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Evaluation of the Safety Performance of a 500-kV AC Substation Grounding Using IEEE Standard 80-2013

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ABSTRACT

The fundamental purpose of grounding electrical power systems and substations is to ensure safety of equipment and workers. To achieve this purpose, a high-resistivity surface material is recommended by IEEE Standard 80-2013, which defines the methodology to calculate safety parameters, including touch potential and step potential, considering the presence of a high-resistivity material such as gravel in the grid station, including raceways. However, concrete is generally used for raceway construction, whereas gravel material is used for constructing switch yards. As the resistivity of concrete is far less than gravel, this practice may lead to injury and even death, because workers and visitors walk on these pathways. This study conducted the safety analysis of concrete used as surface material. After the collection of data from an operational 500-kV grid station at Nokhar, Pakistan, simulations and analyses were performed using the Electrical Transient Analyzer Program software using IEEE Standard 80-2013. The results indicate that the use of concrete poses a considerable threat to equipment and personnel safety, because the measured values of touch and step potential exceed standard values. This is followed by the proposal and validation, through simulations, of a cost-effective, non-intrusive, and environmentally friendly solution by recycling old tires as surface material.
Keywords: Grounding system, recycling, resistivity, safety, step potential, touch potential

Introduction

The ground mesh or ground grid is a substantial part of a substation. Proper functioning of a grounding system ensures personnel and equipment safety [1]. A well-designed grounding system in a grid station provides benefits such as elimination of risk to the equipment's structure or performance by enabling discharge of electric current into the earth. It also ensures safety of the individuals working in the premises of the grid station by eliminating threats associated with the exposure to electric shock occurring during fault. A grounding system also helps to control unwanted odd harmonics and to protect equipment from fault over-currents caused by lightning [2, 3]. There are several equipment components interconnected with the grounding system of a grid, including the ground grid, overhead ground wires, underground cables, neutral conductors, foundations, and earth wells [1]. The design of a ground grid, a network of bare conductors, is of vital importance, because poorly designed systems pose life-threatening hazards worldwide. Hence, the problems related to ground grid construction and design should be addressed. The most common problem encountered in high-voltage substations is potential gradient increase that poses a threat to safety [4].

Several researchers have studied the problems related to the construction of grounding systems for substations and have provided solutions using optimization techniques [5]. Research efforts have been engaged to explore the most efficient and economical grounding grid, considering bi-stratified and multi-stratified soils, induced over- or under-voltages, and short circuit or fault currents [6-8].

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A low-resistance grounding grid can ensure the safe operation of installed apparatus and personnel safety; however, there are other important factors, including high touch potential and step potential, that contribute to the safe operation of grounding systems of electric power plants and substations [9]. Hence, it is necessary to consider these parameters during the fabrication of the design.

The IEEE guide for safety in alternating current (AC) substation grounding uses guidelines prescribed by IEEE Standard 80-2013 for substation grounding, which describes the concept and use of safety criteria, practical aspects of design, procedures, and evaluation techniques for grounding system assessment [1, 10]. Additionally, it provides safe limits of touch and step potential to avoid the loss of any equipment or human life. In combination with other standards, it provides a complete information guide for the construction and functioning of a substation grounding system that may be used in a distribution, transmission, or generation plant. IEEE Standard 81-2012 and IEEE Standard 81.2-1991 provide procedures for measuring resistivity of earth, overall resistance of ground grid, grid conductor's continuity, and surface gradients [11, 12]. IEEE Standard 837-2014 prescribes testing criteria for safe connections of a grounding system [13], and IEEE Standard 142-2007 provides information about practical installation of a grounding system [14]. IEEE Standard 665-1995 prescribes safe grounding practice of generating substations [15], and IEEE Standard 367-2012 addresses the important phenomenon of asymmetrical component of fault current and highlights the consideration of fault current division factor [16].

Safety criteria of a grounding grid depend on important factors, such as surface material resistivity, reduction factor of effective foot contact resistance, surface layer derating factor (C_s), magnitude of fault current, seasonal effects, and fault or short circuit duration [1]. Different safety parameters of grounding grids are defined in the next section. In this study, safety of a substation has been analyzed considering surface material resistivity in substation yards and on raceways. In usual construction, a layer of high-resistivity material, such as gravel, is spread over the soil surface; hence, the formulas discussed in [2, 4, 6] incorporate gravel properties in calculations. In contrast, the raceways in substations are constructed with concrete material, which exhibits resistivity less than that of gravel and in the range of 21 to 100 Ω m [1]. Considering safety as a primary constraint in electrical power systems, the main objective of this study was to investigate the use of concrete material on raceways.

The same issue was analyzed in a NEETRAC (National Electric Energy Testing, Research and Application Centre) Project. The research work investigated the impact of different surface materials on touch and step potential. However, the scope was limited, considering a small area of 144 square feet rather than the whole switchyard of a substation [17]. In July 1989, an analysis of the whole switchyard of a grid was performed by considering a plastic sheet beneath concrete pathways [18], which is not an actual practice [1]. This research work was conducted as a case study to perform the safety analysis, using IEEE Standard 80-2013, of an operational substation, a 500-kV grid station at Nokhar, Pakistan that used concrete as the surface material for raceways. The analysis was performed based on the actual parameters measured and obtained through field surveys. Ongoing global efforts focus on the recycling of waste tires for sustainability of the environment [19, 20]. Reports have already suggested the recycling of old tires for thermal insulation purposes [21, 22]. Considering the dielectric properties of the rubber used to manufacture tires, rubber is already in use as an insulator to encapsulate electronic circuits [23]. Additionally, research work presented in [24] has suggested the use of waste rubber from scrap tires for application as a high-voltage insulating material. Therefore, a solution, which is not only cost-effective but also environmentally friendly because of the use of recycled tires, has been proposed, which was validated through simulations.

Definitions of Safety Parameters of Grounding Grid

Ground Potential Rise (GPR)

If a distant point is considered as a point of zero potential or earth potential, then GPR corresponds to the maximum electrical potential that can be attained with respect to that point. It is calculated by multiplying the values of maximum grid current with total resistance of grid [25].

Surface Layer Derating Factor (C_s)

Surface layer derating factor is basically a correction factor of effective foot resistance in contact with a finite depth surface material. It is calculated by using the following formula derived from the IEEE guide for safety in AC substations [1, 10].

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

where h_s represents surface material depth, ρ represents soil resistivity, and ρ_s represents surface material resistivity.

Touch Potential (V_{touch})

If a person touches a grounded object inside a substation, there will be a potential difference arising between GPR and the metallic structure potential known as touch potential [25]. It is calculated as:

$$V_{touch} = I_B(R_B + 1.5\rho) \quad (2)$$

where R_B indicates body resistance, considered equal to 1000 Ω for analysis as per IEEE Standard 80-2013 [1]. I_B represents the value of tolerable body current, which is calculated as:

$$I_B = \sqrt{\frac{S_B}{t_s}} \quad (3)$$

where t_s represents fault or short circuit duration in seconds, and S_B represents an empirical constant equal to 0.0135 and 0.0246 for a human body weighing 50 kg and 70 kg, respectively [1].

The tolerable limit of touch potential can be calculated as:

$$V_{touch(tolerable)} = \frac{1000 + 1.5\,(C_s \cdot \rho_s)}{\sqrt{t_s}} w \quad (4)$$

where w represents a constant equal to 0.116 for a 50-kg body and 0.157 for a 70-kg body [1].

Step Potential (V_{step})
If a person walking in a substation traverses a length of 1 m without establishing contact with any grounded object, the potential difference observed is termed as step potential [25]. It is calculated as:

$$V_{step} = I_B(R_B + 6\rho) \quad (5)$$

whereas its tolerable value is estimated by:

$$V_{step(tolerable)} = \frac{1000 + 6\,(C_s \cdot \rho_s)}{\sqrt{t_s}} w \quad (6)$$

Fault Current Projection Factor (C_p)
C_p is defined as the projection factor of fault current for the future system growth of a substation during its life span [26].

Maximum Grid Current (I_G)
The maximum current flowing in a substation between grounding grid and surrounding earth is referred to as maximum grid current [2]. Its design value is estimated as:

$$I_G = C_p \times D_f \times I_g \quad (7)$$

where D_f represents the decrement factor, and I_g represents rms symmetrical current.

Fault Current Division Factor (S_f)
S_f represents the ratio of the symmetrical component of grid fault current to the homopolar (zero sequence) component of the current [27].

$$S_f = \frac{I_g}{3I_0} \quad (8)$$

where I_o indicates the zero sequence component of the current.

Materials and Methods

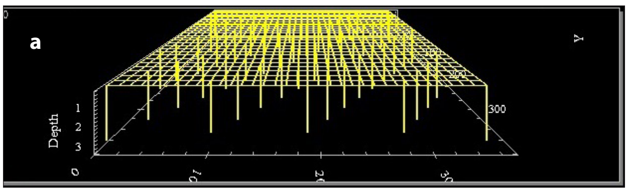
Grid Survey for Data Collection
Grounding grid data was collected from the 500-kV Substation at Nokhar, Pakistan. The ground grid has been installed already and has been operational since April 2009. Photographs of the substation are presented in Figure 1, which clearly indicate that gravel has been used as surface material in the substation switchyard, with concrete used as the surface material on pathways.

Safety analysis of the ground grid was performed using the Electrical Transient Analyzer Program (ETAP) to determine if safety parameters were within tolerable limits, considering the resistivity of different surface materials. The main objective was to analyze the safety parameters of raceways that have been

Figure 1. a, b. Photograph of NOKHAR substation showing gravel as surface material in the switchyard (a). Photograph of NOKHAR substation showing concrete as surface material on the pathways (b)

Table 1. Data collected from the 500-kV Grid Station in Nokhar, Pakistan

Sr. No.	Parameter	Value	Sr. No.	Parameter	Value
1	Voltage level	500 kV	16	Area covered by gravel material	354.9 m × 361.95 m
2	Fault current magnitude	40 kA	17	Area covered by concrete material	25 m × 125.8 m
3	Fault duration, fault clearing time, and shock time	1 sec	18	Resistivity of gravel (ρs)	3000 Ω·m
4	Fault current division factor (Sf)	0.6	19	Resistivity of concrete (ρs)	100 Ω·m
5	Cp (relative increase of fault current during substation life span)	100%	20	Ground conductor used	Copper annealed soft drawn
6	X/R ratio	50	21	Conductor area	120 mm^2
7	Ambient temperature	−5°C to 50°C	22	Ground conductors in horizontal direction under gravel	31
8	Weight of the body	70 kg	23	Ground conductors in vertical direction under gravel	32
9	Top soil layer resistivity (ρ)	50 Ω·m	24	Ground conductors in horizontal direction under concrete	4
10	Bottom soil layer resistivity	150 Ω·m	25	Ground conductors in vertical direction under concrete	13
11	Depth of the top soil layer	2 m	26	Conductor used for the rod	Copper clad steel rod
12	Depth of the bottom soil layer	Infinity	27	Diameter of the rod	16 mm
13	Surface material in substation yard	Gravel	28	Length of the rod	3 m
14	Surface material on raceways	Concrete	29	No. of ground rods under gravel	60
15	Surface material thickness (hs)	200 mm	30	No. of ground rods under concrete	10



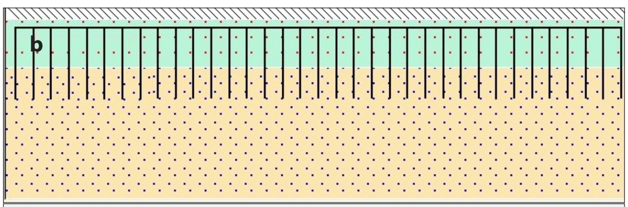


Figure 2. 3D Model of the grounding system (a). 2D model of the surface composition from top to the bottom with top layer as surface material and the bottom two layers as per data collected from NOKHAR grid (b)

constructed using low-resistivity material, such as concrete. The data collected for simulation are listed in Table 1. The modeling of the substation grounding system in ETAP is illustrated in Figure 2 (Figure 2a shows the three-dimensional model of the grounding system and Figure 2b depicts the two-dimensional model of the surface composition).

Simulation Using IEEE Standard 80-2013

The data collected from the 500-kV Nokhar grid station grounding system were modeled in the Ground Gird System (GGS) module of the ETAP software. This module provides flexible design techniques for ground mesh and incorporates IEEE 80-2013-prescribed methods [28]. Simulations were performed considering different case scenarios to calculate touch potential and step potential. This was followed by the validation of the proposed solution through simulations.

Safety Analysis of the Grid Station

Safety analysis of the grid station grounding system was performed for gravel- and concrete-covered areas using the GGS module of ETAP. The worst-case fault current of 40 kA is based on values obtained by conducting field surveys. The value was included after considering the current division factor of 0.6. For the 500-kV substation, a 3-phase short circuit fault in the system results in the occurrence of the worst-case scenario, thereby generating maximum fault current. The GGS module of ETAP is used to analyze the safety of the substation grounding system based on the level of fault current without considering the location of the fault. Therefore, the fault injection point can be located anywhere in the grounding. While performing modeling, shield wires were connected to both ends of the ground grid to maintain the induced voltages at the lowest level. As per IEEE Standard 80-2013 guidelines [1], tolerable limits of touch and step potential, considering that the value of t_s ranges from 0.03 s to 3 s, can be calculated using the data listed in Table 1 and the equations mentioned in the previous section. Fault clearing time, from 0.03 s to 3 s, was selected in compliance with IEEE Standard 80-2013. The allowable values of touch and step voltage are calculated with a fault clearance interval of 1.0 s, considering the fact that the human body has a permissible current fibrillation of up to 3 s.

Tolerable limit for touch potential for a 70-kg body is estimated as:

$$V_{touch} = (1000 + 1.5C_s.\rho_s)\frac{0.157}{\sqrt{t_s}} \quad (9)$$

Tolerable limit for step potential for a 70-kg body is estimated as:

$$V_{step} = (1000 + 6C_s.\rho_s)\frac{0.157}{\sqrt{t_s}} \quad (10)$$

Substituting the value of all parameters and ρ_s for gravel material in Equation (1), we obtain the following:

C_s= 1-(0.09×(1-50/3000))/(2×0.2+0.09)

C_s= 0.819

Substituting the estimated value of C_s in Equation (9) and Equation (10) helps to obtain the tolerable limits for touch potential and step potential respectively as:

$$V_{touch}\ (\text{Tolerable}) = (1000 + 1.5 \times 0.819 \times 3000) \times (0.157/\sqrt{1})$$

$$V_{touch}\ (\text{Tolerable}) = 735.6\ \text{V}$$

$$V_{step}\ (\text{Tolerable}) = (1000 + 6 \times 0.819 \times 3000) \times (0.157/\sqrt{1})$$

$$V_{step}\ (\text{Tolerable}) = 2741.5\ \text{V}$$

Similarly, the tolerable limits for the pathways covered with concrete can be calculated to obtain the following values:

$$V_{touch}\ (\text{Tolerable}) = 178.4\ \text{V}$$

$$V_{step}\ (\text{Tolerable}) = 242.5\ \text{V}$$

Simulations were performed to compute the values of touch potential and step potential for the area covered with gravel and the pathways covered with concrete.

Results

Results for the Existing System

Results are listed in Table 2.

Results indicate that the values of touch potential and step potential for the area covered with gravel are well within tolerable limits. However, the tolerable limits are exceeded by the calculated values of touch potential and step potential for pathways covered by concrete material. Hence, raceways constructed with a low-resistivity material, such as concrete, are not safe for individuals working and walking in the substation.

Table 2. Results for gravel- and concrete-covered areas

Surface material	V_{touch} (volts)		V_{step} (volts)	
	Tolerable	Calculated	Tolerable	Calculated
Gravel	735.6	107.3	2741.5	105.3
Concrete	178.4	2116.8	242.5	1425.9

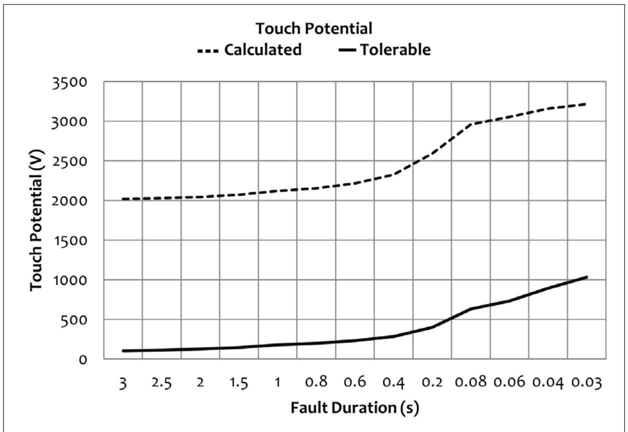


Figure 3. Impact of decreasing fault duration upon touch potential

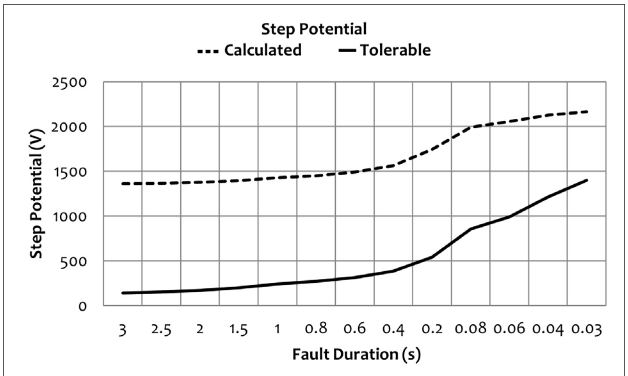


Figure 4. Impact of decreasing fault duration upon step potential

Impact of Varying Fault Duration and Surface Material Depth

According to Equation (4) and Equation (6), the tolerable limits of touch and step potential are directly proportional to C_s and ρ_s, whereas these parameters exhibit an inversely proportional relationship with t_s. To propose a solution, the values of these variables were varied over a wide range to investigate their respective impact on safety. First, the value of t_s was changed from 3 s to 0.03 s to analyze the impact of fault duration and clearance time on step and touch potential. The values of step and touch potential for various fault clearance times (0.03 s, 0.04 s, 0.06 s, 0.08 s, 0.2 s, 0.4 s, 0.6 s, 0.8 s, 1 s, 1.5 s, 2.0 s, 2.5 s, and 3.0 s) were obtained through the conduction of simulations. The results obtained are presented in Figure 3 and Figure 4. Equations (9) and (10) explain the increase in tolerable limits,

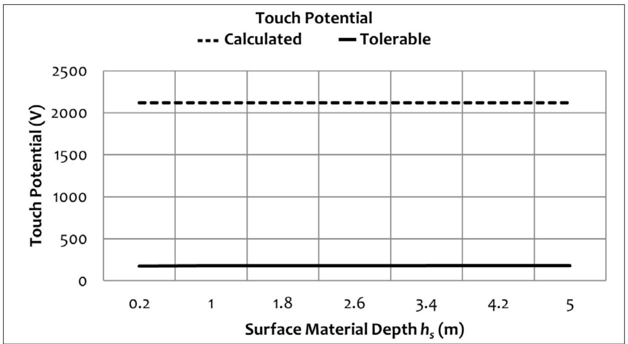


Figure 5. Impact of increasing surface material depth upon touch potential

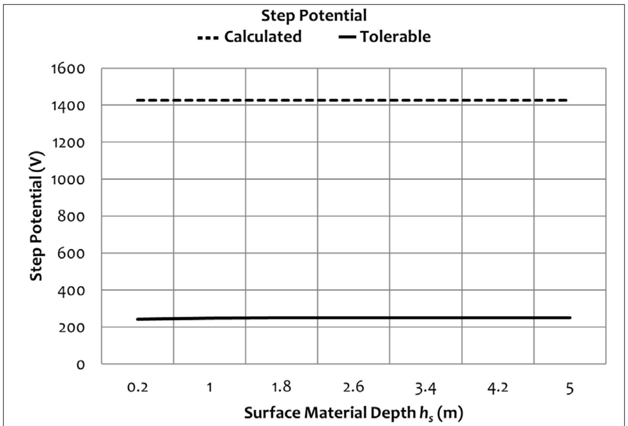


Figure 6. Impact of increasing surface material depth upon step potential

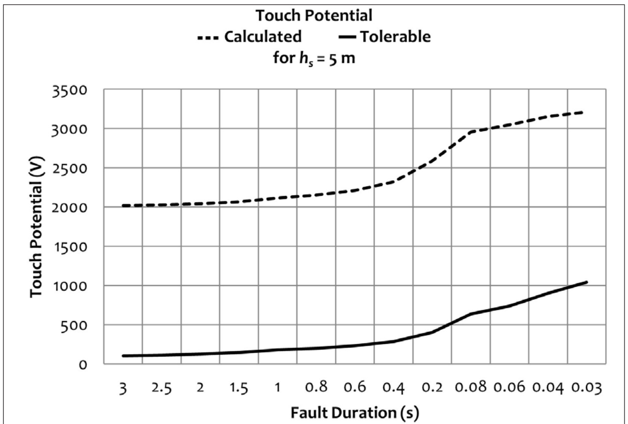


Figure 7. Impact of simultaneously increasing surface material depth and decreasing fault duration upon touch potential

as the tolerable limits for touch potential and step potential are inversely proportional to t_s. Moreover, ETAP is used to perform the simulation as per IEEE Standard 80-2013, which states that touch and step potential exhibit an inversely proportional relationship with t_s. Therefore, the results show an increase in both calculated and tolerable values; hence, no improvement in the present scenario was observed.

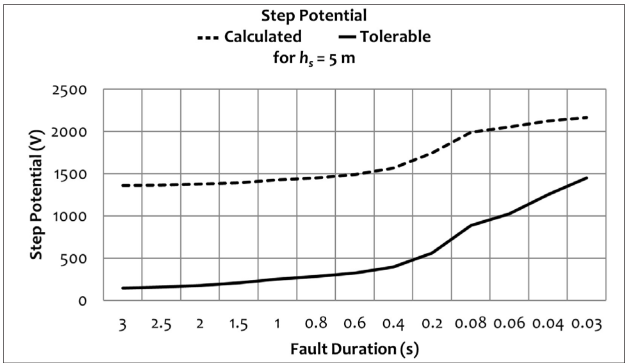


Figure 8. Impact of simultaneously increasing surface material depth and decreasing fault duration upon step potential

To analyze the impact of C_s, the value of concrete depth on raceways was increased from 0.2 m to 5 m, and results have been shown in Figure 5 and Figure 6.

Almost straight lines in Figure 5 and Figure 6 indicate negligible variations in tolerable and calculated values of both touch and step potential obtained by increasing the depth of the surface material, such as concrete, on raceways.

Simulations were also performed by decreasing the value of t_s and by increasing the value of surface material depth simultaneously. The results for h_s equaling to 5 m have been shown in Figure 7 and Figure 8.

Results clearly indicate that the installation of concrete material on raceways does not pose safety, even if the abovementioned parameters are changed. Hence, one valid solution is the installation of a high-resistivity surface material over the substation yard, including raceways.

Results for the Proposed Solution and Validation

Safety analysis was performed using gravel as the surface material on the total area of the substation, including raceways, and the results have been shown in Table 3, indicating that touch and step potential values were within tolerable limits.

However, replacement of concrete with gravel material will require a substantial amount of civil works. Moreover, walking on a rough gravel surface poses another health and safety hazard. This necessitates the formulation of a more appropriate solution to cover the already constructed concrete pathways with a thin layer of a high-resistivity and rugged material. Rubber tires are an essential part of automobiles. The solid waste produced by the ever-increasing number of used tires has emerged as a considerable environmental hazard in recent years [29, 30].

Polybutadiene is extensively used in the manufacturing of tires [31]. In addition to high electrical resistivity, polybutadiene exhibits properties of a rugged material, such as high tensile strength, tear resistance, and flexural strength, as shown in Table 4 [32]. It is also known to have extremely high imperme-

Table 3. Results for gravel used uniformly in the substation yard

Surface material	V_{touch} (volts)		V_{step} (volts)	
	Tolerable	Calculated	Tolerable	Calculated
Gravel	735.6	182.7	2741.5	189.8

Table 4. Properties of polybutadiene rubber

Sr. No.	Property	Value
1	Flexural strength	47 MPa
2	Flexural modulus	560 MPa
3	Tensile strength	180 MPa
4	Tear strength	140 MPa
5	Dielectric strength	94-106 KV/mm
6	Electrical resistivity	10^{14} Ω·m

Table 5. Results for waste tire rubber layer used over concrete pathways

V_{touch} (volts)		V_{step} (volts)	
Tolerable	Calculated	Tolerable	Calculated
6062.1	2116.8	23777.4	1425.9

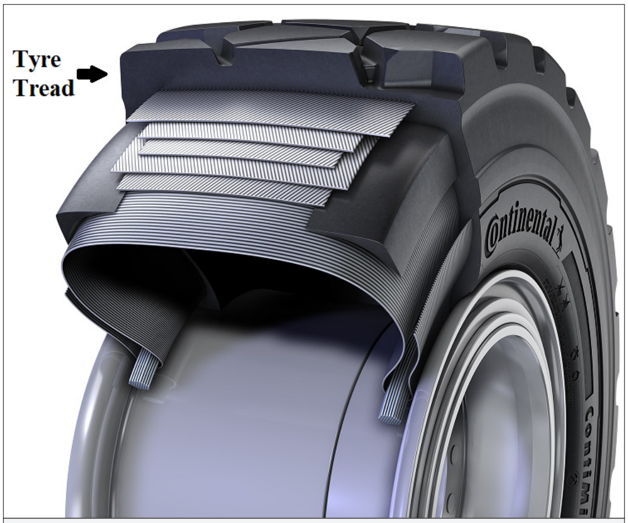


Figure 9. Rubber Material as Tread of the Tyre [35]

ability and thermal stability [33, 34]. Tires are designed to ensure optimum road grip, and this highlights tires as an anti-slip surface that may increase the safety of personnel against any slipping hazard. These properties render it suitable for utilization in an open environment, where it can be safely subjected to different climatic and working conditions.

Therefore, this research work proposes the utilization of a thin layer of tread of used tires as surface material over concrete material pathways, which will substantially increase surface layer resistivity. Figure 9 shows the rubber layer used as the tread of the tire [35]. Concrete pathways were analyzed for safety by placing a 0.6-in (15 mm) layer of waste tire rubber over concrete. The results obtained are shown in Table 5, along with the tolerable limits calculated using the methodology already presented. The value of electrical resistivity used for calculations is 99,999 Ω·m (lower than the actual resistivity) because this is the highest possible value that can be used for simulation in ETAP.

The calculated values of touch and step voltages on pathways are well within tolerable limits. The results agree with the conclusions reported by previous studies [23, 24]. This method of recycling of used tires to facilitate safety in substations not only helps to avoid the incurrment of substantial costs associated with the civil works required to replace concrete with gravel but also contributes toward sustainability of the environment. Tire tread surface being a rubber surface may not allow the seepage of water because of rain and other factors. This may be addressed by adding micro holes through the tires' surface to allow the seepage of water. Air in these holes, being an excellent dielectric, is not expected to affect the safety performance of the recycled tires as surface material. However, further investigations may be conducted in the future to validate the solution. Similarly, tires are made of flammable rubber material; however, tires are subject to high temperatures under harsh weather conditions, and conventional vehicles using tires also pose as fire hazards; however, tires demonstrate satisfactory performance. Moreover, designs to improve fire-retardant properties of tires and rubber by adding fire-retardant materials are being proposed [36, 37]. This will ensure that tires being recycled in the future and used as surface material in substations are also fire-retardant.

Conclusions

Practical use of concrete as the surface material for pathways in a 500-kV substation was analyzed in this study using guidelines prescribed by IEEE Standard 80-2013. The results show that the calculated values of touch potential and step potential exceed the tolerable limits. This renders personnel and equipment safety a serious concern at the raceways, because in case of any ground fault or short circuit, touch and step potential values will exceed tolerable limits within and outside the grid station because of transferred voltage criteria. Any person walking in the substation or touching any grounded object on the paved path may be subjected to fatal shock. Installation of a low-resistivity material, such as concrete, on paved paths is not safe even if its depth is increased or fault or short circuit duration is decreased. Therefore, it is recommended to use a high-resistivity material as surface material in substations, including raceways, to ensure safety of equipment and people in grid stations. Simulations indicate that the system poses safety if gravel is used as the surface material in the entire substation. Results also show the effectiveness of a practically more viable and environmentally friendly solution achieved by recycling used tires. A layer of synthetic rubber, that is, polybutadiene, from waste tires is used as a high-resistivity surface layer material over concrete. This increases overall resistivity, ensuring that the calculated touch and step voltages remain within tolerable limits.

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