second and third layer showed the values of soil resistivity of $610.0205 \Omega \cdot m$ and $487.6068 \Omega \cdot m$, having the thicknesses of 0.2014 m and 1.3932 m , respectively. The fourth layer, denoted as the bottom layer, had a resistivity of $873.3768 \Omega \cdot m$ and an infinite thickness.

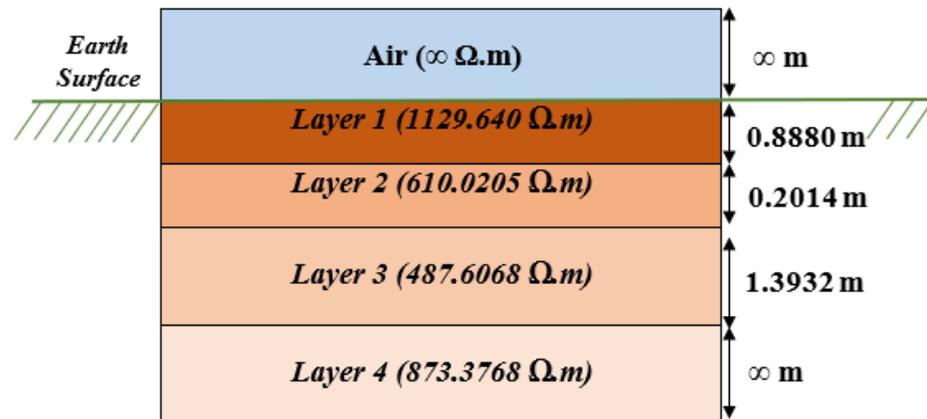


Figure 10. Soil profile interpretation for the Tower T50.

3.2. Case Study B: Tower Footing Resistance Computation for Different Earthing Designs

In this section, the tower footing resistance computation is presented for three different design arrangements: (i) default design with counterpoise (Design A) (ii) radial and ring electrodes (Design B) and (iii) diamond with counterpoise and electrodes (Design C). Specifically, the TFRs were computed for three conditions of soil structure, as described in Section 3.1. Figure 11 presents the TFRs for the three types of earthing design buried in a two-layer (T42), three-layer (T48) and four-layer (T50) stratified soil. Results indicated that the Tower T42 had the highest TFR value as compared with Tower T48 and Tower T50. In this case, the resistance was influenced by the first layer, which had a high soil resistivity. This particular layer had a soft topsoil, porous enough to retain ample air and water. In comparison, the middle and bottom layers were harder and more compact than the top layer. These layers did not contain any organic matter and consisted of a rock that made them very rough [45]. Changing Design A for Design C reduced the TFR of each tower by more than 50% (66% for T42, 54.7% for T48 and 63.2% for T50). Table 5 summarizes the TFR values improvements when Design B or Design C were deployed to each of the towers.

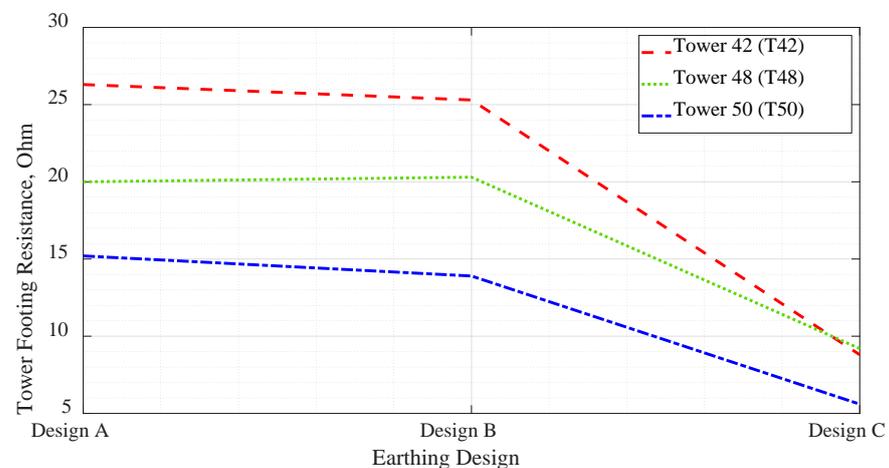


Figure 11. Influence of design arrangements on tower footing resistance in a 2-layer, 3-layer and 4-layer soil in Towers T42, T48 and T50, respectively.

Table 5. Tower footing resistance analysis of different design arrangements.

Earthing Design	Tower Footing Resistance Value, Ω		
	Tower T42	Tower T48	Tower T50
Design A	26.3	20	15.2
Design B	25.3	20.3	13.9
Design C	8.8	9.2	5.6

3.3. Case Study C: Effect of EEC on Electrodes

An EEC is deployed in regions with high soil resistivity to enclose electrodes to reduce tower footing resistance (TFR). This is normally indicated in case of a high soil resistivity (SR) value measured at the site, typically above $500 \Omega \cdot m$ in the case of a 500 kV tower. The use of EEC was incorporated in Design C, where it was considered as the better solution by TNB. The TFR value was found to be reduced by Design C and was further improved when the EEC was applied. Results of the use of this earthing design with the EEC are summarized in Table 6. They indicated that the TFR of the Tower T42 was reduced from 8.8Ω to 7Ω , whilst for Tower T48, the TFR decreased from 9.2Ω to 7.7Ω and from 5.6Ω to 4.6Ω for Tower T50. Therefore, EEC was found to be very effective at reducing the earth resistance to less than 5Ω , as per TNB requirement for the 500 kV lines in Malaysia.

Table 6. TFR analysis of Design C encased with EEC.

Tower	Design C	
	Tower Footing Resistance Value, Ω	
	Without EEC	With EEC
T42	8.8	7
T48	9.2	7.7
T50	5.6	4.6

Similarly, a decreasing trend of TFR after the addition of EEC is shown in Figure 12, which clearly indicates an improvement made by the EEC deployment.

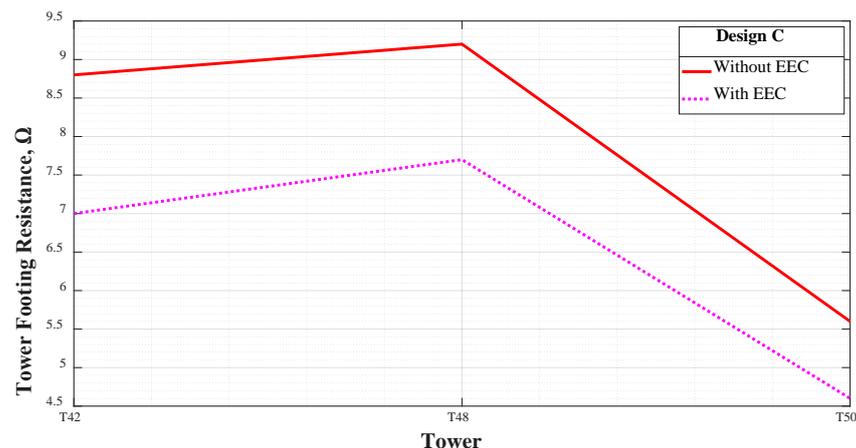
**Figure 12.** Comparison of the TFR value with and without EEC implementation for Design C.

Table 7 shows the percentage of TFR reduction after the addition of EEC to T42, T48 and T50 using the Design C. It can be seen that the EEC provided a promising solution, particularly for the towers located in a rocky area, where low soil resistivity and TFR are hard to achieve. Reductions of 20.45% for T42, 16.3% for T48 and 17.86% for T50 were obtained from this simulation.

Table 7. Percentage reduction of TFR for selected towers.

Earthing Design with EEC	% Reduction of TFR		
	Tower T42	Tower T48	Tower T50
Design C	20.45	16.3	17.86

It is interesting to note that the results obtained in this work are crucial for the next step of the line performance study. In the context of the criticality of this 500 kV line, which is known as very critical and a backbone of the transmission network in Peninsular Malaysia, this work was able to quantify the significance of each approach considered by the power utility via several earthing designs. Despite the fact that the solutions are unique to each utility, especially in the Southeast Asia (SEA) region, this work can be shared within the interested community of power utilities. Although the TFR generally decreases when EEC is applied to a selected design, the reduction may not be substantial [46]. This is particularly true in the case of these 500 kV lines, located in a high-terrain area with a rocky soil. It can be observed that the TFR is heavily dependent on weather conditions, such as the amount of rainfall, soil moisture and temperature of the surroundings, which is applicable for a country such as Malaysia [47]. When the temperature is too high, it leads to dryness of the soil, thereby affecting the soil resistivity value. Thus, it can be inferred that EEC is able to reduce the TFR, thus improving the overall transmission line performance.

4. Conclusions

This paper presented an analysis of TFR for different earthing designs and arrangements, taking into account the deployment of EEC. Three earthing designs were considered and simulated in the CDEGS environment, adopted from the current practice of the power utility, to improve the transmission line performance. The significant contribution of this work consists in the information, crucially required by the power utility, concerning the TFR values related to each design and the percentual improvement made by deploying EEC. This quantification of information is required for choosing the most technically and financially viable approach to earthing design to be deployed in TFR reduction and thus in improvement of the overall transmission line performance. As highlighted earlier, this work is significant because this 500 kV line is considered critical in Malaysia. Therefore, a much stringent requirement was put in place, especially on the TFR value that needs to be maintained. Even 1 Ω improvement can be translated into tens of thousands of Malaysian Ringgit worth of investment and several ohms of reduction will certainly help the power utility to significantly cut down their operational expenses.

In conclusion, the study confirmed that characteristics of the soil profile and the earthing arrangement design play an important role in the earthing system. The application of EEC surrounding the electrodes is a convenient, simple and easy way to reduce High TFR can lead to an outage of the transmission tower, especially on backflashover, and it is well known that the higher the soil resistivity, the higher TFR of that particular area [48].

Author Contributions: Conceptualization, M.Z.A.A.K., M.O., M.S.A.R. and U.A.U.A.; methodology, N.A.F.M.N.; validation M.Z.A.A.K.; formal analysis, N.A.F.M.N., M.S.M.N.; investigation, N.A.F.M.N., N.H.N.A. and N.H.Z.; writing—original draft preparation, N.A.F.M.N.; writing—review and editing, N.A.F.M.N.; supervision M.Z.A.A.K., M.O., M.S.A.R. and U.A.U.A.; project administration, M.Z.A.A.K., M.O., M.S.A.R. and U.A.U.A.; funding acquisition, M.Z.A.A.K., M.O., M.S.A.R. and U.A.U.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universiti Tenaga Nasional through UNITEN Bold Grant and URND for RA Scheme. Special thanks to Tenaga Nasional Berhad (Grid Maintenance) team for their kind support on the data.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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