Earthing design considerations for Macarthur Wind Farm Project – 140 Wind Turbine Generators (WTG)

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Abstract:

Consolidated Power Projects (Australia) was contracted by Leighton Contractors (Australia) to undertake the design for AGL/Meridian's Macarthur Wind Farm located approximately 14 km North-West of Hawkesdale in rural Victoria Australia. The earthing studies and their detailed designs were subcontracted to LineTech Consulting (New Zealand). The wind farm comprises of one hundred-and-forty 3 MW wind turbine generators (WTG) and six 20 MVAr capacitor banks with a maximum nominal generation capacity of 420 MW. Included in this subcontract were the design of the earth grids for all 140 WTG, the Macarthur Wind Farm Substation, the 132/132 kV Tarrone Transition Station and part of the 132/500 kV Tarrone Substation. In addition to the earth grid designs, the magnetic coupling between the 132 kV Macarthur Wind Farm Tarrone 132 kV overhead line and the Port Campbell to Adelaide Pipeline needed to be studied. This examined unsafe induced voltage magnitudes on the pipeline during single phase to ground faults occurring along the overhead. The proposed paper documents the engineering process and calculation methodology for the Macarthur Wind Farm earthing designs, and lists the local and international design standards applied.

An engineering objective was to determine the distribution of fault current from the main national transmission grid 132/500 kV Tarrone Substation to each individual WTG. This fault current is distributed via two stations, two 33 kV overhead line-to-cable transition stations, and an array of 33 kV cable and overhead line networks between the Macarthur Substation and the WTG.

The final WTG design is based on a variable depth ring type of earth grid. The study concerns itself with conditions under single phase-to-earth fault operating conditions at TRTS and the due impact of induced voltage and distribution of fault current to interconnecting services such as underground cables (UGC) or neighbouring fences. The paper concludes with a summary of the salient earthing design considerations for a large scale wind farm such as Macarthur and highlights the importance of calculating the fault current distribution between UGC, overhead shield wires (OHSW) and earth return paths. A lightning frequency (Hz) sensitivity analysis is performed on various earth grid design options.

1. Background

The Macarthur Wind Farm is a large sized wind farm approximately 14km North-West of Hawkesdale in rural Victoria Australia. It comprises of a hundred-and-forty 3MW wind turbines (WTG) with a maximum total nominal generation capacity of 420MW. The electrical energy produced by the WTG's is collected at 33kV via two circuits of overhead lines and four circuits of underground reticulation and transmitted to four switchboards at the new 132/33kV Macarthur Wind Farm Substation. The energy is then stepped up to 132kV via two 33/132kV transformers and transmitted to SPAusNet's upstream 132/500kV Tarrone Terminal Station (TRTS) via approximately 14km of double 132kV overhead line circuits. At Tarrone Substation, this is again stepped up to 500kV via a 132/500kVA 600MVA transformer before being connected into (TRTS). The TRTS comprises a 132kV switchyard and a 132/500kV transformer bay connected through a short 132kV overhead line. The reticulation crosses several farmlands bounded by fences.

In addition to the above, there is also a gas pipeline that traverses the 33 kV reticulation in several locations. Both the 132/33kV transformers are connected to earth. On the 33kV side, the star-point is connected to earth via neutral earthing resistors which limits their earth fault to 1kA. The 132kV side of the neutral is solidly earthed.

2. Scope of the design

The scope of the design is to design an earthing design for the Macarthur Wind Farm Project which provides safety for personnel and public, protection of electrical network equipment, and ensures correct system protection operation. The study concerns itself with conditions under single phase-to-earth fault operating conditions, and in the case of the WTG the conditions due to the impact of induced voltage for lightning protection.

3. Design process

The design process followed the substation earthing guide as illustrated in Figure 1-1 of the ENA EG1: 2006 Earthing Guide. The design process documented below mentions salient considerations in applying the ENA guideline. These include applied standards, hazard analysis, soil electrical resistivity measurement, fault current distribution, earth conductor sizing, permissible voltage limits and probability safety criteria.

3.1 Applied standards

Relevant local standards have been applied which include: ENA EG1: 2006 Earthing Guide; ENA EG-0 Power System Earthing Guide Part 1: Management Principles Version 1 – May 2010; AS/NZS 1768:2007 Lightning Protection; AS 3000: 2007 Wiring Rules. International standards include IEC 61400-24 Wind turbines – Part 24: Lightning protection (Edition 1.0 2010-06).

3.2 Hazard analysis

Locations and conditions are identified where staff or the public may be exposed to shock hazards. Such hazards include touch, step, transfer and hand-to-hand contact voltages. For each location it is necessary to calculate the expected shock voltages for a single phase-to-earth fault scenario. Risks were quantified when measured against the relevant standard mentioned above. Hazardous touch voltages can appear on exposed metal parts such as metallic fences and main valves on the pipeline. Mitigation options for each unsafe condition are identified.

3.3 Soil electrical resistivity measurement

On site soil electrical resistivity (Ω-m) measurements have been obtained by applying the Wenner Four Electrode Method and these are processed within CDEGS RESAP to provide soil models for each site. The Marquardt Model has been applied to all calculations. From the provided soil electrical resistivity measurements, a three-layer soil model is found to be the most appropriate. Soil electrical resistivity test results were provided for two traverses, perpendicular to each other where possible. Measurements were taken using probe spacings varying from 0.50 and up to 100 m. Generally, the maximum value of each spacing from each traverse is used to determine the soil electrical resistivity model. Moisture has a great influence on the resistivity value of soil, and the resistivity of a soil can be determined by the quantity of water held by the soil and resistivity of the water itself. Conduction of electricity in soil is through water. It may be noted that electrical resistance drops with increasing moisture to a more or less steady minimum electrical resistance value at about 15 % moisture [1]. A further increase of moisture level in soil will have little effect on soil electrical resistivity. In many locations the water table is deeper in dry weather conditions. The soil tests were performed during January 2011. This represents the middle of the driest months (between November and April). As the measurements were carried out during the dry months, no effect on the water table and subsequent soil electrical resistivity measurements need be assumed. Therefore the design does not provide any adjustment of the soil model due to diurnal variation of upper soil.

3.3 Fault current distribution

The CDEGS HIFREQ module is applied to calculate the fault current distribution between conductive return paths (OHSW, Optical Ground Wire (OPGW), and metallic cable sheaths) and earth return; as well as the overall design of each earth grid. CDEGS HIFREQ is also applied in calculating the low frequency induction (LFI) between the 132 kV OHL and the gas pipeline and fencing. CDEGS modules HIFREQ, FFTSES and AutoTransient were used to compare lightning response to various earth grid design options for WTG. Basic assumptions were made during the calculation of the LFI. These include:

a) Sources of unbalanced currents such as “through unbalance” and “circulating unbalance” and their effects are not included in the calculations. A balanced load configuration is assumed within 132 kV OHL circuits for normal operating conditions and just prior to single phase fault conditions.
b) WTG and nonlinear loads can cause harmonic emissions [2]. As the modelling and analysis [3] of WTG are beyond the scope of the LFI studies; the calculations assume that there are no significant harmonics generated from the WTG and are therefore neglected.
c) The LFI calculations take into account the effect of stray current (commonly referred to as ‘holidays’) flowing along the pipeline through imperfections or installation damage in the insulation coating. In order to account for these defects, two modelling options are available. Firstly, the pipeline can be modelled in sections representing a series of grounding-leakage resistances (R_{pi}). The total number of leakage resistances (m) must equal the number of OHL structures (n) with their respective footing resistances (R_{gi}) [4]. Unfortunately this modelling technique exceeds the CDEGS HIFREQ limitation of components and is therefore not pursued. The second modelling option is to reduce the resistance of the coating without segmenting the pipeline [5]. This option has been applied in these studies.

d) Induction due to lightning striking the overhead line is excluded from the calculations, as there are no available quantitative voltages for lightning induced surges on pipelines. The most recent AS/NZS 60479.1:2010 'Effects of current on human beings and livestock - Effects of lightning strokes on human beings and livestock' [6] provides a comparison of electrical injury and lightning injury with no guidelines for voltage limits.

3.4 Earth conductor sizing

In addition to determining the size of earth conductors by ampacity calculations contained in ENA EG1-2006 Section 10.2 Equipment Selection; an allowance is made for the expected reduction in the cross-sectional area of the copper electrode and conductors due to expected corrosion. The basic prerequisite for corrosion is the presence of high moisture content. In addition to high moisture content the following factors facilitate the corrosion process: high concentrates of sulphate, chloride, ammonia compounds or sulphide; poor aeration of soil which supports anaerobic bacteria activity; high differentials of oxygen or neutral salt; high amounts of organic or inorganic acids; and stray DC currents. To accurately determine a 'reduction factor', a comprehensive soil composition analysis and moisture content record would be required for each WTG site. Measuring, testing and analysis of the soil for the project would be time consuming and costly. As an alternative to the former, the design assumes an overall 30 % reduction of buried copper over a 25 year period.

3.5 Permissible voltage limits

Permissible voltage limits are applied to all relevant WTG, cable transition stations, transition stations and substations to assess the safety to personnel and public during a single phase-to-earth fault. Permissible step and touch voltage limits are calculated in accordance with IEEE STD 80-2000 and based on a 50 kg person. Actual calculated voltages are compared to these limits and where non-conformance occurs; mitigation applied by either modifying the earth grid conductors or applying a high resistance ground layer. Step Voltages (SVs) and Reach Touch Voltages (RTVs) are based on step and touch distances of 1 m. Mesh touch voltages are situated on the outer perimeter fence. 'Hot Spot' Electrical Potential Rise (EPR) contours for zones of 430 V, 650 V and 1,000 V are calculated. Fence touch voltages are calculated for both the perimeter fence and the fence surrounding the capacitor banks. Fault currents and clearing times vary for each voltage and high voltage site.

3.6 Probability safety criteria

ENA software ARGON Version: 3.2.0.0 & Calculator Version: 2.0.0.0 is applied in the safety assessment process for determining the probability of coincidence, determining the probability of fibrillation and in evaluating any potential target risk range.

4. WTG earth grid design

An initial WTG earth grid design was modelled. It consisted of:

- a circular inner electrode ring installed 1m from the base of the WTG tower at a depth of 0.8m,
- a rectangular outer ring electrode installed 1 m from the perimeter of the WTG foundation and at a depth of 1.3m,
- 4m x 3m long copper-bonded vertical earth electrodes installed at the 4 sides of the outer ring electrode,

- simplified electrical equivalent foundation which represents approximately 5% of the actual REBAR, and
- individual soil electrical resistivity models were applied to each WTG.

Of note is the variable depth of earth electrodes. The inner ring electrode is buried at 0.8m and the outer ring at 1.3m, such that the conductors joining the two rings together will have an appropriate variable depth. This is illustrated in Figure 1. Size of the buried copper conductor is 70mm^2, which is assumed to be the final conductor cross-sectional-area after the maximum expected corrosion has occurred.

The above design was simulated with a fault current of 1 kA as this is the maximum fault current that the WTG external earth grid will be subjected to due to a 33 kV fault. It does not consider a fault occurring at (and between) the generator and the transformer. The transformer is installed within the base of the WTG tower. The initial earth grid design modelled is illustrated in Figure 1. Resultant profiles[1] for each of the 140 WTGs of WTG grid resistance (GR), EPR, RTV, and SV are illustrated in Figure 2. Fault clearance time is 578ms.

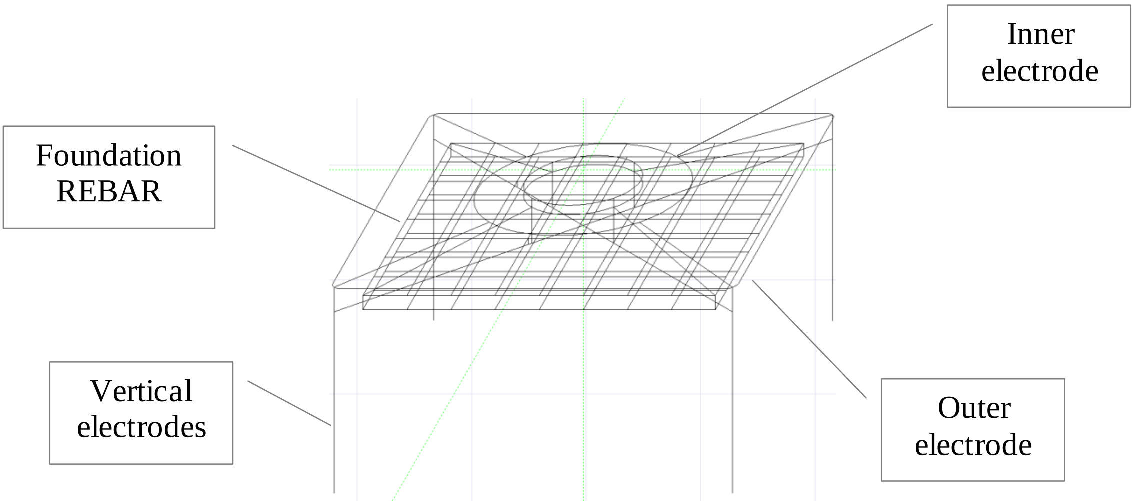
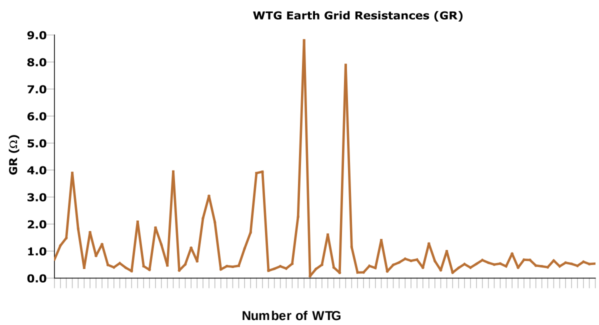
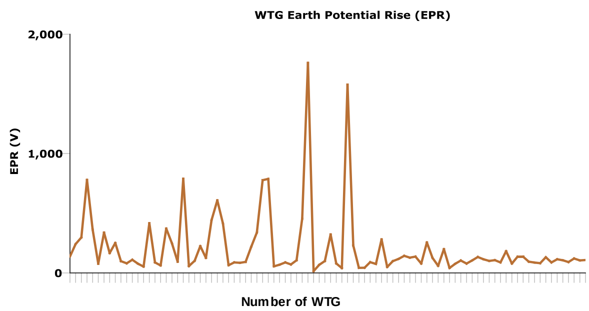


Figure 1: Basic WTG earth grid design

The maximum grid resistance for each WTG earth grid is established at 5Ω which complies with AS/NZS 1768:2007 for sensitive electronic equipment. With the standard design earth grid; there were only two WTG that exceeded 5Ω.





[1] Horizontal axis displays the number of WTG – due to the quantity individual numbers are not displayed

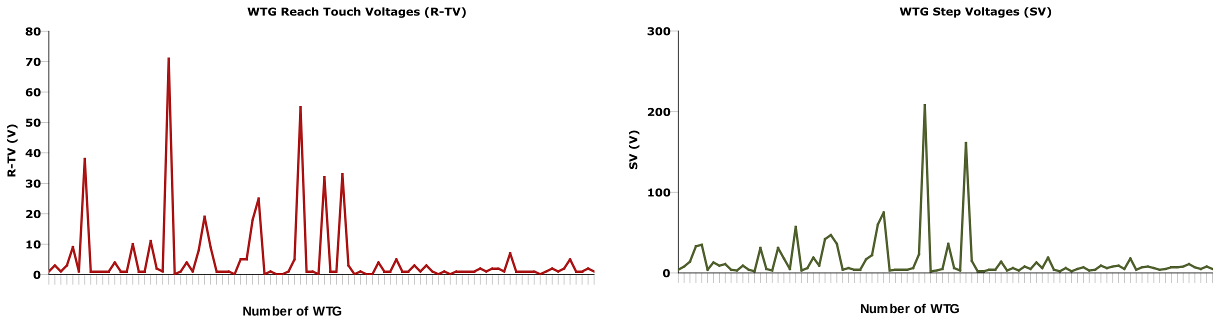


Figure 2: Result profiles of WTG earth grid

Reviewing their soil models, depths of soil layers and resistivities of each layer; the standard earth grids were appropriately modified for the two WTG that exceeded a maximum of 5Ω grid resistance. Earth electrodes were extended 3m to 6m and an additional electrode was positioned in the centre as illustrated in Figure 3, demarcated in red.

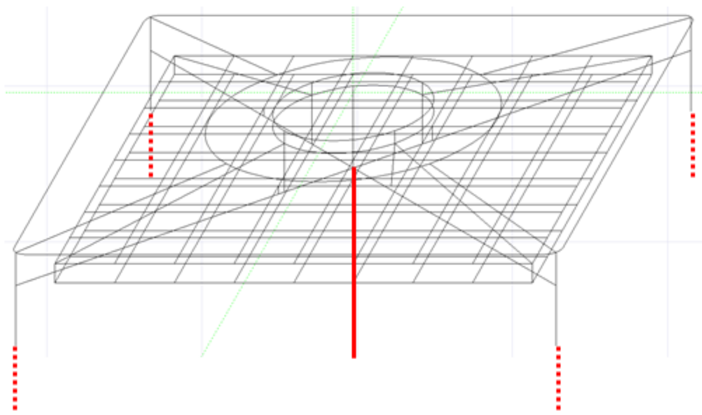


Figure 3: Variation to standard WTG earth grid design

5. Lightning transient response of WTG earth grid

Due to their height and often located on elevated topography, WTGs are more susceptible to lightning strikes than normal distribution and transmission assets. The CDEGS program modules HIFREQ, FFTSES and AutoTransient are applied to compare lightning response to various earth grid design options. The methodology consisted of the frequency decomposition of the time domain signal; and the computation of the frequency domain electromagnetic field response. Representation of the frequency response is adequate in achieving the objective and therefore the time domain electromagnetic field response was not included in the study. The transient behaviour of the WTG subjected to a lightning strike is investigated using the field theory approach. A lightning strike is simulated by injecting a 20kA current surge based on the standard double exponential model. The dynamic electromagnetic field response is obtained by decomposing the lightning discharge current into its frequency domain spectrum using the forward Fast Fourier Transform with the CDEGS FFTSES module. The EPR are then computed at selected frequencies of the selected frequency domain spectrum. The input time signal is analysed by converting it into the discrete frequency spectrum. The sampling exponent is to a power of 2. The selection of the time duration is determined by the time duration determines the frequency resolution and is represented by the relationship -$\Delta f = {}^{1}/_{T}$; and the time duration should be selected so that the input signal is very small at the end of the time window. The study considers $T = 300\ \mu s$ which corresponds to $\Delta f = 3333.3$ Hz. The rise time of the voltage surge is $1\ \mu s$. To be conservative, a time step of 0.1 μs is chosen which corresponds to a 300/0.1 = 3000 sampling points. As the sampling exponent is to a power of 2 for the number of sampling points, the value $2^{12} = 4096$ is chosen. The Nyquist frequency is therefore:

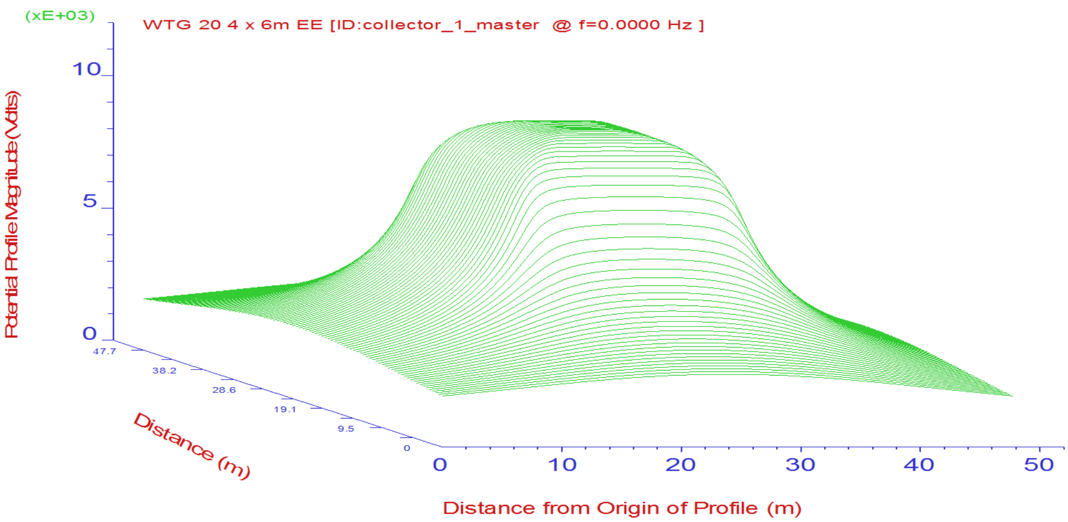
$$f = \frac{4096}{2 \times 300} \times 10^{6} = 6.827\ MHz$$

The lightning surge discharge current is defined by a double exponential type function: $I(t) = I_m \left(e^{-\alpha t} - e^{-\beta t}\right)$ where $\alpha = 1.4 \times 10^{4} s^{-1}$ and $\beta = 6 \times 10^{6} s^{-1}$. The lightning waveform is characterized by a typical lightning stroke with a rise time of 1 μs and a half-value of 50 μs. Table 1 lists the calculated results for various earth grid design options for a randomly selected WTG 20 and contains the lowest, mid-point and highest frequency spectrums.

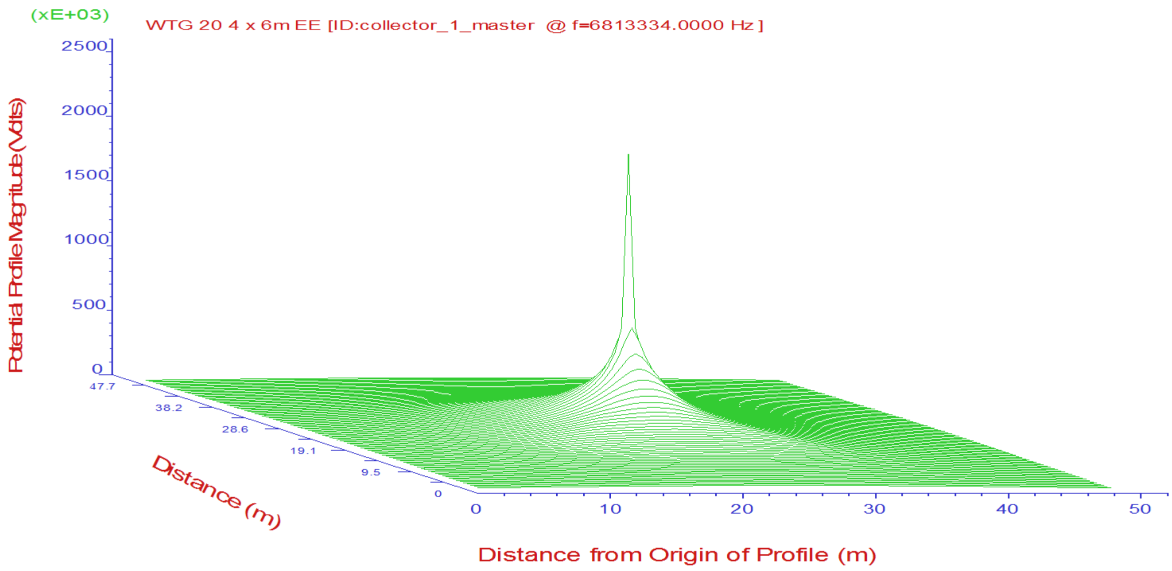
Table 1: Summary of EPR results – WTG 20

Frequency (MHz)	EPR (kV)					
	Length of 4 Earth Electrodes			Length of 5 Earth Electrodes		
	3 m	6 m	12 m	3 m	6 m	12 m
0.003 (DC)	11.11	10.3	8.78	11.1	10.28	8.76
0.973	394.9	397.3	397.0	310.0	307.0	236.0
6.813	2 206.8	2 206.6	2 206.6	2 128.0	2 120.0	2 117.0

Graphical representations of the results are illustrated in Figure 4 (a) and (b).



(a) DC Component



(b): 6.813MHz Frequency

Figure 4: EPR versus frequency domain

The EPR profiles at all frequencies are the highest in the centre of the WTG for all scenarios. These profiles change with different frequencies due to the change in the frequency dependant impedance. Reviewing the above table provides the following facts:

a) Increasing the length of vertical earth electrodes has a negligible effect on reducing the EPR for high frequency discharge current. A larger effect is realised at the low frequency end, DC component.
b) Similarly, an additional fifth earth electrode has the same negligible effect.
c) Low frequency EPR profiles extend over a larger area than high frequencies.

The above EPR values vary with different soil electrical resistivities with the variation being proportionally similar. In addition to the single Earth Continuity Conductor (ECC) connecting WTGs to the collector substation via their respective collector networks, WTGs have a counterpoise conductor installed when they are located at the end of a collector network where only one ECC bonds to the WTG. The ECC is 50 mm^2 bare stranded copper conductor buried at a depth of 1 m, and the counterpoise conductors, with length of 40 m, are the same conductor also buried at 1 m depth. AS/NZS 1768:2007 Table 4.6 specifies 35 mm^2 as a “typical section dimension of main current-carrying components”. The effect of the counterpoise decreasing the footing resistance has not been included in the calculations and their installation results in lower resistance values than what are represented in Figure 2.

6. Interconnection between TRTS & TRSS

Earthing design for the interconnection between TRTS and TRSS concerns itself with conditions under single phase-to-earth fault operating conditions at TRTS and the due impact of induced voltage and the distribution of fault current to interconnecting services. This section of the design includes the guidelines provided in ENA EG-0: 2010 Power System Earthing Guide Part 1: Management Principles. The interconnecting earthing grid design must guarantee the safety of personnel during earth faults by ensuring the compliance to parameters including but not limited to, RTVs and SVs. The study assumes that the fault occurs at TRSS. Following from this assumption the most obvious fault current distribution would be between the OHSW and the ground return. This distribution is illustrated in Figure 5.

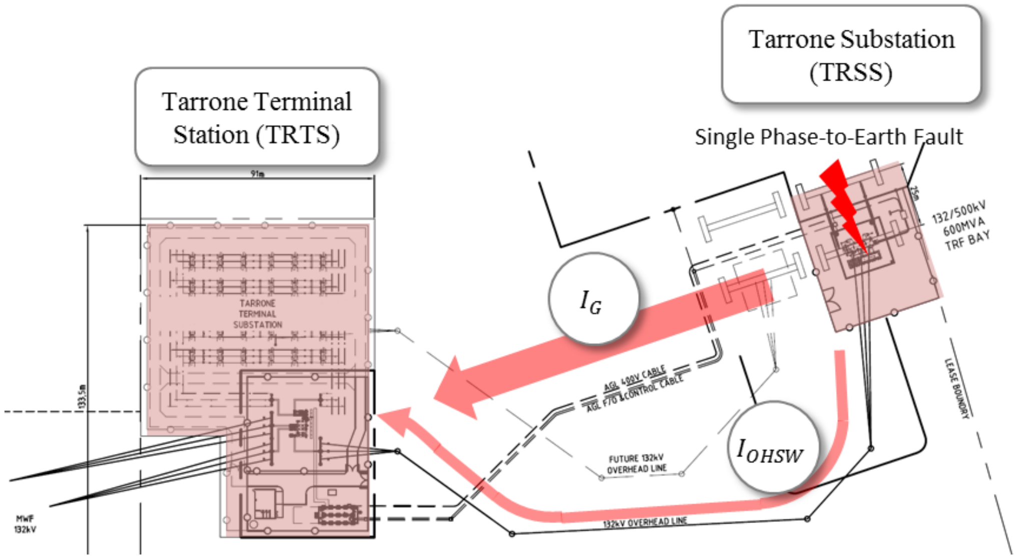


Figure 5: Fault current distribution – ground return & OHSW

A fault is considered within TRTS at the incoming gantry and the study contained two primary scenarios: no ECC connection between TRTS and TRSS, and ECC connecting TRTS and TRSS. This considers a combination of both insulated and uninsulated ECC. This is illustrated in Figure 6. The number of ECC is determined by the reduction that the additional ECC has on the fault current through the protection cable screens. In addition, there are scenarios which consider various protection cable screen sizes, 2.5, 4, and 6 mm^2. Determining the various screen sizes provides the sensitivity of the fault current split versus screen size.

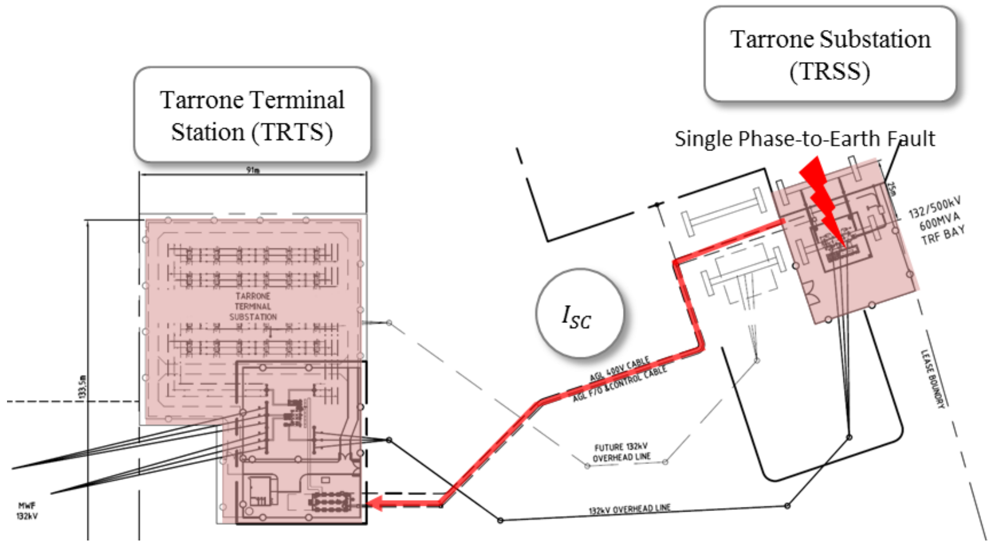


Figure 6: Fault current distribution – cable screens

The final design proposal consists of the installation of 3 ECCs between TRTS and TRSS. These include a single 185 mm^2 copper conductor solidly connected to each earth grid. As with the WTGs ECC, the ECC installed under the OHL is also a bare conductor. This is to help mitigate safety hazards such as EPR, RTVs, and SVs. The ECC shall be installed directly beneath the 132 kV OHL and solidly connected to each OHL structure. The 2 ECC (ECC 1 and ECC 2) installed with the protection cables shall be insulated.

RTVs at OHL towers that are non-compliant weren't necessarily non-compliant after performing a probability risk assessment as per ENA EG-0. This compliance is based on the fact that a fatality due to contact with an external voltage can only occur if both a person is present when a fault occurs and the RTV or SV generated is sufficient to allow a large enough current to pass through the body for sufficient time to cause fibrillation of the heart muscle. The probability that an individual will be present and in contact with an item at the same time that the item is affected by a fault; is termed the Probability of Coincidence ($P_{coincidence}$). The probability that the heart will enter ventricular fibrillation due to contact with an external voltage is the Probability of Fibrillation ($P_{fibrillation}$). This is represented by the following simple equation:

$$P_{fatality} = P_{coincidence} * P_{fibrillation}$$

From a probability assessment point of view, and with conservative input parameters, the design is considered 'compliant' with a negligible risk as the individual coincident probability ($P_{coincidence}$) = 0.346 and the probability of fatality ($P_{fatality}$) is 1.43e-7.

7. Summary

An important input into the earth grid calculations was determining the fault current distribution between metallic and soil return paths. WTG and station earth grid designs are based on their individual soil electrical resistivities. However, the soil return path along overhead lines and cables are based on a uniform soil electrical resistivity. A sensitivity analysis between extreme soil variations was carried out to compare the unsafe voltage results. The final WTG design is based on a variable depth ring-type of earth grid. A high lightning frequency (Hz) sensitivity analysis was performed on various earth grid design options, proving that the length of the earth electrodes has a marginal effect on the EPR.

8. References

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