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Safety assessment of high voltage substation earthing systems with synthetic geotextile membrane

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Abstract

High voltage substations built within areas prone to vegetation or with unfavourable subgrade conditions are paved with the addition of punched geotextiles and non-conductive synthetic fabrics underneath switchyard surfacing. The aim of this research is to identify the impact of synthetic textiles on earthing system performance through numerical analysis with the state-of-the-art software package. The new layer interferes with the earthing grid's performance with different behaviour depending on the installation above or underneath the layer with considerable impact taking place when the earthing grid is installed above the geotextile layer. Rods penetrating the geotextile can alleviate the potential voltage distribution issues and improve the earthing system performance regardless of the native soil stratification.

Keywords: substation earthing; synthetic geotextile; tolerable voltages; high voltage.

I. Introduction

Personal safety is paramount for HV substation earthing systems in addition to system requirements for neutral voltage reference, earth fault detection and electrostatic control [1]. Substation safety is assessed by comparing attained surface voltages, expressed as touch and step voltages as well as transferred voltages, to tolerable limits [2][3]. Surface voltages depend on soil stratification where fault currents prefer to go through layers of lower resistivities with less voltage gradients while high resistivity layers contribute to greater gradients and thus, touch and step voltages [4]. Polyester geotextiles with pores around 100 microns are laid underneath switchyard surface at an average depth of about 900 mm to control vegetation. Different types of geotextiles may be used to improve subgrade soil conditions during construction. The insulating nature of the geotextile interferes with the native soil stratification by introducing a very thin layer with very high resistivity. Example installation underneath a new switchyard is shown in Figure 1. The recent research review on native soil modifications indicates that the relations with high voltage substation earthing and synthetic geotextiles have not been studied [5][6][7][8][9][10][11][12][13]. This paper sheds some light on the subject since the trend to involve geotextiles is on the rise for substations within Australia and other parts of the world. The paper investigates the mechanism of action of the included layer as well as two case studies for green and brown field applications.

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II. Materials and Methods

A. Fault current in soil

The introduction of geotextile underneath switchyard surface can be modelled as a thin layer with very high electrical resistivity. The level of earthing grids above or under the geotextile controls the surface voltage distribution and overall resistance to remote earth. For earthing grids above the geotextiles, fault current normally prefers to flow through the surface layer creating gradients proportional to the layer resistivity which can negatively impact the safety assessment. For earthing grids installed under the geotextiles, no significant changes are envisaged to grid resistance. Surface voltages will be very similar to the case with no geotextiles.

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Figure 1. Installation of geotextile underneath new switchyard during construction

B. Geotextile modelling

Geotextiles are made of polyester, which is a dielectric material with a typical bulk resistivity of about 10^{11} to 10^{15} Ωm [14]. Although the commercially available geotextiles to control vegetation are permeable to water flow with surface flow rates vary between 100 to 200 litre/m^2/sec [14], it is considered to have a very high electrical resistivity since the pores are not sufficient to achieve reliable native soil contact through the geotextile in dry conditions.

The geotextiles are not normally tested for the electrical resistivity and an estimated value of 10,000 Ωm has been considered for the dry material based on corresponding values for a porous insulating material like wood [15]. Higher values reaching 50,000 Ωm are assumed for dry conditions. Various manufacturers have been approached for electrical testing of their material with negative feedback since the electrical testing of geotextile is a non-standard test.

Due its thin construction and insulating properties, it is not possible to measure or even detect the presence of a geotextile once installed using site based soil resistivity measurements (e.g. Schlumberger, Wenner methods) [16]. The geotextiles are envisaged to interference with the soil resistivity measurements by blocking the deeper soil layers interaction and a quick results saturation will be reached versus spacing.

The geotextiles are modelled in current distribution, electromagnetic interference, grounding and soil (CDEGS) structure analysis software embedded soil volume option. Since the soil model with geotextiles has a high degree of heterogeneity, memory allocation and processing time is considerably greater than cases with no geotextiles.

C. Safety criteria

Tolerable touch and step voltages are traditionally considered to compare versus attainable voltages within and around high voltage installations to assess the personal safety criteria parameters. With the use of high resistivity layer, the tolerable touch and step voltages, if the earthing grid is installed underneath the geotextile, will be impacted as the deeper native soil will be, theoretically, out of action and replaced by the high resistivity layer. Equation (1) from IEEE 80:2013 simplified formula for surface layer derating factor C_s [3]

$$C_s = 1 - \frac{0.09\left(1-\frac{\rho}{\rho_s}\right)}{2h_s+0.09} \tag{1}$$

where ρ represents the geotextile resistivity, ρ_s surface soil resistivity and h_s is the depth of the geotextile.

With estimated values ranging from 5,000 Ωm to 50,000 Ωm for geotextile resistivity depending on soil dryness and seasonal variations, the tolerable touch and step voltages will be higher than that with no geotextile, assuming a uniform soil model. The increase in a tolerable touch voltage is inversely proportional to the surface soil resistivity with behaviour shown in Figure 2 for 50 kg weight persons. The tolerable touch voltages ($V_{touch50kg}$) are calculated for fault duration t of 0.5 seconds based on IEEE 80:2013 Equation (2) [3]

$$V_{touch\ 50kg} = (1000 + 1.5 \times C_s \times \rho_s)\frac{0.116}{\sqrt{t}} \tag{2}$$

where native/surface soil resistivity is relatively low (less than 50 Ωm), an increase in the tolerable touch voltage of up to 350 % can be obtained in dry conditions where the geotextiles are assumed to have very high resistivity values in the range of 50,000 Ωm. in the other hand, where the soil is wet, as the water

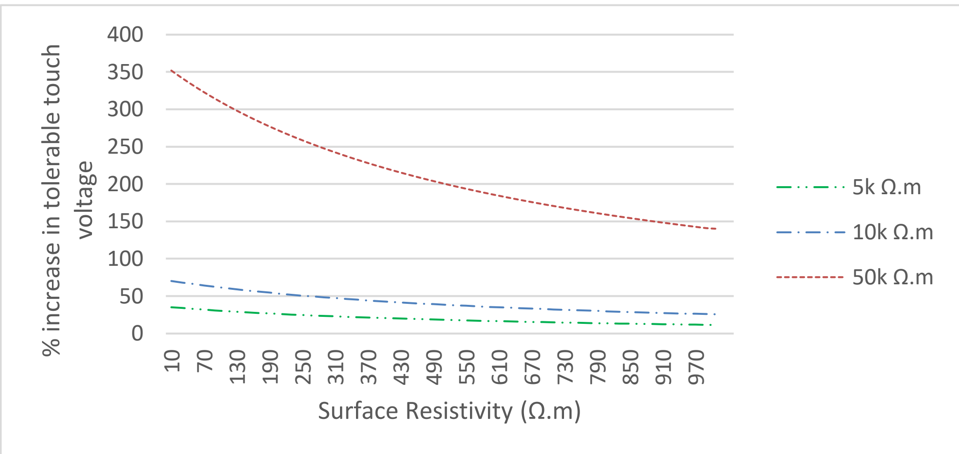

Figure 2. Touch voltage increase (%) versus surface soil resistivity (0.9 m deep geotextile)

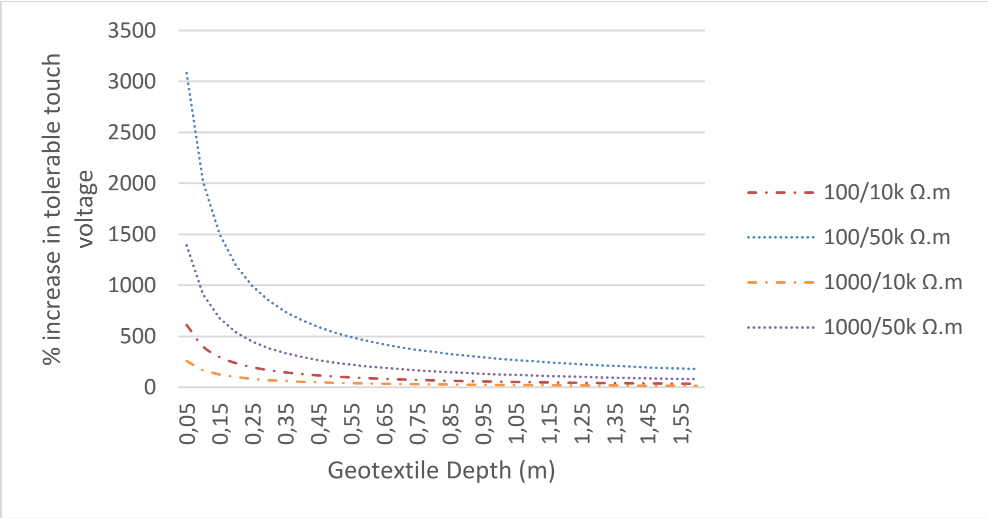

Figure 3. Touch voltage increase (%) versus surface textile depth

flows through the membrane, resistivity is assumed to decline sharply and less effect on tolerable touch voltage is envisaged.

The depth of the geotextile layer also affects the tolerable voltages as with shallow installations, the high resistivity layer will be near to the surface and hence, its effect will be greater. Variation of touch voltage with geotextile depth is typically depicted in Figure 3 with two different surfaces (native) soil resistivities 100 Ωm and 1000 Ωm. A sharp drop in the tolerable touch voltages is observed for geotextile installations deeper than 0.15 - 0.2 m from the finished surface. Typical geotextile installation depth is about 0.5 - 1 m.

III. Results and discussions

A. Case study I

The first case under study is for a new open terminal substation 500/220 kV with overall dimensions of 144 x 70 m. The native soil measurements at site modelled with CDEGS RESAP [17] with a 3-layer stratification as shown in Figure 4. High resistivity layers on a low one are considered in this case where deeper layers permit most of the current to propagate through away from the surface.

Earth fault current of 10 kA is used to represent the available 500 kV single phase to earth fault with a duration of 100 ms. Tolerable touch and step voltages

Figure 4. Native soil model showing 3-layer soil with high on low resistivity stratification

Table 1.
Modified soil model

Soil Layer	Soil Resistivity (Ω m)	Layer Thickness (m)
ρ 1	150.00	0.9
ρ 2	10000.00	0.05
ρ 3	288.61	0.63
ρ 4	12.93	2.63
ρ 5	4.77	Infinite

have been calculated using IEEE 80:2013 formulae [3]. Switchyard surfacing with an average resistivity of 150 Ωm is added as a top layer along with needle punched polyester geotextile with 100 micron pores to represent the final soil stratification as shown in Table 1. Tolerable touch and step voltages for the substation are tabulated in Table 2.

1) Initial grid design with no geotextile

Unsymmetrically spaced earthing grid with overall dimensions of 124 x 48 m and 10 x 1.5 m rods used for this substation initially without considering additional geotextile as shown in Figure 5. Substation Fence has a separate earthing ring not connected to the main grid. The initial grid design is meeting the tolerable touch and step criteria.

CDEGS results for the initial grid design with no textiles shows an earthing resistance of 0.122 Ω achieving the safety criteria within and around the site with tolerable touch voltages about 1100 V and 816 V, respectively (based on IEEE 80:2013 criteria for a 70 kg (inside) and 50 kg (outside) person including a footwear resistance of 2000 Ω per foot).

2) Modified grid design

Although the addition of geotextile raises tolerable touch voltage by about 25 %, the overall earthing resistance increases by about 61 % with unsafe touch voltages within the substation. Accordingly, the grid design is set for improvement by replacing 1.5 m rods with longer ones (3 m each) and an additional 13 x 3 m rods spread throughout the grid. The improvement is considered to utilize the deeper lower resistivity soil layers.

It is evident that the addition of geotextile completely covering the earthing grid increases the overall earthing system impedance to remote earth, which in turn may require additional remedial solutions in case that the associated touch and step voltages exceed the tolerable limits. Nevertheless, in this case, the increase in resistance and touch/step voltages with geotextiles is much more than the increase in tolerable voltages and hence, additional remedial solutions are required by installing additional rods.

B. Case study II

The second case under study is for an existing substation with overall dimensions of about 140 x 110 m and proposed extension of 90 x 70 m as shown in Figure 6 where geotextile is used under the earthing grid extension due to soil stability conditions. The existing earthing grid is adequately designed with tolerable touch and step voltages. The native soil measurements at site modelled with CDEGS RESAP [17] show a 2-layer stratification as shown in Figure 7 indicating a lower layer with high resistivity. This is a case of interest as the addition of rods is not supposed to significantly affect the earthing grid impedance. The extension does not include additional sources for fault current contributions and hence, the EPR is considered virtually constant (it will be practically lower than the existing situation since additional conductors within the extension area reduce the overall earthing system resistance and EPR accordingly).

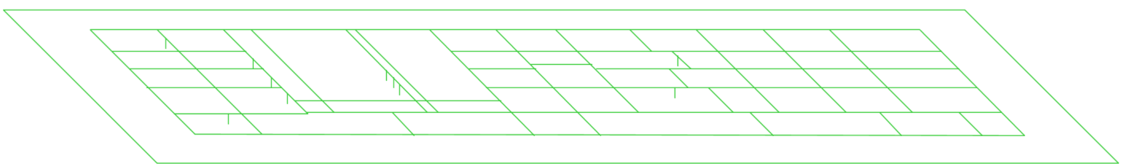

Figure 5. Earthing grid model in CDEGS with buried conductors and fenceline

Table 2.
Earthing grid performance parameters for case I

Parameter	No Fabric	Fabric	% Change	Modified design
Earthing system impedance (Ω)	0.122	0.197	61.5	0.133
Fault current (kA)	10	10	0.0	10
Earth potential rise (EPR) (V)	1225	1977	61.4	1335
Max. attainable touch voltage within substation (V)	958	1576	64.5	984
Tolerable touch voltage inside substation (V) – 70 kg	1105	1454	31.6	1454
Max. attainable touch voltage outside substation (V)	46	59	28.3	51
Tolerable touch voltage outside substation (V) – 50 kg	816	816	0.0	816
Max. attainable step voltage inside substation (V)	551	718	30.3	452
Tolerable step voltage inside substation (V) – 70 kg	2929	4326	47.7	4326
Max. attainable step voltage outside substation (V)	7	20	185.7	17
Tolerable step voltage outside substation (V) – 50 kg	2164	2164	0.0	2164

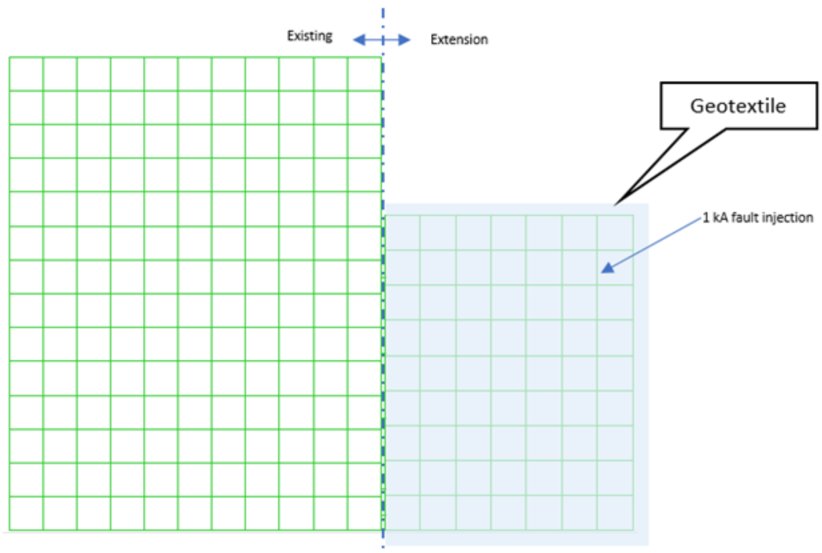

Figure 6. Earthing grid CDEGS model with existing and extension conductors

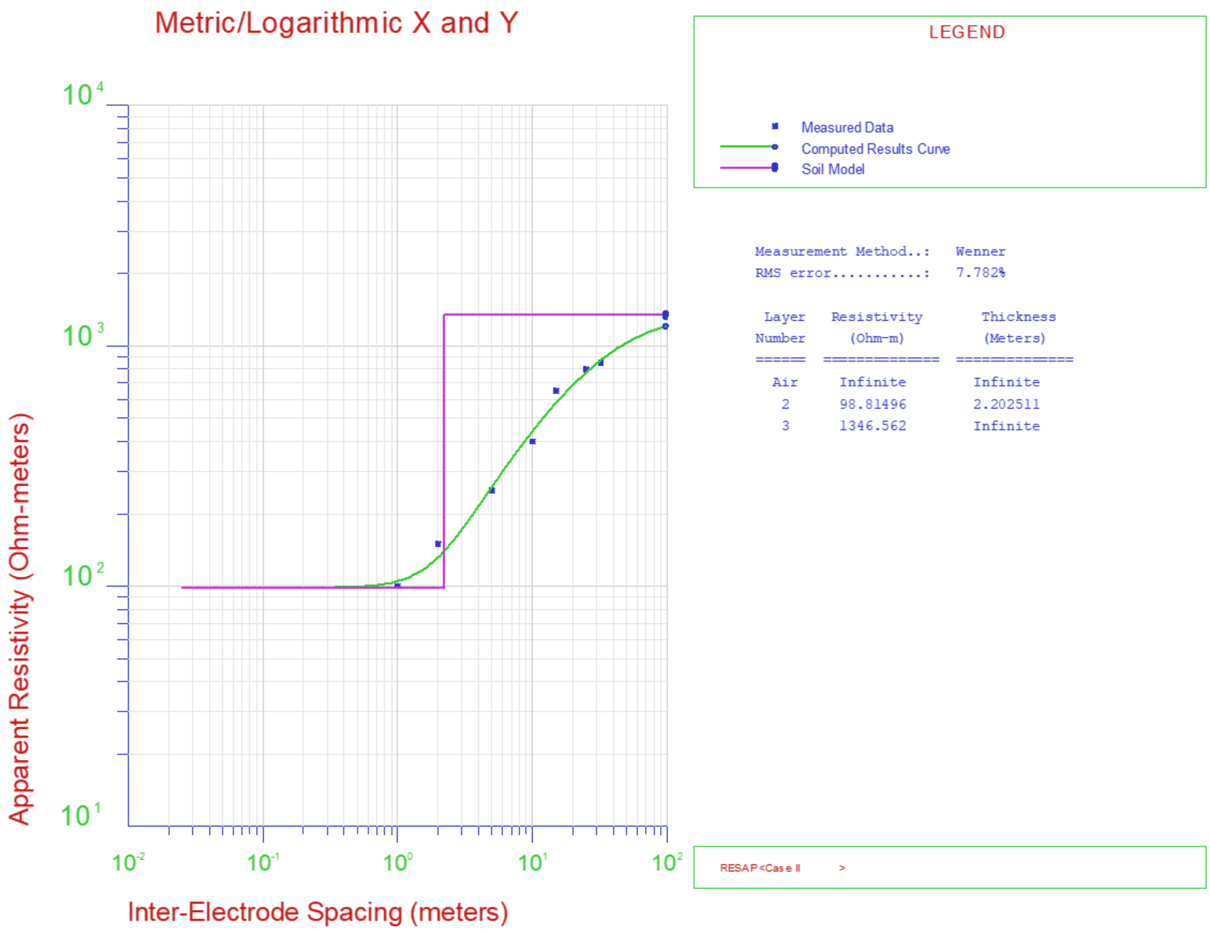

Figure 7. Native soil model showing 2-layer soil with low on high resistivity stratification

In the case of faulty equipment within the extension area, earth return fault current will leak from earthing conductors at the existing earthing grid rather than the new extension area as the immediate vicinity of the extension has a high resistivity layer underneath it. Nevertheless, a portion of the leakage current will flow upwards within the surface paving layer.

The leakage current density confirms the hypothesis due to the higher resistivity layer underneath the grid extension. The lower leakage current density results at higher surface voltages, touch, and step voltages accordingly since the voltage drop over top soil from the grid to surface is smaller with less current leaking into deeper soil. The increase in surface voltage and touch voltage is

Table 3.
Earthing grid performance parameters for case II

Parameter	Extended grid without fabric				Extended grid with fabric			
	Total	Existing	Extension	Ratio (%)	Total	Existing	Extension	Ratio (%)
Earthing system impedance (Ω)	2.76	[redacted]	[redacted]	[redacted]	2.77	[redacted]	[redacted]	[redacted]
Fault current (kA)	1	[redacted]	[redacted]	[redacted]	1	[redacted]	[redacted]	[redacted]
Earth potential rise (EPR) (V)	2760	2760	2760	[redacted]	2769	2769	2769	[redacted]
Max. attainable touch voltage within substation (V)	117	117	112	-4.27	124	124	119	-4.03
Tolerable touch voltage inside substation (V)	[redacted]	675	675	0.00	[redacted]	675	897	32.89
Max. attainable touch voltage outside substation (V)	234	234	225	-3.85	247	247	239	-3.24
Tolerable touch voltage outside substation (V) - barefoot	[redacted]	267	267	0.00	[redacted]	267	267	0.00
Max. attainable step voltage inside substation (V)	66	52	66	26.92	77	51	77	50.98
Tolerable step voltage inside substation (V)	[redacted]	1758	1758	0.00	[redacted]	1758	2647	50.57
Max. attainable step voltage outside substation (V)	86	86	83	-3.49	96	85	96	12.94
Tolerable step voltage outside substation (V)	[redacted]	371	371	0.00	[redacted]	371	371	0.00

Table 4.
Earthing grid performance parameters for case II – with additional 3 x 3 m rods

Parameter	Extended grid without fabric				Extended grid with fabric			
	Total	Existing	Extension	Ratio (%)	Total	Existing	Extension	Ratio (%)
Earthing system impedance (Ω)	2.76	[redacted]	[redacted]	[redacted]	2.77	[redacted]	[redacted]	[redacted]
Fault current (kA)	1	[redacted]	[redacted]	[redacted]	1	[redacted]	[redacted]	[redacted]
Earth potential rise (EPR) (V)	2760	2760	2760	[redacted]	2769	2769	2769	[redacted]
Max. attainable touch voltage within substation (V)	117	117	112	-4.27	124	124	119	-4.03
Tolerable touch voltage inside substation (V)	[redacted]	675	675	0.00	[redacted]	675	897	32.89
Max. attainable touch voltage outside substation (V)	234	234	225	-3.85	247	247	239	-3.24
Tolerable touch voltage outside substation (V) - barefoot	[redacted]	267	267	0.00	[redacted]	267	267	0.00
Max. attainable step voltage inside substation (V)	66	52	66	26.92	78	60	78	30.00
Tolerable step voltage inside substation (V)	[redacted]	1758	1758	0.00	[redacted]	1758	2647	50.57
Max. attainable step voltage outside substation (V)	86	86	83	-3.49	97	85	97	14.12
Tolerable step voltage outside substation (V)	[redacted]	371	371	0.00	[redacted]	371	371	0.00

accompanied by an increase in tolerable touch voltages as highlighted earlier. The increase in touch voltage is much less than the increase in tolerable limits. Comparative results are tabulated in Table 3.

The fabric has about 0.3 % effect on the overall resistance and EPR increase despite of the extension area representing about 29 % of total earthing system. Notwithstanding that, the surface voltage distribution and leakage current density are altered with the presence of geotextiles. Touch and step voltages appear to increase at both the geotextile covered and uncovered area. This behaviour is ascribed to higher surface voltages.

3 x 3 m rods are added to the corners of the extended grid to check the modified grid parameters. Additions of rods +2.2 m in length, although the deeper layer has a higher resistivity, stabilises the voltage and current distribution where provided, alleviating the effect of geotextile on step voltages increase. If the soil model has a lower deeper resistivity layer, rods will be more effective in diverting fault current into deeper layers and hence, less surface voltage gradients. Table 4 summarises the findings with additional rods. Due to the higher resistivity deeper soil layers, the addition of rods has a negligible effect on resistance and EPR.

IV. Conclusion

The introduction of geotextiles changes the earthing system behaviour by interfering into leakage current distribution into the surface and deep soil layers. The location of the earthing grid affects the results with considerable impact taking place when the earthing grid is installed above the geotextile layer. The tolerable touch and step voltages increase proportionally to the ratio between the surface soil and geotextile resistivity where the latter is considered to change with seasonal variations and soil water content. A typical tolerable touch voltage increase of about 60 % is envisaged for native surface soil of 100 Ωm. The addition of geotextiles and associated increase in tolerable touch (and step) voltages may alleviate the need for additional high resistivity finish materials. Earthing system behaviour in the presence of geotextiles depends on whether the textile covers the grid area completely or partially. The greatest impact on earthing system impedance and surface voltage distribution is expected for new substation installations where geotextile covers the grid completely. With partial coverage such as substation extensions, the impact is negligible on overall earthing system impedance. Vertical rods penetrating the geotextile layers when the earthing grid is installed above it are effective to alleviate the increase in surface voltages due to geotextiles even with deeper soil layers having a high resistivity. Rods should be spread through the earthing grid and corners to ensure proper current dispersion into deeper soil layers away from the surface as possible.

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Declarations

Author contribution

M. Nazih as the contributor of this paper. Author read and approved the final paper.

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Conflict of interest

The author declares no conflict of interest.

Additional information

No additional information is available for this paper.

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