2019 International Symposium on Lightning Protection (XV SIPDA), São Paulo, Brazil, 30th September – 4th October 2019.

Global and Brazilian Perspectives on Managing Ground Potential Rise at Overhead AC Transmission Structures during Power Frequency Faults

Invited Lecture: CIGRE Technical Brochure 694 Tutorial

William A. Chisholm
Associate
METSCO / EDM / Kinectrics
Toronto, Canada
W.A.Chisholm@ieee.org

José A Jardini
Electric Power and Automation
Engineering Department, USP
São Paulo, Brazil
jardini@pea.usp.br

Paulo Edmundo Freire
Paiol Engenharia
São Paulo, Brazil
Paiolengenharia.com.br

George Watt (CA)
Convenor, CIGRE B2.56

Lionel Figueroa (FR)
Secretary, CIGRE B2.56

Oswaldo Regis (BR)
Member, CIGRE B2.56

***Abstract*—The awareness of the potential safety risk is paramount in the safe operation of overhead transmission lines. The consequence of safety hazards from touch, step and transferred voltages due to Ground Potential Rise (GPR) cannot be ignored or under-estimated. A CIGRE Technical Brochure [1] has been developed to provide a brief overview of the source of the GPR problems related to ground current from ac line faults to the line grounding systems. The GPR issues are sensitive to the soil resistivity near the tower and to other factors. Any safety risk mitigation may require stringent measures at locations where public access is frequent and to a lesser degree when the access is extremely rare. The GPR mitigation should be designed to ensure any potential hazards be kept to acceptable levels.**

Keywords—grounding; transmission line; electrocution risk; touch potential; step potential; soil resistivity

I. INTRODUCTION

Grounding systems on AC transmission lines provide low-resistance, low-impedance paths to ground that can dissipate fault currents without causing damage to the facilities. When a line to ground fault occurs on an AC transmission line, the ground fault current will flow basically through two conductive paths – the ground wires and the towers' grounding systems. The latter will produce potential rise at the base of every connected structure. Voltage gradients will form on the ground surface near the structures. This introduces a second goal in grounding system design – which is to protect the public in the vicinity of grounded facilities from the hazards of electrical shock.

Many references treat the problem of improved grounding for lightning performance [2] [3] [4] [5] [6]. Other resources consider the influence of transmission line faults on adjacent infrastructure [7]. However, there are relatively few modern treatments of GPR safety issues [8] outside the electrical substation environment [9]. The ground surface potential gradients and the magnitude of potential rise on transmission structures and on metallic objects nearby will depend on structure location relative to the line fault location, fault current magnitude, coupling of the phase conductors with the overhead ground wires, soil resistivity and other factors. The CIGRE B2 Study Committee, Overhead Lines, recognized an opportunity to raise the awareness of GPR risks from ac faults on transmission lines, and to discuss these risks using modern "As Low as Reasonably Practicable" or ALARP principles, which are also known under other acronyms ALAP, ALARA and SFAIRP [10]. This work, assigned to Working Group B2.56, coordinated with similar progress in substation electrical safety risk analysis in the CIGRE B3 study committee [11].

Some countries have made considerable investments in technologies such as residual current devices (RCD) and cordless tools that have effectively reduced the rate of electrocution in the home and workplace. Transmission utilities need to adapt to the increasing expectation that their structures will be equally safe. The consequence of possible safety hazards from touch, step and transferred voltages due to ground potential rise (GPR) cannot be ignored or under-estimated in this evaluation. In making any such evaluation of safety, concepts from other industries should be coordinated. For example, the International Commission on Radiological Protection recommended in 1959 that all doses of ionizing radiation "be kept as low as practicable and that any unnecessary exposure be avoided". By 2001 [10] [12], this concept was extended in the United Kingdom to cover all aspects of workplace health and safety, including exposure to electric current. Debate continues about the coordination of what can be achieved technically, the role of minimum dose levels and coordination of what is reasonably achievable, considering the monetary value of preventing a fatality (VPF) [10]. Some vocabulary is found in ISO Guide 73 [13] that the *risk* of an electrical fatality at a transmission structure, for example, would be a product of the *probability that a fault will occur* on that structure and the probability that a *stakeholder will be present* and subject to this *risk source*, leading to an event with a *consequence*.

II. CIGRE Technical Brochure 694 Development

A. CIGRE Working Group B2.56

The terms of reference for CIGRE Working Group B2.56 were fulfilled in 2017 [1]. The scope was restricted to ground potential rise (GPR) at transmission line structures during power frequency faults. The case during which the ac fault has already been established was considered, as the treatment of GPR caused by lightning discharge fell outside the scope. Also, the guide did not address induction from adjacent lines or inductive and capacitive effects on pipelines, railway lines, large transport vehicles, etc. under normal operating and fault conditions. At the publication of the Technical Brochure (TB), the contributors were [1] :

G. WATT, **Convenor**	CA	D. LIEBHABER	US
L. FIGUEROA, **Secretary**	FR	J. LUNDQUIST	SE
W.A. CHISHOLM	CA	D. MATEUS	PT
C. CREW	AU	P. MORAN	IE
M. FAIRHURST	UK	V. NAIDOO	ZA
T. DE GRAUW	AU	O. REGIS	BR
M. JANSSEN	NL	P.H. PRETORIUS	ZA
J. JARDINI	BR	R. PUFFER	DE
J. KELLEHER	IE	H. STEGEMAN	NL
M. KVAMGREN	SE	C. WANG	CA

After an introduction, the TB described fault current considerations for shielded and unshielded lines, probability of fault occurrence and simultaneous exposure to the public, analytical models to establish fault current distribution and the resulting GPR. As these calculations depend intrinsically on local soil resistivity, and the resistivity varies considerably from structure to structure [14], a treatment suitable for the most common two-layer cases was set out. Safety considerations using this model relate to the comparison of body current flow with electrical safety standards such as IEEE 80 [9] and IEC 60479 [15]. Case studies support calculations of electrocution risk in summer and winter conditions. Links to the literature related to conductive coordination, conclusions and three Annexes complete the TB.

CIGRE has a policy to release its work to the public, through the web site www.e-cigre.org, after a two-year period when only the CIGRE members have free access. For the convenience of the reader, several aspects drawn from the text of TB 694 are included in this document. However, direct access to the full TB is encouraged.

B. Development of CIGRE TB694 Tutorial

After the publication of the TB, the B2.56 group prepared a tutorial. This was intended to be adopted by the respective CIGRE WG members to cover issues in their own countries, always recognizing that local regulations and standards must be respected. The original tutorial was prepared, considering the situation in the USA and Canada and delivered as a webinar with global reach, then in Madrid in 2018. A revised version was organized for presentation at a lightning symposium in St. Petersburg, Russia. It is now time to reveal a version of the TB 694 tutorial that focuses on the relevant situations in Brazil.

C. Adaptation of CIGRE TB694 Tutorial

The specific updates to the TB 694 tutorial, supported by this text, include:

1) Evaluation of the risk of EPR exposure from transmission lines in the context of the overall electrocution rate, relying on the relevant medical cause of death reporting system in Brazil;

2) Illustration of specific exposure concerns for rural and urban situations developed from Brazilian utilities;

3) Discussion of safe step potential and touch potential guides and standards within Brazil;

4) Discussion of fault occurrences observed on transmission lines in Brazil, including an approach to establish the probability of someone or some group touching or standing near the structure at that time;

5) Discussion of the effect of grounded shield wires, noting the wide use of this lightning protection for transmission lines in Brazil and its consequences on the X/R offset of the fault current.

III. Motivation: Electrocution Rates

A. Safety Measures for Domestic Electrical Systems USA

Electrical power is an inherently dangerous resource. A short-duration current flow of 150 mA can overwhelm the internal electrical activity inside the heart, causing ventricular fibrillation, where currents of 15 A flow in household circuits and 1500 A may circulate in transmission lines. Internationally and by country, the safety of electric power is managed through a complex set of equipment and installation standards including [15]. Multi-grounded neutrals were found to be safer in ac electrical systems starting from 1900. The three-prong plug with separate ground and neutral connections was invented shortly after. In the USA, three-prong plugs with separate neutral and ground circuits were introduced in 1947 for laundry area receptacles by their National Electrical Code (NEC) and were required for all new 120-V receptacles by 1962.

The USA National Electrical Manufacturers Associating (NEMA) assert that a progressive increase of Ground Fault Circuit Interrupter (GFCI, known as Residual Current Devices within IEC) installations from none in 1968 to >30 M in 2000 led to a reduction in annual electrocution rate from 2 per population of 10^6 to 0.7 per 10^6 during a 25-year phase-in period [16]. The present National Electric Code (NEC) calls for application of GFCI with 6 mA trip level in garage, laundry, bathroom and outdoor receptacles. The UL-943-2015 specification for GFCI includes shuttering, self-test and denial-of-power safety features that address poor reliability experience in areas of high lightning activity.

The positive experience with GFCI in the USA can be expressed as VPF (value of preventing a fatality). Each GFCI represented an investment of approximately USD \$100 and has a 30-year service life. Thus, the reported reduction from 600 to 200 fatalities per year in [16] from 30 M installations gives a VPF of (USD 3B) / (400×30 years) or USD \$250,000.

B. Electrocution Rate in the USA

The International Classification of Diseases ICD-10CM codes [17] organizes cause-of-death reporting in the medical community. Broken power line (or high voltage cable) is a circumstance causing injury and has a specific ICD code: W85. A search of annual death causes, filtered by ICD code, reveals in the USA [18] that in the 19-year period 1999-2017, there were 334 deaths from accidental exposure to electric current – total – W85 to W87. These broke down as:

- W85, Exposure to electric transmission lines, applicable to Broken Power Line: 82 annual deaths
- W86, Exposure to other specified electric current, 84 annual deaths
- W87, Exposure to unspecified electric current, 168 annual deaths

According to the Center for Disease Control (CDC), the data from the Multiple Cause of Death Files, 1999-2017, were consolidated from jurisdictions participating in the Vital Statistics Cooperative Program. Additional details are listed in Table 1.

There are no corresponding sub-codes for "exposure to transmission lines, initial encounter" code W85. These could distinguish phase-to-ground flow of current from direct contact with an exposed phase, where the victim becomes part of the ground path, from risks associated with step, touch or transferred potentials discussed in CIGRE TB 694 [1].

The single code for "Transmission Lines" in Table 1 does not describe the line voltage either, but does specify the inclusion of "Broken power line (causing electric shock)" as well as exposure to electric current from high-voltage cable or transmission lines and the generic exposure to electric transmission lines.

C. Comparisons with Risk of Death from Lighting

In the USA, mortality from ICD-10 code X33 (Victim of lightning, exposure to forces of nature) has declined over the past 100 years to a plateau of about 0.09 per million in 2015. The ICD system also includes T75.0, "Effects of lightning" but no mortality was listed with this code in [18] or Table 1. The shift in mortality with a corresponding change in fraction of the rural population was noted by Holle [19] in Fig. 1.

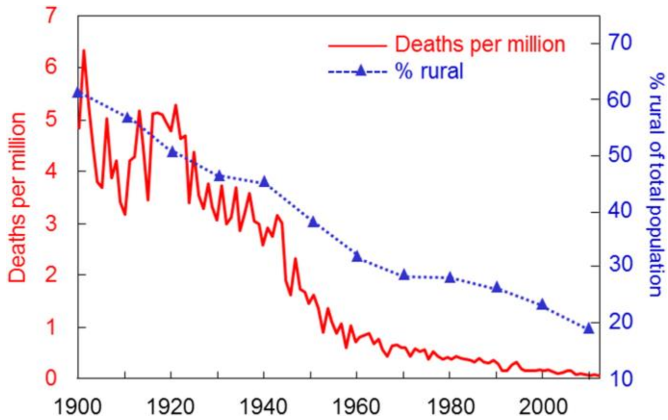


Fig. 1 Annual mortality rate from lightning, trend, 1890 to 2013 [19]

The tendency to higher mortality from lightning for rural areas and areas of higher ground flash density persists in the period 1999-2017. Records of death from lightning, Code X33 in Table 1, also suggest that people are more likely to be killed by transmission lines (code W85) and other exposures to electric current in the home and workplace (codes W86, W87).

TABLE 1 ANNUAL MORTALITY IN THE USA FROM EXPOSURE TO ELECTRICITY AND LIGHTNING, 1999-2017 [18]

Annual Mortality, per 10^6 of population		**Exposure to Electric Current**			**Lightning**	
		Transmission Lines	***Other Specified***	***Other Not Specified***	***Ground Flash Density***	
	ICD-10 Code	***W85***	***W86***	***W87***		***X33***
Northeast	Urban (Metro)	0.16	0.16	0.27	Low	0.07
Midwest	Urban (Metro)	0.23	0.20	0.50	Medium	0.09
South	Urban (Metro)	0.33	0.37	0.70	High	0.18
West	Urban (Metro)	0.15	0.17	0.36	Low	0.07
Northeast	Rural (Non Metro)	0.30	0.28	0.48	Low	n/a
Midwest	Rural (Non Metro)	0.40	0.39	0.81	Medium	0.15
South	Rural (Non Metro)	0.65	0.62	1.16	High	0.26
West	Rural (Non Metro)	0.41	0.26	0.61	Low	0.26

D. Safety Measures for Domestic and Industrial Electrical Systems in Brazil

In Brazil, most of the distribution utilities adopt the TN-C grounding system, with the distribution PEN conductor (common neutral and ground) multi-grounded along the low-voltage distribution line. Brazil was the first country to adopt an IEC Type N plug in 2007. Its domestic wiring codes require at least one ground rod for each domestic power entrance. Large domestic appliances have provisions for a local ground connection.

In Brazil, the Ministry of Labor regulates health and safety of workers through directives including the Consolidation of Labor Laws (CLT) and the Regulating Standards (NRs). Their Electricity Regulatory Agency, ANEEL, was created in 1996 to regulate production, transmission, distribution and commercialization of electricity and to ensure compliance with federal policies and directives [20]. All ANEEL resolutions are available at www.aneel.gov.br/biblioteca/pesquisadigit.cfm.

E. Electrocution Rate Data in Brazil

The Brazilian group ABRACOPEL (Brazilian Association Awareness of Electricity Danger) maintains specific annual data on accidents of electrical origin. The most recent summary of 2018 data is found at the link in reference [21]. There were 1424 recorded accidents, including both fatalities and injuries. A total of 38 fatalities were noted for lightning (*Descarga atmosférica*) compared to 622 fatalities from shocks associated with all electrical networks. This ratio matches the experiences noted for the USA in Table 1, with the sum of codes W85, W86 and W87 exceeding the fatality rate for X33 by a factor of ten. The rates are linked by the population of Brazil, which was about 211 million persons in 2018. Thus, the 38 fatalities for lightning in Brazil would give a code X33 rate of (38 / 211) = 0.18 per 10^6, like the urban areas in the south of the USA. The population in Brazil increased from 202 million in 2013 to 211 million in 2018. Normalizing the total number of electrical accidents in Fig. 2 with the census data suggest that the electrical accident rate has increased modestly in the past six years.

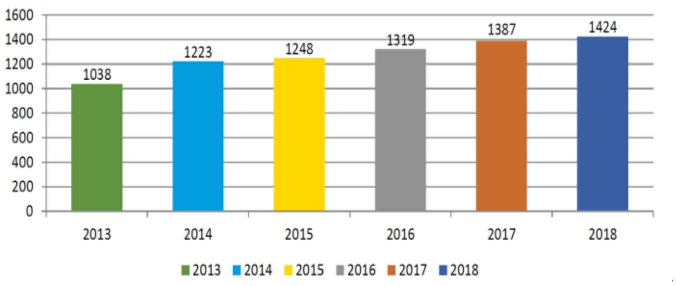


Fig. 2 Total number of accidents with electricity in Brazil, 2013-2018 [21]

Evidence that electricity is an inherently dangerous resource is provided in Fig. 3. There is only a 24% chance of surviving a reported electrical shock accident in Brazil.

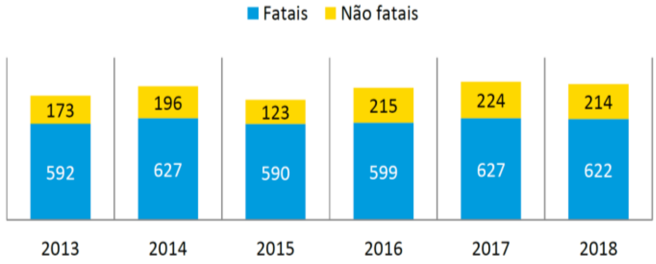


Fig. 3 Fraction of Fatal to Non-Fatal Outcomes from Electric Shock Accident, Brazil, 2013-2018 [21].
Legend: Blue bar, white letters: Fatal; Yellow bar, black letters: Non Fatal

The annual electrical accident report for Brazil [21] provides a breakdown by region in Fig. 4, with the Northeast having 261 fatalities in 2018, followed by southeast (123), south (97), central (73) and northeast (68). These records were not normalized by population density in each region.

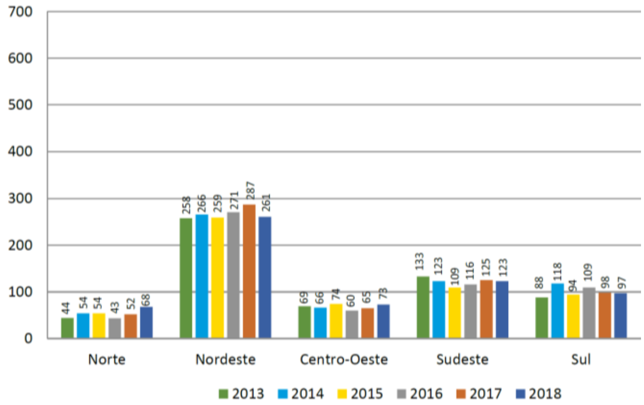


Fig. 4 Comparison of fatalities from electric shock by region in Brazil, 2013-2018 [21]

The rate of fatality from any exposure to electric current in Brazil is nearly 3 per 10^6, two to three times higher than the rates for USA regions in Table 1. The total electrical fatality rate in Fig. 4 has stayed constant in the period 2013-2018.

Across all of Brazil, the most common exposure in 2018 was contact with a distribution line (172 fatalities or 28%), followed by single-family house (168 fatalities or 27%). There were two fatalities in 2018 associated with contact to transmission lines and five deaths at substations. There were 59 accidents in urban areas that were classed as "poles, streets and avenues". Data for the entire reporting period 2013-2018 are aggregated in Fig. 5.

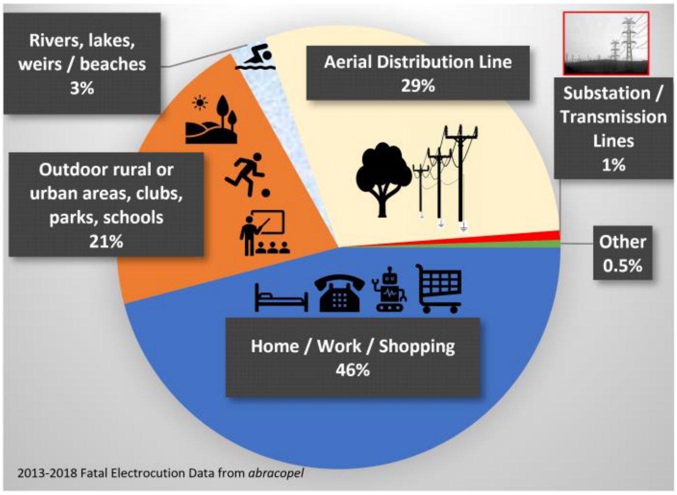


Fig. 5 Locations of fatal electrocutions, average fraction over 2013-2018, data aggregated from [21]

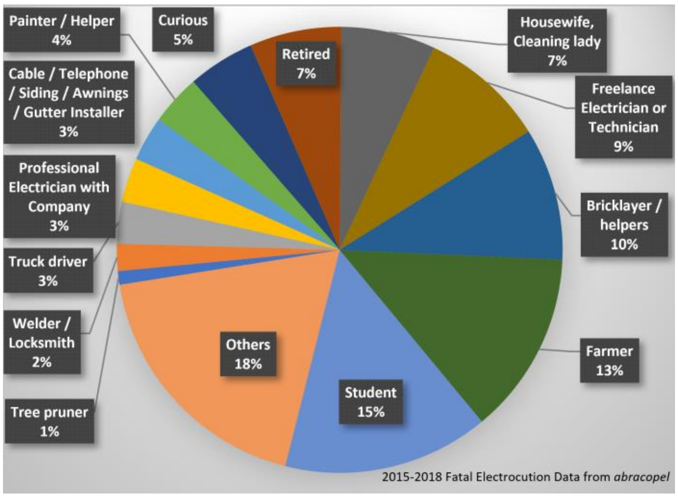


Fig. 6 Occupations of persons fatally electrocuted in Brazil, 2015-2018, data from [21]

CIGRE Technical Brochure 694 deals with ground potential rise associated with faulted lines, rather than with the direct-contact accident scenarios with exposed, energized phase conductors or with electrical wiring safety in the home. Its application is thus for the 21% of fatal electrocutions that occurred in *outdoor areas, clubs, parks and schools* in Fig. 5 with some relevance for the 3% of fatal *electrocutions associated with water*.

The occupations of greatest risk to electrocution from contact with aerial distribution lines in Brazil are masons, students, independent electricians, painters, farmers, electricians working for a company, the curious, truck drivers and professional installers (cable, phone, siding, awnings, gutters). When all types of contact are considered, the six-year average fatality rates were highest (in order) for students (people without a defined profession), farmers, self-employed professionals in the electrical field and housewives, including domestic workers. Fig. 6 shows, however, that electrocution fatalities in the period 2015-2018 affected many other professions.

When analyzing risk exposure, demographics such as age at death can be important. Fig. 7 shows that adults aged 21 to 40 years (*anos*) were at the greatest risk of fatal electrocution in Brazil in the period 2013-2018.

A significant number of electrical fires, 537 in 2018, led to 60 fatalities from overload and faults in the home and farm buildings. Among the causes can be example: old building; bad tap connection; lack of maintenance; multiple appliances in the same inlet; touch of agricultural vehicles; houses close to transmission line; ignition due to heat/vent/air conditioning. In a modern development, 39 fires from charging of cell phones led to 23 deaths.

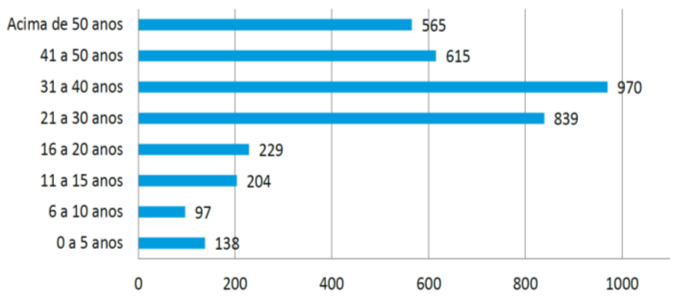


Fig. 7 Age distribution of persons fatally electrocuted in Brazil, 2013-2018 [21]. "Acima de 50 anos" is "Greater than 50 years".

F. *Electrocution Data for Other Countries*

In common with Brazil, many other countries such as Australia maintain annual reports [22] of electrical injury hospitalization and fatality. In contrast to a constant annual electrical fatality rate of about 3 per 10^6 in Brazil, the trend in Australia was a decline from 3 fatalities per million population in 1999 to less than 1 per 10^6 per year in the period 2011-2016. Conversely, there was an increase from 8945 to 9986 electrocutions in India from 2011 to 2016, giving annual fatality rates that increased from 7.2 to 7.6 per 10^6 over the period 2011-2016.

CIGRE Technical Brochure 694 [1] addresses the electrical risk from ground potential rise at faulted towers, rather than the risks of direct contact. The public expects that exposed portions of towers grounding systems will be at safe potentials, and it is the duty of utility electrical engineers to satisfy these expectations to a level that matches risk of having electricity in the home or workplace. The consensus design risk level suggested as "generally acceptable" is 1 per 10^6 fatalities per year. This risk level is achieved through a combination of limited exposure and technical features related to the local soil resistivity and ground potential rise.

IV. Typical Ground Potential Rise Exposures and Mitigation Methods in Brazil

A. *Typical Soil Conditions in Brazil*

Earth characteristics are fundamental parameters in the design of line grounding and for the calculation of the ground fault current distribution along the transmission line. Resistivity ρ (Ωm) is a measure of how much the ground resists to the flow of electricity. It can be defined by the relationship of voltage ΔU (V) between two electrodes of cross-sectional area S (m^2), and with separation ΔL (m), crossed by a current I (A):

$$\rho = \frac{\Delta U \cdot S}{I \cdot \Delta L} \tag{1}$$

The soil layers are complex systems consisting of solids, liquids and voids. Ground resistivity varies with the mineral content, degree of compaction, temperature and moisture. The fraction of contained water is significant in the weak electrolyte system. Topsoil moisture varies seasonally and thus, the same happens with the soil resistivity. The tower-to-tower variation in the soil resistivity ρ is also large, and a log-normal distribution with standard deviation $\sigma_{\ln\rho} = 0.9$ has been suggested [14] considering typical 250-300 m span length.

Within Brazil, it is feasible to interrogate the *geosgb.cprm.gov.br* database to obtain detailed maps of geological data, in a .kml format compatible with Google Earth. A highly detailed geology map for the state of Minas Gerais is shown in Fig. 9. This can be compared with the simplified three-level resistivity mapping, based only on geological period, in Fig. 8.

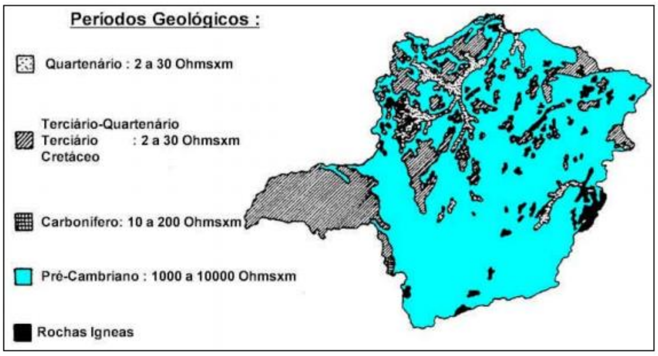


Fig. 8 Traditional resistivity map for State of Minas Gerais based on geological period

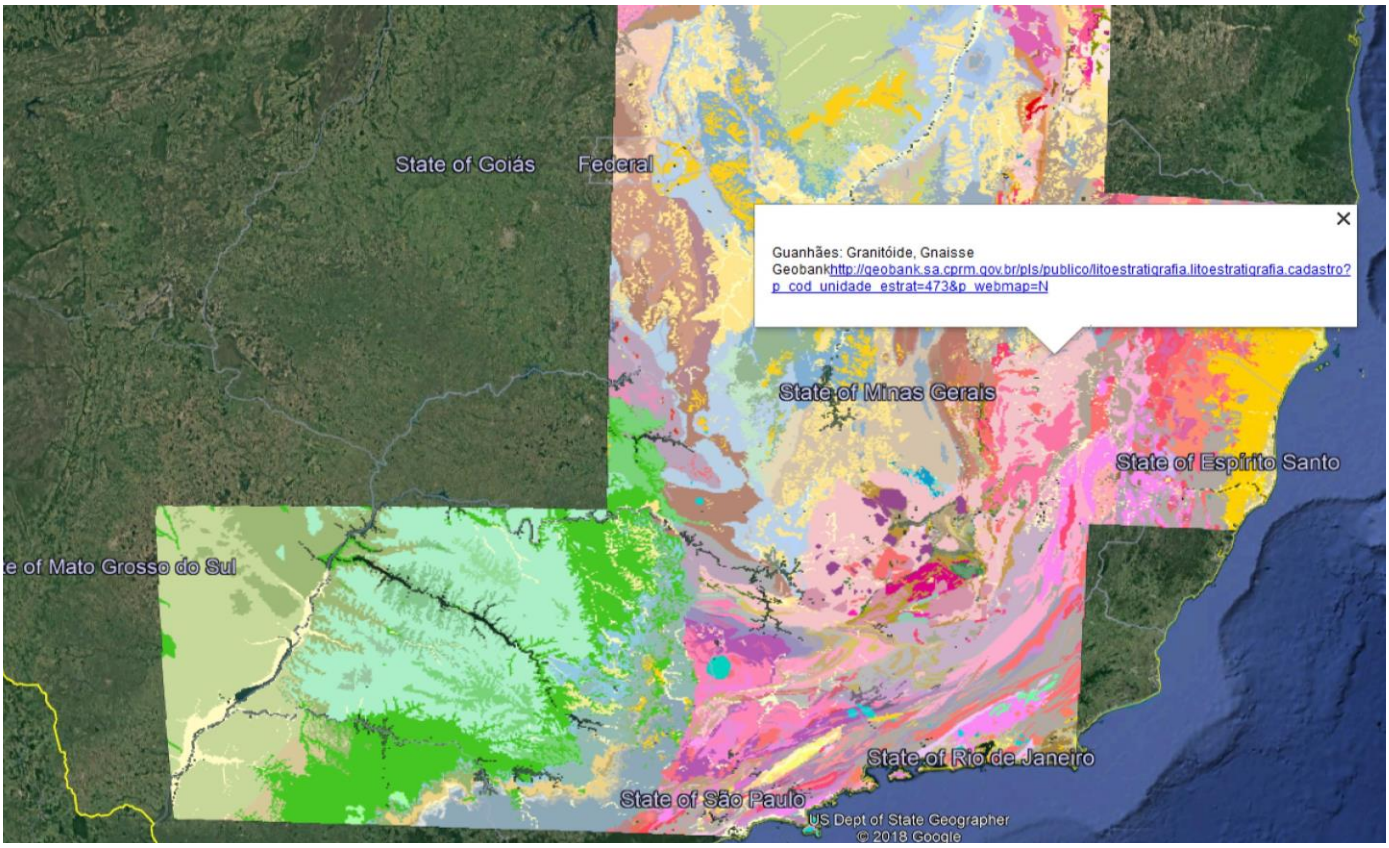


Fig. 9 "Carta Geológica da Folha, Belo Horizonte / Rio de Janerio / Rio Doce / Paranapanema" from **geosgb.cprm.gov.br** providing detailed and interactive readout of rock type in Google Earth .kml files

Expansion of Fig. 9 reveals a high level of detail, with a typical 100-km line traversing ten or more rock types in the monolithic region of "Pre-Cambrian" rock in Fig. 8 suggested to have 1000-10000 Ωm resistivity.

As a best practice, in the United Kingdom, the British Geological Survey has developed a country-wide map of soil resistivity specifically for electric power system grounding calculations [23]. Surface soils are ranked for clay content by the USDA in the USA to evaluate the possibility of using ground penetrating radar for farming, and fraction of clay content is an estimator of surface soil resistivity. A project to map rock types to uniform soil resistivity was also completed by TVA in the USA to make their "TTHOR" database, based on US Geological Services (USGS) data similar to Fig. 9.

To design a grounding electrode, it is usual to develop or find a ground resistivity survey, often using one or two orthogonal Wenner soundings [24] at each location. For each survey line, the average apparent resistivity curve is plotted as a function of probe separation distance. This is inverted or fitted to produce a geoelectric model. Often, a three-layer model is needed to represent the basic geoelectrical structure of the ground:

- Superficial layer – typically organic and/or dry soil, with medium to high resistivity and shallow depth of less than 1 m, with significant increase in resistivity when frozen;
- Intermediate layer – typically the water saturated ground, with low resistivity and a wide variation of width, depending on the regional tectonic setting; this is "unconsolidated surface materials such as soil or other regolith" [25]; and
- Basement layer - usually presenting higher resistivity to infinite depth, due to higher density or crystalline bedrock.

Evidence and resources for using multi-layer soil modeling are accumulating globally. For example, the depth to bedrock (DTB) has recently been estimated, with 1 m vertical resolution and 250 m horizontal resolution. These estimates were developed in part using records of more than 2000 boreholes and 274,000 water wells in Brazil [25] to train a set of global remote observations. Fig. 10 shows a wide variation in the estimated DTB within Brazil and in many other countries. The DTB estimates in Fig. 10 join other resources such as the ITU atlas of conductivity [26], airborne and ground-based electromagnetic measurements described in [1] for the structure GPR calculations.

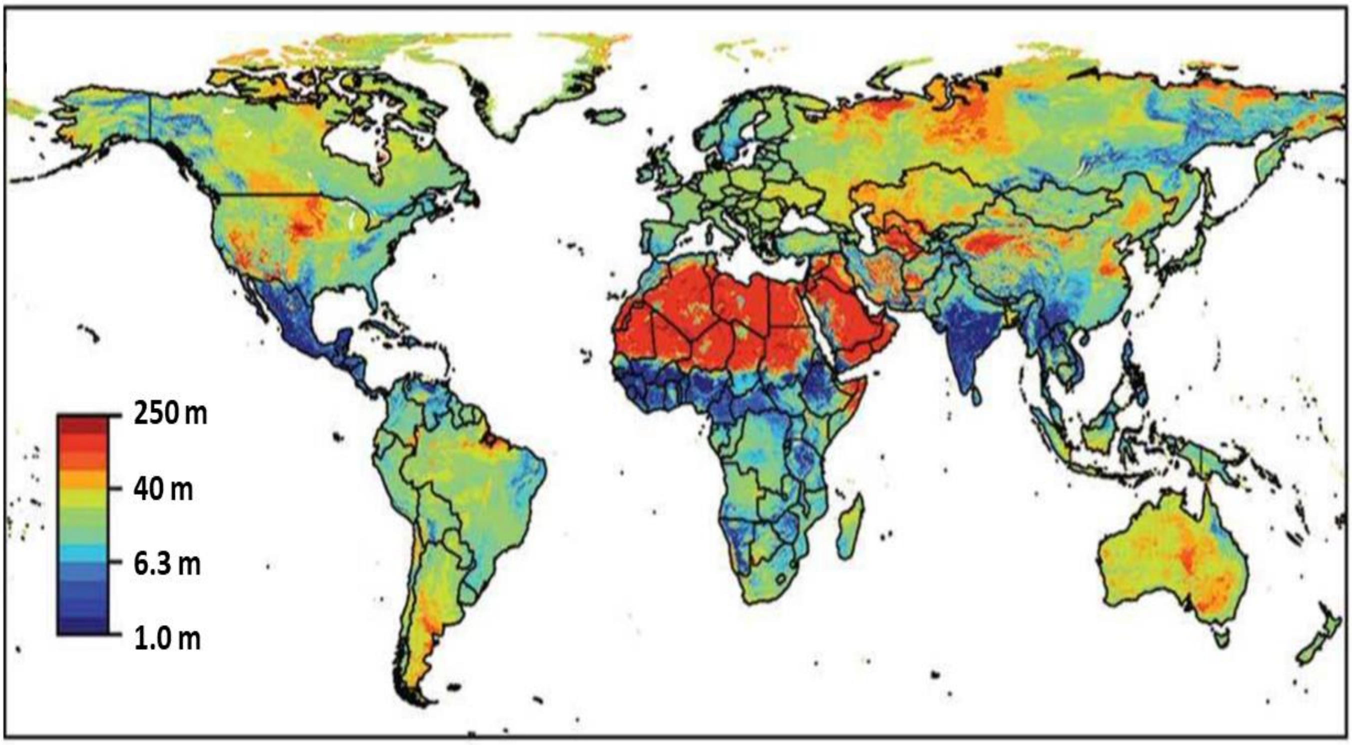


Fig. 10 Absolute depth to bedrock, estimated from 15 global covariates, adapted from [25]

B. Typical Transmission Line Ground Electrodes in Brazil

Many publications such as [27] provide typical Brazilian transmission tower dimensions of 30 m height with four square legs, 6 m side length for 138 kV systems. For the 230 kV structures of 43.3 m height, the legs form a rectangle with 6.6 m across the right-of-way and 9.8 m along the line direction. Transmission lines in Brazil are shielded with at least one overhead groundwire, and the implications of X/R offset in any fault current are discussed in Appendix 1. Each structure is grounding with four buried, horizontal "*counterpoise*" wires. The typical counterpoise is Ø 3/8" SM zinc-plated steel with 9.14 mm diameter and 51 mm² section, buried at a depth of 0.5 m. These grounding configurations are summarized in Fig. 11.

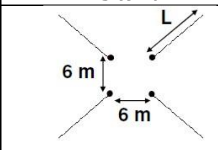
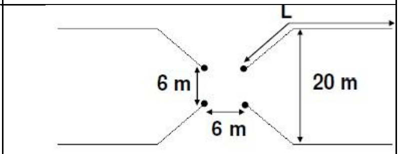
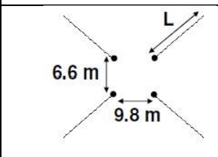
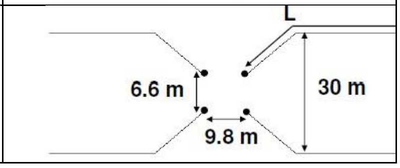
	Type I, Radial Counterpoise for Soil Resistivity $100 \leq \rho \leq 300$ Ωm L = 5 to 10 m	**Type II, Radial Counterpoise for Soil Resistivity $600 \leq \rho \leq 4000$ Ωm L = 30 to 110 m**
138 kV Steel Lattice		
230 kV Steel Lattice		

Fig. 11 Dimensions of typical transmission tower ground electrodes for adequate lightning performance in Brazil [27]

Two typical types of ground electrodes are shown in Fig. 11. Type I with four radial counterpoise are used for soil resistivity $\rho \leq 300$ Ωm. Type II counterpoise extend the X-shape counterpoise for $\rho > 600$ Ωm with four wires that are buried along the transmission right-of-way. These ground electrodes with long buried counterpoise are easy to install and reduce the ground potential rise from lightning impulse or ac fault currents. Their main purpose is in providing the greatest reduction in lightning impedance while not wasting resources on excessive length that contributes additional series inductance. The inductive reactance is negligible at power frequency but dominates the electrode response for characteristic lightning equivalent frequency components of 100-500 kHz at peak of current wave. Near the tower, the four radial wires also provide some degree of reduction in touch potential, although they are not as effective as buried rings for this purpose. Far from the tower, at remote ends of the counterpoise, there will be enhanced step potentials. If the paths of the buried counterpoise run anywhere near adjacent metallic fences or buried pipe infrastructure, the proximity may lead to higher transfer potentials.

The overall length of each counterpoise leg *L* in Fig. 11 is often adjusted to be effective at each tower or along line sections with the same soil characteristics. For this specification, the traditional method is to calculate the length *L* that will achieve a design value of tower footing resistance (TFR).

At CEMIG [28], Table 2 lists specifications for *L* of four-leg counterpoise that depend on the uniform soil resistivity ρ. The corresponding values of computed TFR vary over a 6:1 range from 6 Ω to 42 Ω. A thin 1-m surface layer of low resistivity soil (ρ_1 = 100 Ωm) has a strong effect on reducing the TFR in Table 2 because the burial depth of 5.2-mm diameter conductor was modeled as the minimum value, 0.5 m, fully in this superficial layer.

TABLE 2: FOUR-LEG COUNTERPOISE TREATMENT LENGTH AT CEMIG [28]

Soil Resistivity of Basement Layer ρ_B (Ωm)	**Counter-poise Length L (m)**	**Effective Perimeter in Uniform Soil: P = ρ/TFR (m)**	**Calculated Tower Footing Resistance TFR (Ω)**		
			Uni-form Soil, $\rho_1 = \rho_B$	**Upper Layer: 1m depth, ρ_1 = 100 Ωm**	**Upper Layer: 1 m depth, ρ_1 = 1000 Ωm**
≤ 250	20	41.8	< 6.0	4.4 for ρ_B = 250 Ωm	9.1 for ρ_B = 250 Ωm
251-500	30	53.8	4.6 – 9.3	5.6 for ρ_B = 500 Ωm	11.8 for ρ_B = 500 Ωm
501-1000	40	65.4	7.6-15.3	7.5 forρ_B 1000 Ωm	15.3 for ρ_B = 1000 Ωm
1001-2000	50	76.3	13.1-26.2	10.5 for ρ_B = 2000 Ωm	21.0 for ρ_B = 2000 Ωm
2001-3000	60	87.6	22.8-34.2	12.3 for ρ_B = 3000 Ωm	24.6 for ρ_B = 3000 Ωm
3001-4000	70	98.3	30.5-40.7	13.5 for ρ_B = 4000 Ωm	27.3 for ρ_B = 4000 Ωm
4001-5000	80	109	36.7-45.9	14.3 for ρ_B = 5000 Ωm	29.4 for ρ_B = 5000 Ωm
> 5000	90	119	> 42	19.5 for ρ_B 10000 Ωm	45.6 for ρ_B 10000 Ωm

Table 2 represents modern thinking by limiting the length of counterpoise to 80-100 m. In the 1980s, many utilities including CESP [29] called for the use of continuous counterpoise when the soil resistivity exceeded 1000 or 1600 Ωm. The additional length beyond 100 m is not effective under lightning impulse conditions. Instead, when the soil resistivity ρ is too high, two alternative options can be considered, depending on the probability of a person touching the tower/post of the transmission line:

- If the line is crossing a rural area, which is inhabited, the design may apply counterpoises with intermediate length (about 50 m) in order to enhance the lightning performance of the grounding;

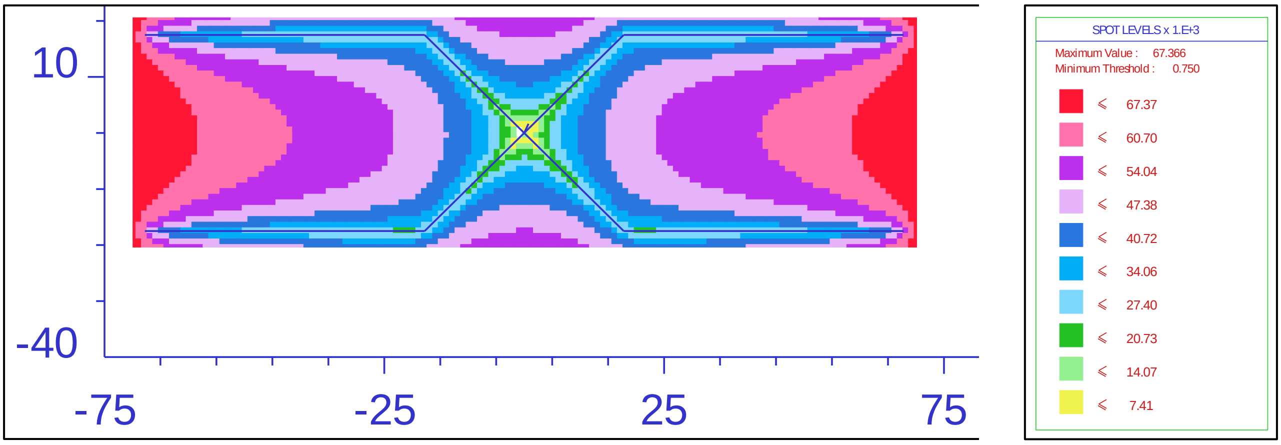
- If the line is crossing a village or is an urban line, then there will not be available space for long counterpoises and mitigation measures shall be applied for the control of step and touch potentials.

C. Step and Touch Potential Calculations for Type II Radial Counterpoise on Isolated Tower

A commercial software program, MALTZ, was used to illustrate the regions with high levels of touch and step potentials using the Type II electrode in Fig. 11. A homogeneous ground resistivity of ρ = 1000 Ωm was considered with a total length of L = 71 m, consisting of the central X shape and four legs, each 50 m long. With a 10-kA fault current, the power frequency ground potential rise (GPR) of the isolated tower would reach 98 kV.

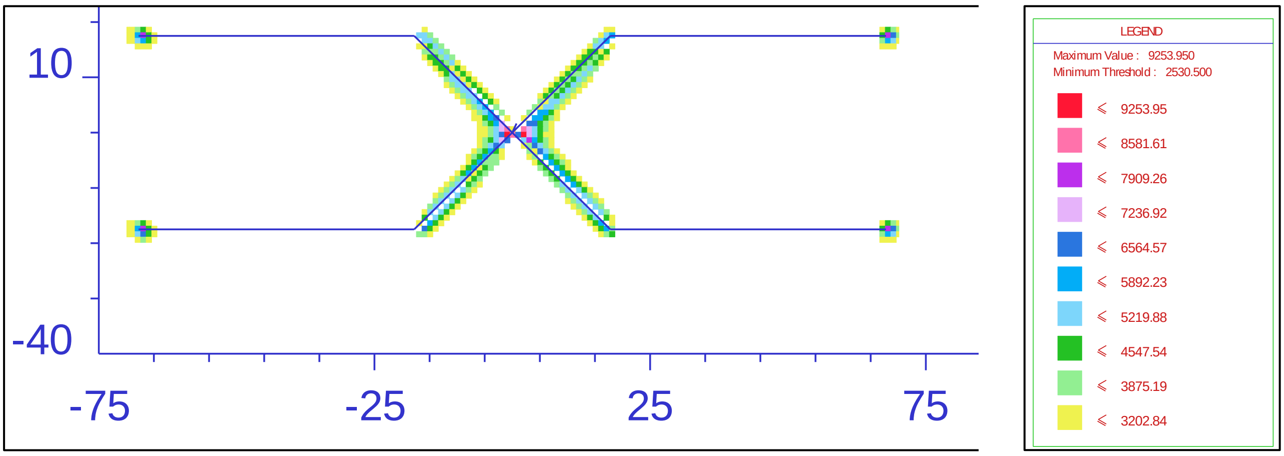
Fig. 12 shows that touch potentials near the structure are a tenth of this magnitude. However, at the remote ends of the counterpoise, transferred potential reaches nearly the full value of GPR. The calculated step potentials show two areas of possible concern – directly over the X where four counterpoises meet, and at their endpoints.

Similar calculations to Fig. 12 and results are found in CIGRE TB694 [1] for the four-leg counterpoise ground electrodes used in France, with L=100 m.



Calculated Touch Potentials for 10-kA tower current, with 71 m counterpoise

Scale (kV per 10 kA)



Calculated Step Potentials for 10-kA tower current, dimensions (m)

Scale (V per 10 kA)

Fig. 12 Calculated Touch and Step Potentials near Type II Radial Counterpoise Electrode in 1000 Ωm Soil

D. Transmission Structure GPR Management Practices at CEMIG

In urban areas, the Brazilian utility, CEMIG, reports that it designs specific grounding systems to control touch and step potentials. In addition, it is common to adopt soil cover layers. A four-leg steel lattice structure in Fig. 13 sits in a vacant lot, surrounded on three sides by houses and with free access from a road. This is an area where children may gather, and perhaps even use the tower legs as fixed points in games of tag.

Fig. 13 Transmission structure with elevated risk of public exposure and surface stone treatment (courtesy CEMIG)

CEMIG sometimes adopts soil cover layers of stone, gneiss or asphalt. Fig. 13 shows that a surface layer of stone extends through the yard, like a substation. In contrast, the legs of the lattice structures in Fig. 14 are somewhat isolated from public access by a low concrete barrier.

Fig. 14 Transmission structure with moderate risk of public exposure, accessible from road, barrier and surface treatment (courtesy CEMIG)

The earth barrier in Fig. 15 performs the same function for a lattice structure located near dirt path. Asphalt surfaces provide additional mitigation around the moderate-exposure-risk towers in both Fig. 14 and Fig. 15.

Fig. 15 Transmission structure with moderate risk of public exposure, accessible from path, earth barrier and surface treatment (courtesy CEMIG)

In addition to surface layers that increase under-foot resistance, CEMIG may install grounding systems composed of vertical rods and horizontal buried cables, forming concentric rectangular or circular rings around the structure legs. The usual separation between rings of 1 m in Fig. 16 may be adjusted to as close as 0.5 m depending on soil resistivity and other factors.

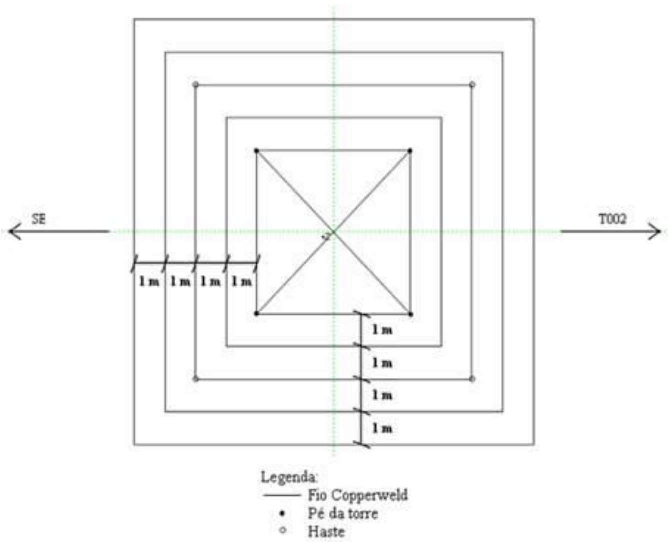


Fig. 16 Buried Concentric Square Rings around Four-Leg Transmission Structure for Step and Touch Management (courtesy CEMIG).

The multiple buried ring electrode in Fig. 16 does not achieve the same reduction in footing impedance as the radial electrode systems in Fig. 11, but it is efficient for managing touch potentials by reducing the electric field gradients along the soil surface near the tower. Increased step potentials at the edges and corners of the square ring may be controlled by a combination of increased ring depth and/or driven vertical rods. A surface layer of flat gneiss stone of high resistivity, grouted with tar, is shown in Fig. 17. This would be located at the edge of a rectangular ring, where step potential concerns would be highest.

Fig. 17 Surface Layer of Gnaisse Stone with Tar Grouting for Mitigating Ground Potential Rise Effects (courtesy CEMIG)

E. Urban Transmission Line GPR Exposure and Management Practices at COPEL

COPEL [30] reported the extension of compact urban transmission lines (UTL) from initial applications at 69 kV (1975) to 230 kV (2004). Three copper-clad grounding rods, each 6 m long and separated by at least 6 m, form the ground electrodes at each concrete pole. Fig. 19 shows that the heads of the rods are driven at least 1.5 m below grade, and electrical connections are made through insulated tubes to reduce step potentials. The touch potential management is provided by a 100-mm thick asphalt layer, in a square around the pole base and protected by stone blocks as shown in Fig. 19.

Double overhead ground wires, one above and one below the phase conductors, provide additional GPR mitigation by reducing the local short-circuit current. Metal davit arms support the underbuilt ground wire and catch any phase conductor that may fall from above. The 69 kV and 138 kV UTL use line post insulators. Braced posts are used for 230 kV to support the loads from its twin-bundle phases.

The use of Google Earth allows a study the present-day visual features of the COPEL UTL, to make a close inspection of the ground surfaces around each concrete pole, and to sample the public exposure to EPR risks at the time of the Street View surveys. In substations, growth of grass over time degrades the benefits of surface stone. Generally, the stone block surfaces of UTL in Curitiba, Brazil were clean but some organic growth between the blocks can be seen in Fig. 20.

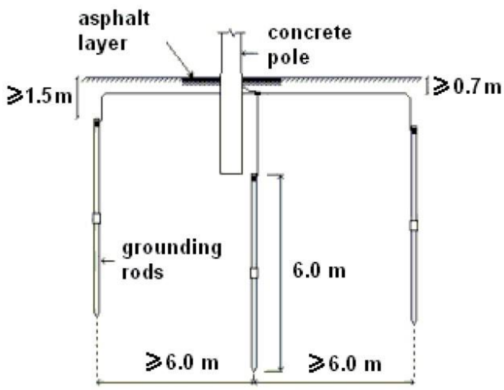


Fig. 18 Side View of Ground Electrode for UTL Pole at COPEL [30]

Fig. 19 Grounding Surface Execution for UTL at COPEL [30] using Asphalt/Stone Block/Mosaic Surface Treatment

Roughly one in ten poles observed in a Street View tour of UTL in Curitiba showed one or more persons walking nearby, but no touch contact was observed in any image.

Foreign Object near UTL pole; Organic Contamination between stone blocks; Google Street View image 7/2018

Public Exposure – 2 persons near UTL Pole, 25° 25’ 51.45” S, 49° 16’ 49.86” W Google Street View Image 12/2018

Public Exposure, 5 persons near UTL Pole,
25° 27' 30.36" S, 49° 17' 50.03" W
Google Street View Image 7/2018

Fig. 20 Typical conditions and public exposures found at UTL concrete poles in Curitiba, Brazil using Google Earth Street Views.

Fig. 21 Comparison of UTL footprint (concrete pole with black/yellow bands, left) with conventional steel lattice structure (raised earth berm, right). Location: 25° 26' 23.33" S, 49° 15' 8.60" W, Google Earth Street View 8/2017.

F. *Historical Transmission Line GPR Exposure and Management Practices at CESP*

The Companhia Energética de São Paulo (CESP) developed their *Instrução TM/035/80* for substation and transmission line grounding in 1980 [29]. The general issues of step and touch potential risk around structures were identified at that time, 35 years before the initiation of CIGRE B2.56. The electrical models from this guide in Fig. 22 and Fig. 23 include a human body resistance R_H of 500 Ω and an un-specified contact resistance R_C from foot to soil (pé-solo). In common with today's IEEE Std. 80 [9], two feet appear in parallel ($R_C/2$) for the touch exposure in Fig. 22 and in series (2 R_C) for step exposure in Fig. 23.

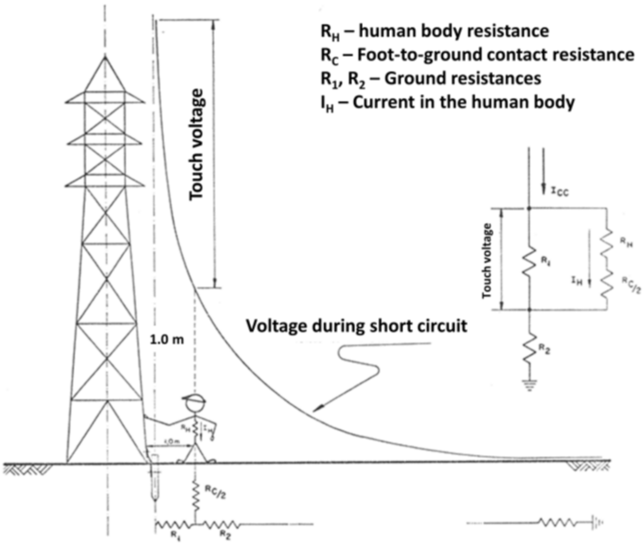


Fig. 22 CESP electrical models for touch potential near transmission structures in São Paulo in 1980, adapted from [29]

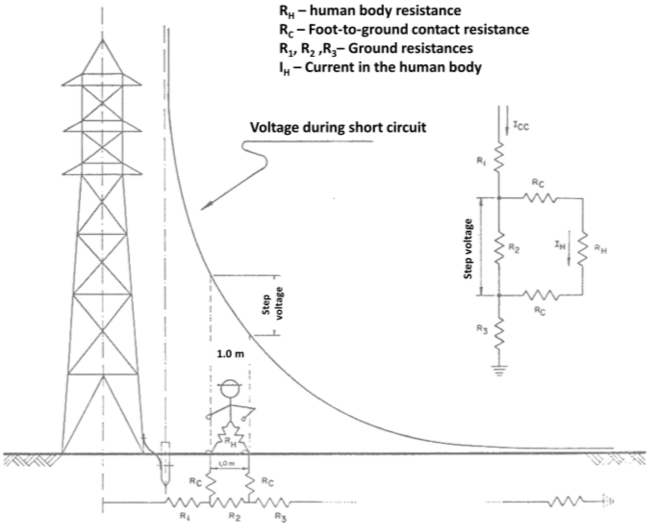


Fig. 23 CESP electrical models for step potentials near transmission structures in São Paulo in1980, adapted from [29]

The CESP guide recommended measuring the step potential by injecting a current to the isolated structure and recording the corresponding potential to a copper or aluminum plate, located 1 m from the tower leg as shown in Fig. 24. The remote current injection probe was located at a distance of ten times the major dimension of the grounding system, a practice that is still endorsed today in IEEE Std. 81 [24]. Voltage rise in response to several impressed currents formed a V/I curve that is expected to be linear. Extrapolation to the expected fault current ICC makes use of the slope found in the experimental data. An upper limit of 50 V measured across a 500 Ω resistance from tower to plate defined hazardous and non-hazardous areas.

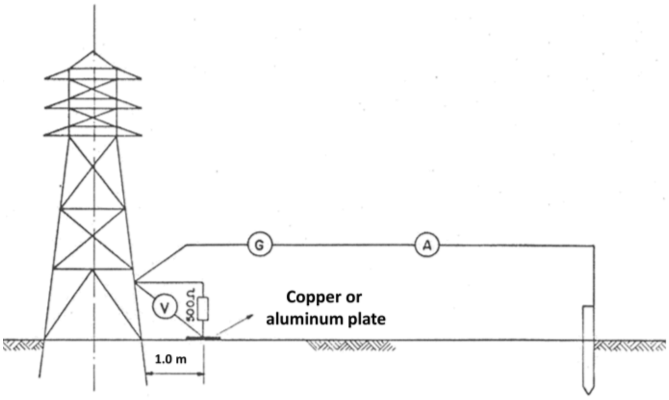


Fig. 24 CESP method to measure touch potentials around isolated transmission structures in São Paulo in 1980, adapted from [29]

The CESP guide also suggested injecting the current into one of two metal plates, and measuring the voltage at a second plate, at a step distance of 1 m. Fig. 25 shows that a 500 Ω body resistance load was inserted between the two plates. The plate radius was fixed as 0.08 m to simulate a human foot in calculations that incorporate the foot resistance as the Thevenin internal impedance of the electrical source. Many areas had a superficial layer of grass that was removed so the contact plate could reach an intermediate soil layer.

In more recent practice, the local current injection lead remains connected to the structure for both touch and step potential measurements. Probes, rather than plates, are recommended in [24] for earth surface potential measurements. Step potentials are obtained from the difference between two touch potential readings, taken at different probe distances using high-impedance earth resistance test instruments, with no simulated body resistance across the terminals. The human body resistance is assumed to be 1000 Ω only in the follow-up calculations [9]. The earth surface potential measurement guide does state that "*Sometimes, measurements include currents through a 1000 Ω or 500 Ω resistance to simulate a human body*" [24].

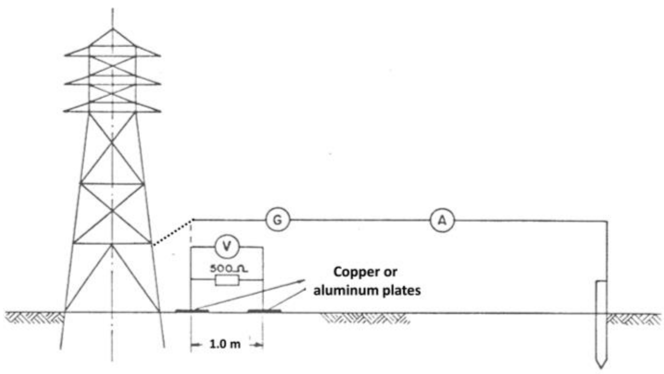


Fig. 25 CESP method to measure step potentials around isolated transmission structures in São Paulo in 1980, adapted from [29]

The CIGRE TB694 [1] proposes an improved method to survey step potentials, based on injection of an impulsive current to the tower base. A portable digital oscilloscope is triggered from the impressed current, and an isolated channel records the corresponding voltage impulse between two probes, located 1 m apart. Direct recording of the potential difference between two probes improves the signal-to-noise ratio of the tests. Also, new technology such as flexible Rogowski coils and integrators has been developed to measure the small fraction of current flowing into the structure's ground electrode when its overhead groundwires are connected to adjacent structures. These high-technology approaches both eliminate the need to isolate the structure electrically before testing. In both cases, the local soil resistivity can be fitted to measurements of touch potentials at several distances, measured from the center of the tower.

V. CONCLUDING REMARKS

The problems of touch and step potentials around transmission structures have been addressed with increasing sophistication in many countries, including Brazil. Design guidance in the 1980s was focused on measuring the footing resistance of isolated towers, mainly to improve safety by reducing the number of lightning faults. Decisions to incorporate buried conductors such as grading rings, or high-resistivity surface materials, have been considered in some Brazilian transmission lines for forty years. These alternative grounding arrangements reduce touch potentials for all faults, not just those that occur during lightning storms when probability of physical presence at a tower is low.

Based on an annual electrical fatality rate about 3 per 10^6 persons, Brazil in 2019 at is something like Australia in 1999. This rate has been driven downward by a factor of three in Australia with a combination of technical improvements in the home (RCD and battery-operated tools) as well as technical improvements in management of power system faults.

The technical content in CIGRE Technical Brochure 694 provides some details in the technical evaluation of step and touch potentials, including a treatment of the effective resistivity for a foot on two-layer soil where the upper layer has lower resistivity than the lower layer. Brazil is an area with a wide range of geological conditions, and its federal programs deliver data that are easy to interrogate using public-domain Google Earth mapping systems. It is thus well positioned to integrate the TB694 process into assessment and mitigation programs to manage ground potential rise at overhead ac transmission line structures during power frequency faults.

VI. RECOMMENDATIONS

Some updates are recommended to the process in CIGRE TB 649 [1] to coordinate with the publication of CIGRE TB 749 [11], dealing with a quantitative risk assessment for substations. Both publications focus on a tolerable fatality level of one in 10^6 per year, but it seems that actual electrocution rates are declining in several countries. Perhaps the fatality rate of one in 10^7 found in lightning risk evaluations [31] and experience may be preferred.

Looking to future work to limit exposure and manage potentials, the B2.56 group that developed TB 649 identified some weakness in our knowledge about electrocution risk, such as large differences between leg-leg and other heart current factors in [15]. These are considerations that would benefit from additional studies to refine the human body electrical model. The living heart is a dipole current source. Its signals appear at the extremities as electrocardiogram (ECG) potentials that should correspond to the heart current split factors tabulated in [15]. Electrocution models in this IEC Guide could also benefit from the medical community data on bioelectric impedance analysis (BIA) at its standard measurement frequency of 50 kHz.

With the widespread exposure of the public to distribution systems, extension of the transmission line GPR concerns and methods to distribution feeders (13.8 and 34.5 kV) seems prudent. Also, there is scope for some review of newer technologies that can improve safety by quickly detecting broken or falling conductors before they touch the ground and can interrupt low-current faults for contacts to soil or surfaces with high resistivity.

Acknowledgements

The authors acknowledge the contributions of Ricardo Arnez, Sandro de Castro Assis, Maruissone Ferreira Guimares and Carlos A.M. Nascimento, providing data that are especially relevant to demonstrating applications of CIGRE TB 694 in Brazil. Sample texts from CIGRE Technical Brochure 694 are provided in the appendices, partly to encourage readers to download the full version from the public domain resource www.e-cigre.org.

References

[1] CIGRE WG B2.56, Ground Potential Rise at Overhead AC Transmission Line Structures during Power Frequency Faults, Paris: CIGRE Technical Brochure 694, 2017.

[2] IEC, Protection against lightning - Part 1: General principles, Geneva: IEC Standard 62305-1 Edition 2.0, December 2010.

[3] EPRI, "EPRI AC Transmission Line Reference Book - 200 kV and Above, Third Edition (Red Book)," EPRI 1011974, Palo Alto, CA, 2006.

[4] IEEE, IEEE Guide for Improving the Lightning Performance of Transmission Lines, Piscataway, NJ: IEEE Standard 1243-1997, Reaffirmed 2008, September 2008.

[5] S. de Almeida, C. Engelbrecht, R. Pestana and F. M. Barbosa, "Prediction of Faults Caused by Lightning for Transmission Operations," *Electra,* vol. 254, pp. 4-19, February 2011.

[6] W. Chisholm, E. Petrache and F. Bologna, "Grounding of Overhead Transmission Lines for Improved Lightning Protection," in *Proceedings of IEEE Transmission & Distribution Exposition*, New Orleans, LA, April 2010.

[7] CIGRE WG C4.207, Guide for the Assessment of Transferred EPR on Telecommunication Systems due to Faults in AC Power Systems, Paris: CIGRE Technical Brochure 592, 2014.

[8] M. El-Kady and M. Vainberg, "Risk Assessment of Grounding Hazards due to Step & Touch potentials near Transmission Line Structures," *IEEE Transactions Power Apparatus & Systems,* Vols. PAS-102, no. 9, pp. 3080-3087, Sept. 1983.

[9] IEEE, IEEE Guide for Safety in AC Substation Grounding, Piscataway, NJ: IEEE Standard 80/2013, 2012.

[10] S. O. Hansson, "ALARA: What is Reasonably Achievable," in *Radioactivity in the Environment, Volume 19,* Oxford, UK, Elsevier, 2013, pp. 143-155.

[11] CIGRE B3 / CIRED, Substation Earthing System Design Optimisation through the Application of Quantified Risk Analysis, Paris: CIGRE Technical Brochure 749, December 2018.

[12] Health and Safety Executive (UK), Reducing risks, protecting people. HSE's decision-making, Norwich, UK: Her Majesty's Stationary Office, http://www.hse.gov.uk/risk/theory/r2p.2.pdf, 2001.

[13] ISO, Guide 73: Risk management - Vocabulary, Geneva, Switzerland: ISO, 2019.

[14] W. A. Chisholm and S. de Almeida de Graaff, "Adapting the Statistics of Soil Properties into Existing and Future Lightning Protection Standards and Guides," in *2015 International Symposium on Lightning Protection (XIII SIPDA)*, Balneario Camboriu, Brazil, 28 September - 2 October 2015.

[15] IEC, Effects of current on human beings and livestock - Part 1: General aspects, Geneva: IEC TS60479-1, July 2005.

[16] NEMA, "Understanding GFCIs," 22 10 2012. [Online]. Available: https://www.nema.org/Products/Documents/NEMA-GFCI-2012-Field-Representative-Presentation.pdf. [Accessed 30 4 2019].

[17] World Health Organization, " International statistical classification of diseases and related health problems, tenth revision (ICD–10). 5th ed," WHO, Geneva, Switzerland, 2018.

[18] CDC, Centers for Disease Control and Prevention, "CDC WONDER online database," National Center for Health Statistics, 01 December 2018. [Online]. [Accessed 7 May 2019].

[19] R. L. Holle, "A Summary of Recent National-scale Lightning Fatality Studies," *Weather, Climate and Society,* vol. 8, no. 1, pp. 35-42, January 2016.

[20] L. M. O. deQueiroz, "Assessing the Overall Performance of Brazilian Electric Distribution Companies," The George Washington University, Institute of Brazilian Business & Public Management Issues, Washington, DC, April 2012.

[21] ABRACOPEL, Brazilian Association for Awareness of Danger from Electricity, "Anuário Estatístico ABRACOPEL – Acidentes de Origem Elétrica 2019 – Ano Base 2018," Brazilian Association for Awareness of Danger from Electricity, http://abracopel.org/wp-content/uploads/ 2019/05/Anuário-ABRACOPEL-2019.pdf, Salto/Sao Paulo, 2018.

[22] Australian Institute of Health and Welfare, "Electrical Injuries: Hospitalisations and deaths, 2014-15 and 2015-16," Injury Research and Statistics Series #117, Canberra, 2018.

[23] C. Berg, "An effective medium algorithm for calculating water saturations at any salinity or frequency," *Geophysics,* vol. 72, no. 2, p. E59, 2007.

[24] IEEE, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System, Piscataway, NJ: IEEE Standard 81-2012, 2012.

[25] W. Shangguan, T. Hengl, J. M. d. Jesus, H. Yuan and Y. Dai, "Mapping the global depth to bedrock for land surface modeling," *Journal of Advances in Modeling Earth Systems,* vol. 9, pp. 65-88, January 2017.

[26] ITU (International Telecommunications Union), "Recommendation ITU-R P832-3, World atlas of ground conductivities," ITU, Geneva, February 2012.

[27] S. Visacro and F. Silveria, "The Impact of the Frequency Dependence of Soil Parameters on the Lightning Performance of Transmission Lines," *IEEE Transactions on Electromagnetic Compatibility,* vol. 57, no. 3, pp. 434-441, June 2015.

[28] CEMIG, "Instrução para Aterramento de Estruturas de Linhas de Transmissão de 69 a 500 kV," CEMIG No. 30.000-ER/LT-3368a, Belo Horizonte, Brazil, July 2003.

[29] CESP (Companhia Energética de São Paulo), "Aterramento em Linhas de Transmissão e Subestações," Instrução TM/035/80, São Paulo, Brazil, 1980.

[30] J. Hoffmann, R. Wiedmer, M. Bubniak and I. Moriera, "Urban overhead transmission lines of compact design for 69, 138 and 230 kV," in *CIGRE B2_102_2010*, Paris, France, 2010.

[31] IEC, Protection against lightning - Part 2: Risk management, Geneva: IEC Standard 62305-2, Edition 2, December 2010.

[32] M. Vintan, I. Mihu and I. Borlea, "Tower Ground Impedance Influence on AC Overhead Line Ground Fault Currents," *Journal of Sustainable Energy*, vol. 1, no. 3, pp. 12-15, September 2010.

[33] M. Pereira and P. V. Esmeraldo, "The Calculation of Short Circuit Currents in Overhead Ground Wires Using the EMTP/ATP," in *4th International Conference on Power System Transients (IPST)*, Rio de Janeiro, 24-28 June 2001.

[34] T. Oliveira, J. M. Carvalho, R. Leborgne, G. Watanabe, J. Abreu and J. Oliviera, "Analysis of the Relation between Voltage Sags Severity and Fault Characteristics," in *IEEE PES Annual Meeting*, August 2010.

[35] H. Dwight, "Calculation of Resistances to Ground," *Electrical Engineering*, vol. 55, pp. 1319-1328, 1936.

[36] E. Sunde, Earth Conduction Effects in Transmission Systems, New York: Van Nostrand, 1949.

[37] CENELEC, Overhead electrical lines exceeding AC 1 kV - Part 1: General requirements - common specifications, Brussels: European Committee for Electrotechnical Standardization, Standard EN 50341-1, December 2012.

[38] D. Entwisle, J. White, J. Busby, R. Lawley and I. Cooke, "Electrical resistivity model of Great Britain : user guide. Nottingham, UK, British Geological Survey," 2014. [Online]. Available: bgs.ac.uk/products/ groundConditions/resistivity.html. [Accessed 26 07 2017].

VII. APPENDIX 1: FAULT CURRENT CONSIDERATIONS

This appendix is based on Chapter 3 of CIGRE Technical Brochure 694 [1] as a place-holder for study until the full document is freely available at www.e-cigre.org.

When a phase to ground fault occurs on an overhead power line in a network with earthed neutral, part of total fault current returns to the source via the shield wires with the current balance injected into the ground through the structure grounding. The current passing through the structure grounding raises the potential of the surrounding ground and returns to the grounded system neutral, which, for a transmission line, will be remotely located at the substations that are feeding the fault. The fault current distribution is influenced by parameters that include the ground wire impedance, the structures foot resistance and the distance between the faulted structure to the feeding substation [32].

Fig. 26 illustrates the fault current share at a faulted tower, showing that part of the current flows down the tower footing, and part flows through the ground wires to the other towers of the line [33]. The maximum fault current is usually due to a phase-to-ground short-circuit. The calculation of this current should consider a network configuration that represents the main planned system conditions for the line life cycle.

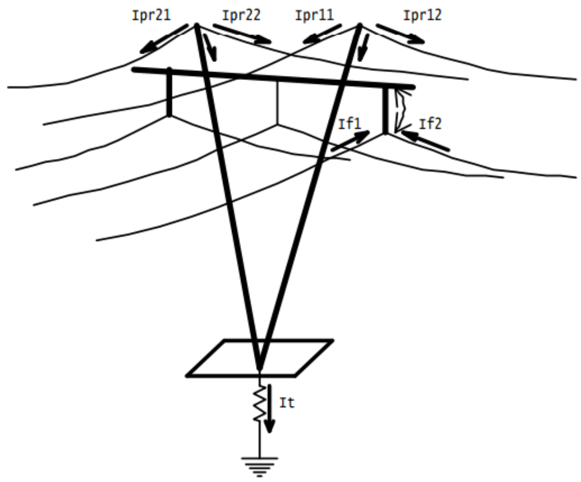


Fig. 26 Fault current split at a tower with shield wires [33]

The typical causes of power frequency faults on overhead lines will vary in accordance with the location of the line - adverse weather conditions; insulator pollution/contamination or puncture; conductor/shield wire failure due to a broken conductor; power frequency flashover due to a system overvoltage, fault-induced overvoltage; bush fire below the line; vegetation regrowth on the line corridor and external interference. CEMIG [34] reported digital fault recorder (DFR) readings on its 230-kV, 345-kV and 500-kV system attributed to a wide range of causes in Fig. 27.

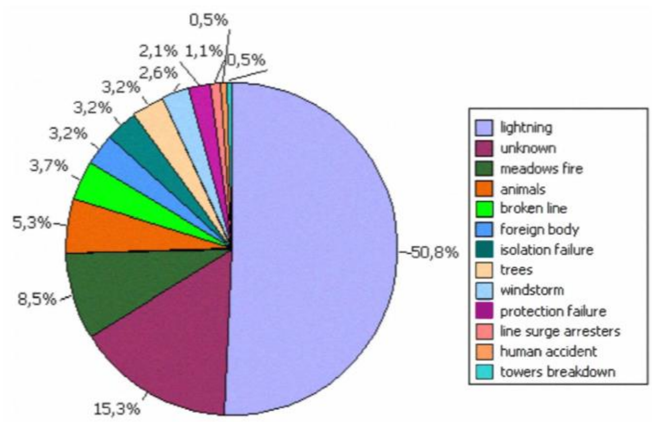


Fig. 27 Causes of transmission line faults causing voltage dips [34]

The fault current I_t at tower base in Fig. 26 has two time-components - a transient and a sustained part. These are considered in the evaluation of thermal rating of grounding cables [9] based on a simplified ratio of inductive reactance (X) to resistance (R). The use of such equivalent network models for overhead transmission lines is a well-known and proven practice. There is some good software commercially available, and the Electromagnetic Transients Program (EMT) simulation tools are preferred by many utilities. The basic electrical parameters of transmission lines are the series (resistance and inductance) and shunt (capacitance and conductance) impedances. These are combined in modal analysis to define the positive, negative and zero sequence parameters of the line. The transmission line can be modeled by using the average span line model or the lumped-circuit model. For the latter, the series resistance R and series reactance X = ωL, with ω being 2π times the power frequency, are lumped together to form the series impedance, and the shunt conductance G and shunt susceptance ωC are lumped together to form shunt admittance.

The transmission line grounding is an important factor when performing the short circuit analysis or fault current division calculation, and typically consists of a combination of rods and directly buried or concrete encased conductors. A poor grounding system contributes to higher ground potential rise (GPR) during a line fault condition. Several empirical formulas are available to estimate the resistance of ground electrodes. Dwight and Sunde published a list of equations to calculate the resistance of different ground electrode configurations [35] [36]. However, empirical formulas do not have good precision, leading often to significant errors when unexpected derivation conditions, such as rod spacing to rod length ratio, are not respected.

Fault current distribution calculation is required to determine the local potential rise at each individual structure during faults. It is discussed in this document only the single-line-ground short-circuit, which are most transmission line faults. It is also necessary to distinguish between the transmission lines with grounded overhead shield wire and the lines without shield wire. Shield wires are installed to improve the line lightning performance, reducing shielding failure and back flashover.

A. Transmission Line without Ground Wire

For a transmission line without overhead shield wire, all the fault current will flow to the ground at the tower location. No current will be transferred by the shield wires, and therefore, the ground potential rise *GPR* (V) can be determined by the product of the local fault current I_f (A) times the tower resistance R_{gn} (Ω): $GPR = I_f \times R_{gn}$.

B. Transmission Line with Ground Wire

For transmission line with overhead shield wire, a substantial portion of the ground fault current will be diverted away from the fault location, and the ground potential rise at the fault location will be reduced. The typical transmission line ladder network for the case without shield wire is shown in Fig. 28.

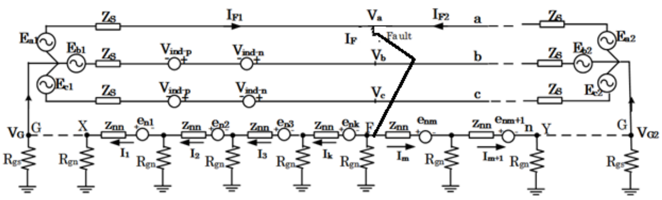


Fig. 28 Ladder network of transmission line with shield wire.

C. Example of Fault Current Distribution Calculation

In order to show the fault current distribution for a line with and without shield wires, a 230 kV, 8 km (60 Hz) transmission line was modeled in an EMT software, considering the parameters of an existing line. For the analysis, the AC systems linked by the 8 km line were represented by equivalent sources. The single circuit horizontally arranged transmission line was represented through 16 segments with 500 m average span, thus, requiring 17 structures. The phase conductors (636 kcmil, 322 mm², Grosbeak) are at a height of 34.9 m above the ground at the structure and at 24.9 m at mid-span. The conductors on phases A and C are separated 7.5 m from the center conductor (phase B). The shield wires (both CAA Petrel) are located at a height of 10 m above the phase conductors and at a horizontal distance of 6.3 m from the center conductor. The ground resistivity considered was ρ = 500 Ωm. In both cases (line with and without shield wires) the line-to-ground fault was set to occur at the middle of the line (phase C-to-structure T9). An average structure foot resistance of 4 Ω was assumed for each structure, and this is high compared to the resistance of the structures themselves, which were disregarded.

Fig. 29 presents the fault current distribution (RMS values) at structure T9 (under fault) and the next two structures on both sides. The currents are computed for the steady-state fault-to-ground condition after the X/R transient has decayed to zero. The 14.59 kA fault current is distributed along with the 17 structures, with the highest current to ground occurring at the faulted structure (T9). Fig. 30 presents the fault current distribution along with all structures of the 8 km line.

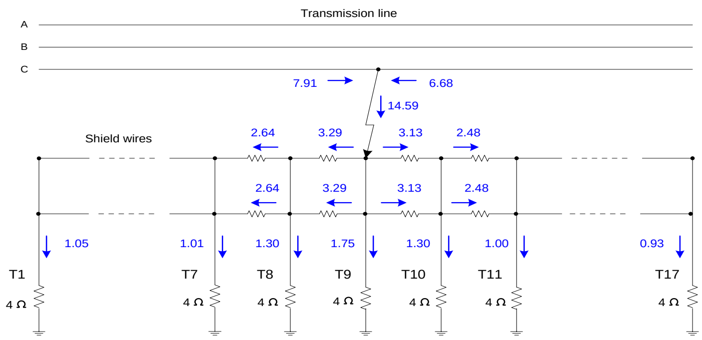


Fig. 29 Steady-state fault current distribution (RMS values, kA) on the line without shield wires.

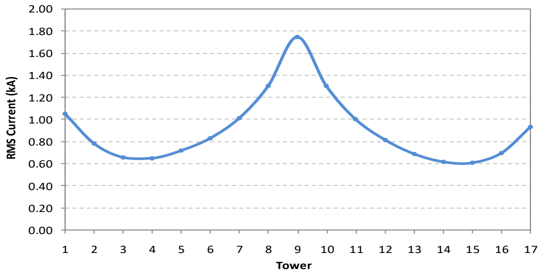
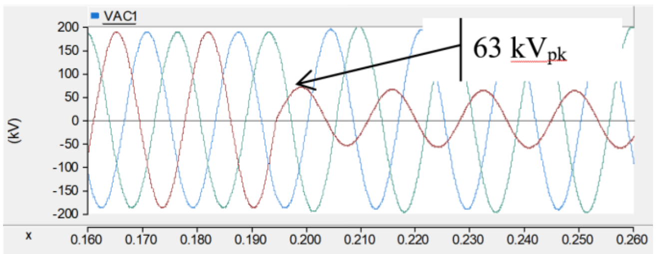
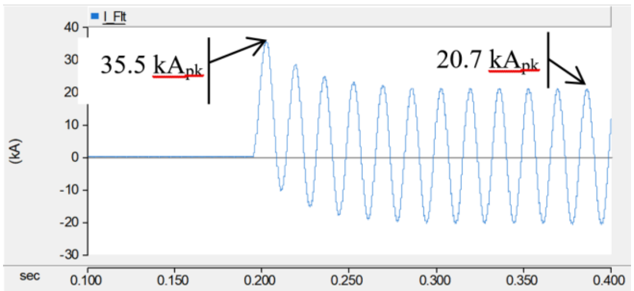


Fig. 30 Fault current distribution along with all structures of the 8 km line.

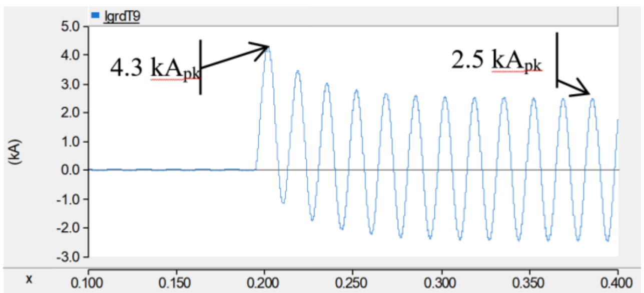
For the case with shield wires, the oscillograms of the voltage drop on the faulty phase (C), of the fault current (I_{Flt} = 35.47 kA) and of the fraction injected in the tower foot, are shown in Fig. 31 a to c. Note that the fault was applied in the instant that produces the worst asymmetry (DC offset) of the fault current. The peak fault current immediately after the fault application reached a value up to 1.7 times the steady-state fault current. This is an indication that DC offset should be considered during the safety analysis.



(a)



(b)

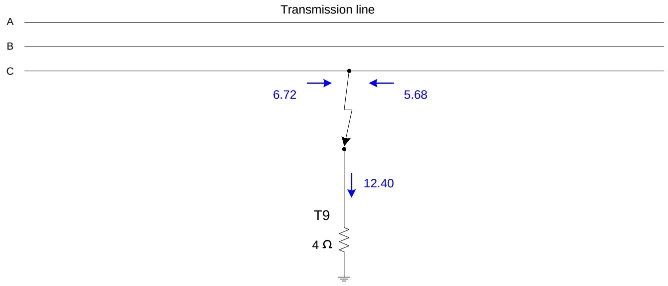


(c)

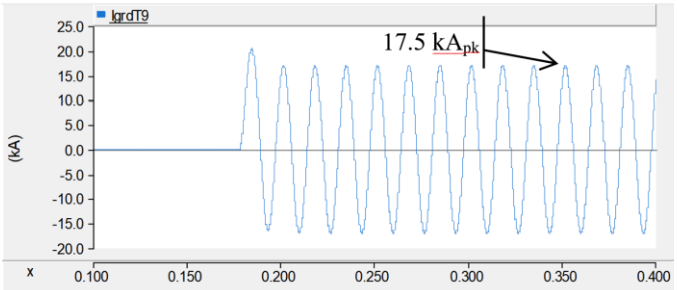
Fig. 31 (a) oscillogram of the 3 phases, showing the voltage drop at faulted phase C, (b) oscillogram of the fault current, (c) oscillogram of the fraction of the fault current injected in the grounding of structure T9.

In a further test, the same line was modeled without the shield wires. In this case, all the fault current flows through the faulted structure (T9). The same system voltage (230 kV) and structure footing resistances (4 Ω) were considered for each structure. The steady-state RMS currents (kA) are shown in Fig. 32 (a). This type of system configuration appears as more hazardous for human and livestock safety, as a much higher fault current (12.4 kA) flows to ground via structure T9, compared to the previous case (with shield wires).

The oscillogram with the peak and steady-state values of the fault current through structure T9 are shown in Fig. 32 (b). Note that the fault current is higher for the line with shield wires (14.6 kA) compared to the case without them (12.4 kA); however, the current flowing to the ground for the shielded line is much smaller (1.75 kA against 12.4 kA). It happens because the hazard (albeit lower) for the shielded line is transferred to the ground across 17 structures, instead of the only one structure for the unshielded line. Therefore, a risk-based approach provides a quantitative comparison of the hazard.



(a)



(b)

Fig. 32 (a) fault current for the case of the line without shield wires, (b) fault current through structure T9.

VIII. Appendix 2 – Safety Considerations

This appendix is based on Chapter 6 of CIGRE Technical Brochure 694 [1] as a place-holder for study until the full document is freely available at www.e-cigre.org.

A. *Safety Standards Currently in Use and Industry Practices*

An overview of pertinent standards and practices in the management of safety considerations associated with structures during an earth fault condition is necessary. Under fault conditions, all the terrain surrounding the structure is subjected to a ground potential rise (GPR). If proper precautions are not taken in the design, the potential gradients along the soil surface may be of sufficient magnitude to endanger a person in the area. The design criteria for quantifying safety considerations include the predicted GPR in conjunction with the probability of the presence of persons in the area (remoteness of the structure). These criteria are only utilized to gauge the risk to humans through electrocution. Considerations of livestock are excluded given their increased step voltage susceptibility, even to stray voltage from normal power system operation as described in IEEE Std. 1695.

The implementation of overhead transmission line grounding systems shall take into account the specific locations where the structures are erected. Different solutions will depend on the perceivable risk to individuals, associated to ground potential rise and resulting expected step and touch voltages. Many utilities consider design requirements for transmission line grounding that coordinate with one of the following:

- CENELEC (Commission Européenne de Normalisation Électrique) EN 50341-1 [37]
- ANSI/IEEE Std. 80-1986 [9] – intended for inside stations but applied in public and frequented zones;
- VDE 0141/7.76 - seldom frequented zones;
- Swiss standard ASE 3569 - 1.1985 - non-frequented zones.

CENELEC EN 50341-1 suggests a flow diagram depicting the design of earthing systems regarding permissible touch voltage in Fig. 33. EN 50341 [37] requires the limitation of touch potentials to permissible levels only at Often Frequented Structures (OFTs) in decision point (2) of Fig. 33. However, conflicts may occur between installing grounding control rings and the mitigation against transferred potentials, which are not mentioned in this flow diagram.

B. Country-Specific Standards for Tower Footing Resistance (TFR)

The CENELEC standard [37] also refers to country-specific National Normative Aspects (NNA) for specific control measures. Some NNAs specify target Tower Footing Resistances (TFR) to aid in reducing step and touch voltages. TFRs are also important input system parameters for power system modeling, and high TFR can reduce the effectiveness of ground fault protection operation. For example, Great Britain specifies 10 Ω or less and Greece specifies 20 Ω. In the French regulation, the TFR must have an appropriate value regarding its purpose.

The use of a single TFR specification, such as TFR ≤ 10 Ω in Great Britain, is practical in part because the soil resistivity is low, for example ρ ≤ 125 Ωm for more than three-quarters of the country-wire resistivity map for power companies [38]. Other areas present more of a challenge. The practice at CEMIG in Brazil was described in Section IV.B.

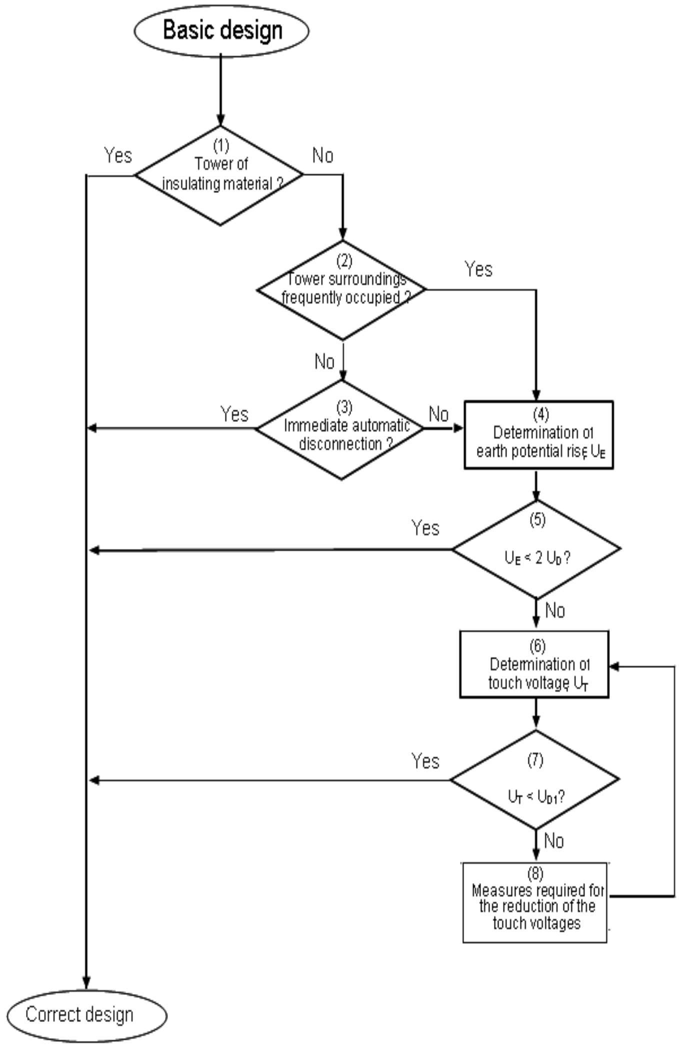


Fig. 33 Design of grounding systems with regard to permissible touch voltage according to EN 50341-1 [37]

Typical step and touch voltage mitigation measures employed by utilities include but are not limited to the following:

- Applying insulating coatings to the structure leg on the lower parts of the tower (typically up to 2 m above the ground), satisfying yes to (1) in Fig. 33. This latter solution is only used for touch voltage mitigation and is efficient up to a limited threshold (typically < 10 kV).
- Applying insulating coatings such as asphalt to the soil near the tower, effectively satisfying yes to (1) in Fig. 33 and also efficient up to a limited threshold (typically < 10 kV).
- Fencing off structure leg, satisfying yes to (2) in Fig. 33.

- Limitation of the access to the constrained zones or to the tower using obstacles, such as a thorny bush or insulated fences. The obstacles can be placed at 1 meter around the tower for touch voltage mitigation, or around the constraint zone for step voltage mitigation. The overall cost of these mitigation techniques to satisfy yes to (2) in Fig. 33 is relatively low.

- Modification of the constrained zone, by the distribution of the fault current to the neighboring towers by means of a more conductive shield wire, to decrease the magnitude of the current at the considered tower. This solution is often studied by transmission system operators (TS), however, may present many impacts (mechanical and electrical) on an existing line.

- Applying high resistivity soil surface materials such as gravel (typical resistivity of 2000 to 5000 Ωm) to significantly reduce the current flowing into the body, increasing U_{D1} in Fig. 33.

- Shield wires also have other functions such as the protection against lightning and the possibility to develop the telecommunication network using OPGW.

- Installation of additional grounding (rods and counterpoise)

- Improvement of the groundings of the adjacent towers, in order to improve the sharing of the fault current with these adjacent towers, a solution that can be used only if there is no other constraint in the vicinity of these towers.

- Conductive loop connecting the four legs of the tower and buried about 0.3 m depth, a solution that leads to a low difference of potential between the foot and the hand, considering touch voltage issues. This technique is not often considered by TSO, due to the copper theft and its relative cost compared to the other touch voltage mitigation techniques.

During a phase-to-ground fault on a shielded line, part of the fault current is injected into the ground at the faulted structure, whereas the remaining current flows away through the ground wire. The current injected into the ground raises the potential (GPR) of the counterpoise system in relation to remote earth, which produces a soil surface potential gradient. As a consequence, people and animals can be subject to step and touch potentials which, depending on their magnitude, may cause electric shock and even ventricular fibrillation.

The circumstances that make electric shock accidents possible are as follow - relatively high current of the phase-to-ground fault; ground resistivity and distribution of fault currents; presence of a person at such a place, at the time of the fault occurrence and in a position that the body is bridging two points of high potential difference; absence of contact resistance; duration of the fault and of the body contact. The relative infrequency of accidents is due largely to the low probability of coincidence of all the unfavorable conditions listed above.

C. Hazards of Step, Touch and Transfer Voltages

The proximity to overhead transmission line structures poses several electric hazards in the form of touch, step or transferred voltages. The flow of high fault currents through structure grounding will trigger a ground potential rise and potential differences may result on the circulation of electrical current through the human body, which is subject to Ohm's law in the same as any other resistive material. An electrical potential applied to it will cause current to flow, and this current can cause injury or death, if higher than the tolerable threshold of the human body. The three most likely paths for current to flow through the body are - hand-to-foot; hand-to-hand through the chest area; and foot-to-foot (as shown in Fig. 34).

Touch Voltage is the potential applied to a person that touches a transmission line structure at the moment that a fault current is flowing into the ground. Step Voltage is the potential difference between the two feet of a person, when walking in the vicinity of a transmission line structure at the moment that a fault current is flowing into the ground, without contacting any other earthed object.

A typical value for tolerable risk (annual loss of life or permanent injury index) as per IEC 62305-2 [31] is 10^{-5}. It is interesting to note that individual fatal risk of 1 in 10 million ($1x\ 10^{-7}$) per year is considered broadly as acceptable to the public in [31]. *This is ten times lower than the annual fatality risk of 10^{-6} considered broadly acceptable in Figure 47 of* [1]. The step and touch voltages will vary seasonally because the resistivity of the ground shallow layer is affected by rainfall and temperature. Every fault-to-ground should be eliminated automatically by the substation or upstream protection, and therefore, indefinitely applied touch voltages are not a design consideration. The elevated potential caused by the line-to-ground fault can also be transferred to adjacent infrastructure, thus creating dangerous touch voltages in third-party infrastructure, unrelated to the utility company, endangering persons who otherwise seemed safe. Transferred voltages can affect large areas, depending on the location of the fault, the relative distance between structures, foot resistance, ground resistivity and magnitude of fault current.

Due to the presence of overhead shield wires, these potentials can arise not only close to the faulted structure but also in several towers before and after. Property and equipment damage may also arise, including communication appliances and low voltage apparatus. Sensitive electronic equipment can be severely damaged by high potential gradients posed by a transferred ground potential rise from faulted structures. Even the equipment designed to operate in industrial environments is not required to withstand voltages in excess of 12% of their rated voltage, according to the IEC 61000-4-14 standard.

The risk posed to humans is that the current that can flow in the region of the heart may be enough to cause ventricular fibrillation. The limits to electric current flow through the human body are stated in IEC 60479-1 (2005) technical standard [15], in terms of magnitude and duration, considering a left hand to feet pathway at power frequency current. The curve C1 is usually considered for the study of the risk of touch potential electrocution, which can be approximated by equations for distinct shock durations - $\leq$ 466 ms; 466 ms $\leq t <$ 760 ms; for 760 ms $\leq t \leq$ 4800 ms; and > 4800 ms. IEC 60479-1 [15] also provides factors for adjusting for the effects of current path, for example with leg-leg factor of 0.04 meaning that, of every ampere of current in a leg-to-leg contact in Fig. 37, 40 mA is considered as I_B in Fig. 35. The series resistance of shoes Z_{ch} is included in the electrocution paths of Fig. 36 and Fig. 38, following guidance in EN 50341-1.

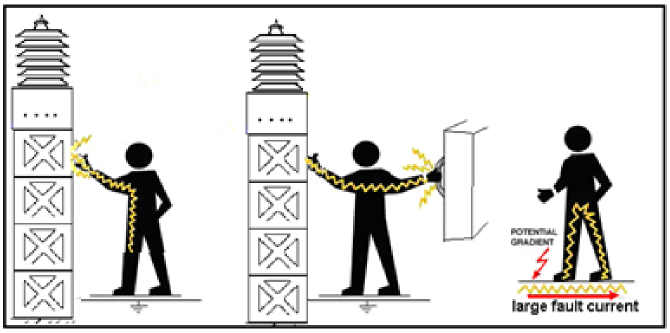


Fig. 34 Touch, reach and step potentials

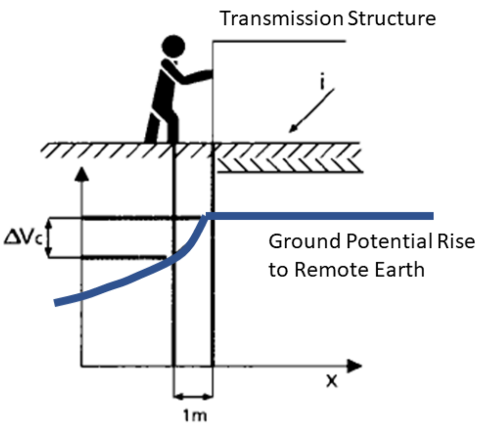


Fig. 35 Touch potential near transmission structure

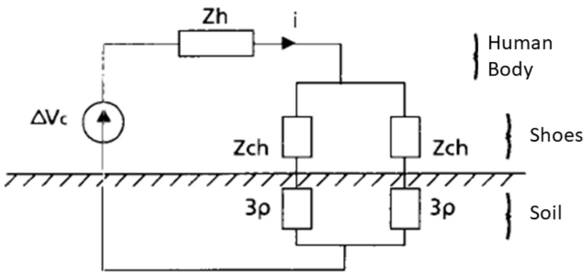


Fig. 36 Touch potential equivalent electrical circuit, including shoe resistance Z_{ch}

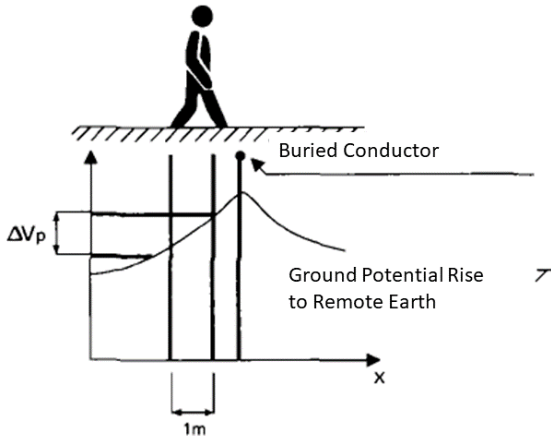


Fig. 37 Step potential near transmission structure

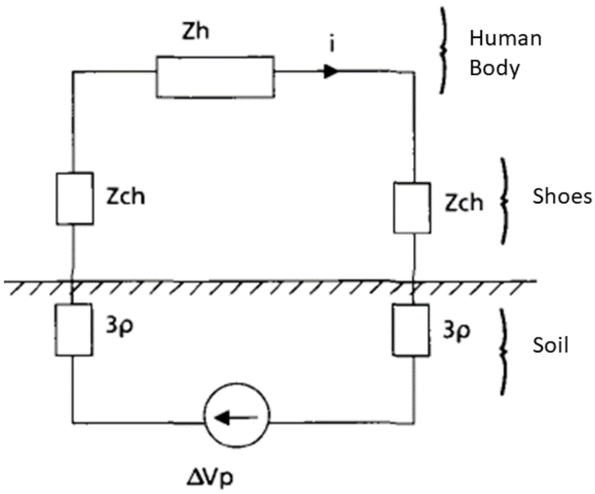


Fig. 38 Step potential equivalent electrical circuit, including shoe resistance Z_{ch}