Protection Against Earth Faults Caused By The Contact Between Conductors And Trees

João Carvalho
Instituto Superior Técnico
Lisboa, Portugal
joao.miguel.oliveira.carvalho@ist.utl.pt

***Abstract*—A major problem of electrical utilities, in particular in the Medium Voltage Network, is the detection of contacts between conductors and trees, due to the highly resistance nature of the earth fault caused by the contact. Under optimal conditions, these contacts could lead to forest fires, threatening the biodiversity and human life, as well as utilities assets.**
For this purpose, we measured the electrical resistance, in situ, of the most common species of trees in Portugal. Based on those measurements, models of electrical tree resistance were developed as function of height and base diameter, for the species of *Pinus Pinaster sp.* and *Eucalyptus globolus Labill.* These models were used to simulate electrical resistance of trees with heights like the ones of the Medium Voltage overhead line conductors. Additionally, we calculated the probability density function of electrical tree resistance in a specific region of Portugal, based on the empirical data; simulations and the latest forest characterization made by Instituto da Conservação da Natureza e das Florestas (ICNF).
Finally, two different settings for earth fault functions of the Protection Systems were studied. Here the probability of the earth fault function detect the contact between conductors and electrical tree resistances were obtained, based on the adopted neutral regime and on the voltage level of Medium Voltage, MV.

***Index Terms*—Electrical Tree Resistance, overhead conductors, Medium Voltage Lines, Ground fault**

I. Introduction

The Medium Voltage Distribution Network is mostly composed of aerial lines, because they are more affordable and easy to install than underground cables. Other advantage of them is the visual inspection, which allows maintenance crews to identify and repair material defects, in the quickest amount of time.
However, one of the major drawbacks of using aerial cables is the influence of external factors such as wind, heat, lightning or even the coexistence with trees. The latter, could cause interruptions due to conductors come into contact with tree branches or their leaves. These contacts occur most frequently during windy periods, through the swing of conductors into tree branches or vice versa [1] [2]. The tree and conductors contact can also be facilitated by the increase of line sag resulting from thermal expansion of the conductor or the growth of a tree beneath the conductor.
Besides the interruption of energy, contacts could cause wildfires, when in presence of hot and dry weather. The fires result from the ignition of branches and consequently hot embers falling to the ground. This is caused by arcing phenomenons at the contact point between the tree and the bare conductor or through the joule heating effect of the electrical composites of the branch, when the fault current flows through the tree branch to the ground. These wildfires, even though being few compared to other causes, have shown to be very dangerous and of big proportions due to the presence of strong winds and of flammable vegetation on the surroundings of the tree. [3].
Despite the enforcement of mandatory clearance requirements by the local government and the efforts of electrical utilities to avoid and mitigate these contacts through vegetation management programs, there is still a considerable number of trees that are not pruned at the right time.
For the Protection Systems and for the usual regulations applied, these contacts are extremely difficult to detect at the initial moment as a result of the high resistance of the tree. Also, there are visible differences between individual species, regarding the electrical resistivity of the wood. Taken these evidences into account, were conducted electrical tree resistances measurements on the most common tree species of Portugal.

A. Grounding System

The Grounding system plays a major role, on the behaviour of the Electrical Network, at the time of an occurrence of an earth fault. In fact, the choice of the Grounding System to install will determine the values of the fault current and of the overvoltages. The grounding system could be divided into two groups: small and large fault currents. The small fault currents grounding systems could be the Isolated and the Resonant grounded neutral. In the latter group, the grounding connection element defines the maximum fault current.For the grounding connection, it could be connected resistance or reactance. The other grounding connection is the solidly grounding system, which is only used on the transmission network [4]. In the presence of a earth fault, the fault current, I_{def}, could be obtained recurring to the symmetrical components.

$$I_{def} = \frac{E_a}{R_{fault} + \frac{Z_d+Z_i+Z_h}{3}} \tag{1}$$

One simplification that could be applied, in case of generators being far away from the earth fault is $Z_d \simeq Z_i$, in which the positive sequence impedance could be given only by the reactance of the upstream and the reactance of the substation transformer.

$$Z_d = j(X_m + X_{td}) = jX_t \quad (2)$$

The zero sequence impedance is given by the impedance of the neutral system,Z_N, in series with the zero sequence impedance of substation transformer,Z_{th}. Z_{th} could be neglected, whenever the winding transformer is delta connected. In addition, there is also the contributions of the parallel of total earth capacitances C_{th}. For a practical matter, its common to calculate firstly the zero sequence admitance $Y_h = \frac{1}{Z_h}$.

$$Y_h = jwC_{th} + \frac{1}{Z_0} \quad (3)$$

where, $Z_0 = 3Z_N + 3Z_{th}$

For each grounding system, equation 3 could be simplified.

- Isolated System
  This grounding system is characterized by an absence of connection to the neutral, thus making the neutral impedance equal to infinite.

$$Y_h = jwC_{th} \quad (4)$$

- Resonant System
  The aim of the resonant system is to neutralize the fault current. However, the existence of non-idealities in the materials equipment reflects in a presence of a resistive fault current. The neutral impedance is given by

$$Z_N = R_p + jX_p \quad (5)$$

  where X_p is called the Petersen's Coil. In most cases, the resonant grounded neutral is not tunnning, with the purposes of reducing the stress on insulation equipments, caused by disturbances on the Network. For that reason, is introduced to the Petersen's coil an overcompensation state, δ.

$$X_p = \frac{1}{3wC_{th}}(1+\delta) \quad (6)$$

- Large fault Neutral system Large Fault Neutral System only differ in the element in use for the grounding connection. In most cases, the choice of the reactance in the grounding system instead of a resistance is based on the neutral point of the Substation transformer being not accessible,due to the fact of MV winding of the transformer is delta connected. The reactance in this cases could be an artificial neutral [1].

$$Z_N = R_N + jX_N \quad (7)$$

B. Earth Fault Protection System

Actually the Protection Unit allow multiple functions and the possibility of combining them. For the Earth Fault Protection System, the most commonly used functions are the define time, inverse and directional Earth fault Overcurrent functions.

- Define Time Earth Fault Overcurrent Function
  The define time Earth Fault Overcurrent Function is characterized by having a defined time of operation, t_{op}, in which the relay trips in case of the earth fault current measured being above of the pickup current, I_{op}
- Inverse Time Earth Fault Overcurrent Function
  This function has the same *modus operandi* of the previous function, regarding the pickup current. In this case, the time of operation is given by a inverse time current function.

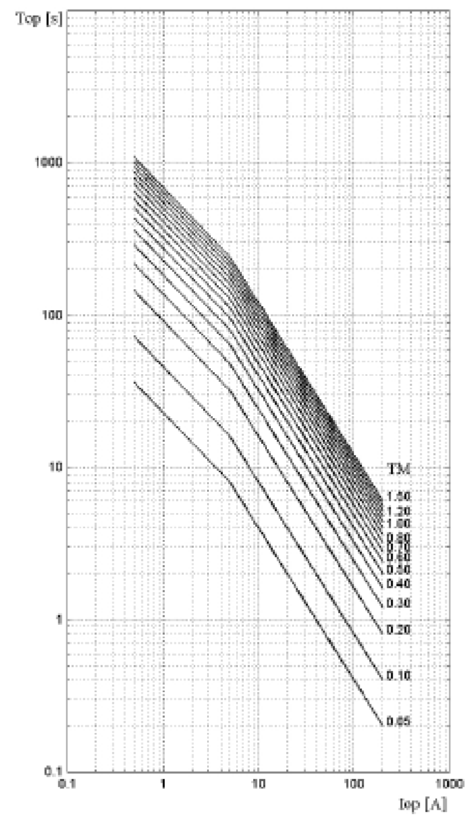

Fig. 1. Characteristic of the inverse time current function, retired from [8]

- Directional Earth Fault Overcurrent Function
  The Directional Earth Fault Overcurrent Function is more complex. This function is based on the direction of the current measured using the angle between the zero sequence voltage and current. This allows the distinction between residual currents of faulty and healthy lines. The operational characteristic of the directional earth fault overcurrent is present in Figure 2.

II. Experiments

To characterize the electrical tree resistance and consequently the earth fault current, measurements of electrical tree resistance were conducted on the most common species and at different sites. The first site is located on Lousã, Coimbra and its a public terrain, with tall bushes on the surroundings of the trees. The second one is located in Leiria, near to houses and with small vegetation near the measured trees. The third and last site is characterized for being a private

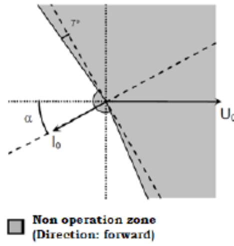

Fig. 2. Operational Characteristic of the Directional Earth Fault Overcurrent function, adapted of [5]

terrain with specific cultures of maritime pine (*Pinus Pinaster sp.*) and of eucalyptus (*Eucalyptus globolus Labill*). There was also a reminiscent presence of cork oak (*Quercus Sober*) and Portuguese oak (*Quercus faginea*), that were also measured. The tree species taken into account, onto this work, were maritime pine, eucalyptus, acácia (*Acácia xanthophloea*), cork oak and Portuguese oak. In Table I is presented the number of trees of each specie that were measured. The specification of maritime pine infected by the pine wood nematode from maritime pine is explained by the observable difference between them on the electrical resistance measurements, being much higher on the maritime pine infected.

TABLE I
NUMBER OF MEASUREMENTS TAKEN ON EACH TREE SPECIE

Specie	Frequency
maritime pine	15
maritime pine infect.	3
eucalyptus	11
acácia	2
cork oak	1
Portuguese oak	3

A. Description of the experiments

For each tree were taken two measurements, R_{tree} and R_{x1-x2}. In both experiments we used one Mega-ohmmeter and steel nails as electrodes. These were were introduced about 5 cm into the tree trunk. The choice of using steel nails is related to the high conductance and low of this material. Besides the measurement of the electrical tree resistance, it was also measured the distance between electrodes, d_e, and the perimeter of the tree trunk at the height of the nail introduced, P, to obtain the wood resistivity of the tree, ρ_{tree}.It was also recorded the ambient temperature and the relative humidity on each measurement, with a ordinary thermometer

R_{tree} was measured between one electrode introduced at 20 cm above into the tree trunk and the other one at the maximum height possible. R_{x1-x2} was measured between one electrode at 20 cm above into the tree trunk and the other at a distance from the previous of 60 cm. In Fig, 3 is presented the configuration of both measurements. ´

On the third location, it was also measured R_{x1-x3}, which differs from the measurement R_{x1-x2} on the height of the second electrode, where in this case has a distance $d_e = 30cm$.

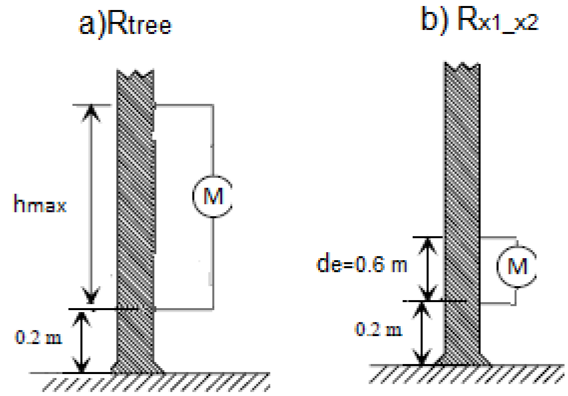

Fig. 3. Configuration of the electrical tree resistance measurements: a-R_{tree} b-R_{x1-x2}

In Fig.4 is presented the measurement R_{x1-x2} taken on a maritime pine in Lousã.

Fig. 4. Configuration of the electrical tree resistance measurements: a-R_{tree} b-R_{x1-x2}

In Table II is presented the results of the measurements taken. It can be seen that maritime pine has a much higher resistance than the other species considered in this work. These results are in accordance with studies made by and are explained by the higher content of lignin in softwoods than in hardwood, making them more conductive. It was also evident the influence of the diameter, between same trees species, where trees with smaller diameters have a greater electrical resistance than larger trees. This can be explained by the increased moisture content in larger trees, resulting in increased conductance. As aforementioned, its also observable the electrical resistance difference between maritime pine healthy and infected by the pine wood nematode. The infected maritime pine infected has resistances in the order of Megaohms, these results are explained by the decay of the moisture content and of organic compounds produced by the tree.

III. Model of electrical resistance

Based on the measurements present on Table II and with the purpose of predicting the electrical tree resistance at heights like the ones of overhead lines, which in the Portuguese MV network could be between 7 to 25 meters, two models of electric tree resistance were developed for the species of maritime pine and eucalyptus as function of height and diameter.

The tree model used is similar to the one proposed by [6]. This model approximated the tree shape as a conical stack of 1 cm tall cylinders, incrementally increasing in diameter from the top to the base. The increment of each iteration was obtained, using the relation

$$inc_{diam} = \frac{(P1 - P2)}{d_e \times \pi} \tag{8}$$

, where inc_{diam} represents the increment of the diameter and $P1$ and $P2$, the perimeter of the tree at the point of electrode 1 and 2, respectively.The initial diameter was considered of being 1 cm. In Fig.5 is presented the tree model.

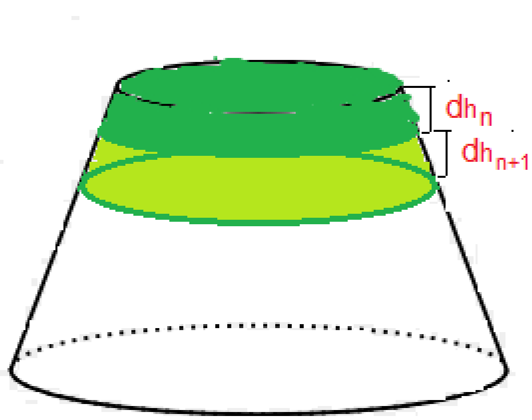

Fig. 5. Representation of the tree model used

Based on the data collected, parameters, m and b, were calculated. These were used to fulfill the resistivity-diameter function stated in [3], as it follow

$$ln(\rho) = m\sqrt[3]{D} + b \tag{9}$$

where ρ is the electrical resistivity and D the diameter. The resistivity of each iteration can be obtained by applying equation 9 and consequently the resistance of that section, by using the relation between the resistivity and resistance,

$$R = \frac{\rho \times h_{stack}}{A} == \frac{\rho \times 1}{A} \tag{10}$$

where h_{stack} is the height of the conical stack of each iteration and A is the cross-sectional area.

Both of the resistivity-diameter functions for the species of maritime pine and eucalyptus, respectively, were obtained using the curve fitting app available on @Matlab.

A. *maritime pine resistivity-diameter function*

For the specie of maritime pine and taking into account the measurements data and the correspondent resistivity obtained and considering equation 9, the function obtained is

$$ln(\rho_{pine}) = 4.955\sqrt[3]{D} + 3.028 \tag{11}$$

B. *eucalyptus resistivity-diameter function*

The same procedure was done for the eucalyptus resistivity-diameter function. The equation obtained is

$$ln(\rho_{euc}) = 4.817\sqrt[3]{D} + 3.134 \tag{12}$$

For simulations purposes, it was defined different final heights and basal diameters to simulate trees that could be in contact with overhead lines and thus obtained their electrical resistance. Regarding the basal diameters, it was considered values of 25, 30 and 40 cm. In terms of height, the simulated trees could be between 5 and 15 meters. In Table III it is shown the electrical tree resistance of both species at different heights and basal diameters.

As it can be seen in Table II and in Table III, trees with smaller diameters have a greater electrical resistance than larger trees. Also, the difference of species and in their chemical compounds reflects on the electrical resistance, where trees like maritime pine have greater resistance.

IV. Forest Characterization of Portugal

Portugal's large biodiversity is not evenly distributed across regions. The differences registered on electrical tree resistance at different tree species, could be helpful to define the settings of overcurrent functions on a certain region dependent on which tree specie is most common in that area.

In fact, the most common tree species, in the southern regions of Portugal, are eucalyptus globulus and cork oak, which are defined by having an electrical resistance in the orders of dozens of kiloohms. In the northern regions, the most dominant species are maritime pine and portuguese oak. The electrical resistance of maritime pine tree is around hundreds of kiloohms- three times greater than the one of eucalyptus. The central regions are characterized by having as most common species maritime pine and eucalyptus globulus.

In Table IV is presented the area of each specie addressed in this study, in each region of Portugal. This data was collected by Instituto de Conservação da Natureza e da Floresta (ICNF), during the 6^{th} Portuguese National Forest Inventory (IFN) [7]. The regions considered were based on the third level of the

TABLE II
ELECTRICAL TREE RESISTANCE MEASURED

Id	Specie	Site	T[ºC]	HR[%]	hmax[m]	P1[cm]	P2[cm]	$R_{tree}[k\Omega]$	$R_{x1-x2}[k\Omega]$
1	eucalyptus	Lousã	23	73	7.7	165	150	10.24	5.3
2	eucalyptus	Lousã	23	73	6.2	125	110	15.55	6.8
3	acácia	Lousã	23	73	5. 6	72	64	13.5	4.24
4	mar. pine	Lousã	25	63	4.6	160	136	19.15	9.1
5	mar. pine	Lousã	26	62	4.25	160	136	67.8	19.4
9	Portuguese oak	Leiria	23	60	3.8	110	97	13.88	4.8
12	mar. pine inf.	Batalha	20	68	2.7	78	71	4300	1220
14	mar. pine	Batalha	27	42	5.6	100	70	51	24.9
16	eucalyptus	Batalha	27	42	4.8	170	110	5.9	3.52
19	eucalyptus	Batalha	27	42	5	36	22	66.6	10.9
25	mar. pine	Batalha	28	44	4.95	40	20	130.3	20.2
28	mar. pine	Batalha	28	44	5	75	40	71.8	17.8
30	eucalyptus	Batalha	28	44	5.3	90	60	15.2	6.3
33	oak	Batalha	28	44	4.9	100	70	9.2	5.2
36	Portuguese oak	Batalha	26	38	4.9	110	80	16.5	6.3

TABLE III
ELECTRICAL TREE RESISTANCE OF SIMULATED TREES

Specie	H [cm]	$R_1[k\Omega]$	$R_2[k\Omega]$	$R_3[k\Omega]$
mar. pine	500	59.71	45.25	37.20
eucalyptus	500	17.77	12.68	9.85
mar. pine	600	76.62	56.67	46.01
eucalyptus	600	22.61	15.85	12.18
mar. pine	700	96.69	69.34	55.47
eucalyptus	700	28.13	19.31	14.67
mar. pine	800	121.42	83.62	65.71
eucalyptus	800	34.54	23.12	17.35
mar. pine	900	153.62	100.02	76.91
eucalyptus	900	42.15	27.38	20.24
mar. pine	1000	199.39	119.37	89.31
eucalyptus	1000	51.42	32.16	23.39

Nomenclature of Territorial Units for Statistics (NUTS III) of Portugal and in some cases, there were unions of regions with the purpose of not dividing a forest in two different regions of NUTS III. In Figure 6, it is shown the correlation between the NUTS III of Portugal and the regions considered by the ICNF.

PROFS	NUTS III
Algarve	Algarve
Baixo Alentejo	Baixo Alentejo
Alentejo litoral	Alentejo Litoral
Alentejo Central	Alentejo Central
Alto Alentejo	Alto Alentejo
A.M. Lisboa	A M. Lisboa
Ribatejo	Leziria do Tejo/Média Tejo
Oeste	Oeste
Centro Litoral	Leiria/Aveiro/Coimbra
Centro interior	Beira Baixa/Beiras e Serra da Estrela
Pinhal Int. Norte	Leiria/ Coimbra
Pinhal Int. sul	Beira-Baixa/Médio Tejo
Beira Interior Sul	Beira Baixa
Beira Interior Norte	Beiras e Serra da Estrela
Dão/Lafões	Viseu Dão-Lafões
Douro	Douro
Tâmega	Tâmega
A. M. PORTO	A.M. Porto
Baixo minho	Cávado/Ave
Alto minho	Alto Minho
Barroso/Padrela	Terras de Trás-os-Montes
Nordeste	Terras de Trás-os-Montes

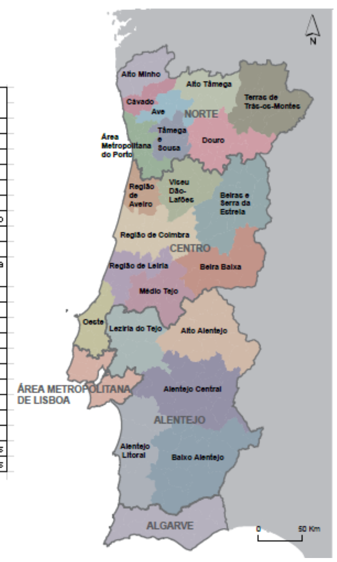

Fig. 6. Correlation between NUTS III of Portugal and the regions considered by IFN

A. Probability density function of electrical tree resistances by region

A probability density function was obtained per region, based on the measurements of electrical tree resistance conducted on section II and on the electrical resistances predicted by the model and present on Table III. It was given a weight probability for each tree specie at each region according to the data collected by ICNF of the distribution of tree species by each region.

For the distribution function, it was used the mixture distribution, due to the differences registered on electrical resistance between inter-species.

$$f(x) = \sum_{i=1}^{n} w_i \frac{1}{\sigma_i \sqrt{2\pi}} exp(-\frac{(x-\mu_i)^2}{2\sigma_i}) \qquad (13)$$

where w_i represents the weight given to the normal distribution,p_i.

In Table V is presented the parameters of the mixture distribution for each region and the Negative log likelihood of each distribution function fitted. In Figure 7 is displayed the Electrical Tree Resistance Distribution of Pinhal Interior Sul.

Despite the strong presence of maritime pine, the substantial presence of eucalyptus tree was noted, shifting the mean value for the dozens of kiloohms.

V. CHARACTERISTIC OF MEDIUM VOLTAGE NETWORK

In order to define a setting for the detection of contacts between bare conductors and trees, it is fundamental to know the parameters of the Network System. For simulation purposes, it was considered the commonly used parameters for the MV Network, present in Table VI.

Other parameter that is extremely important to define is the Neutral System and his impedance. The sizing of the

TABLE IV
DISTRIBUTION OF TREES SPECIES BY REGION

Region	mar. pine [ha]	eucalyptus [ha	acácia [ha]]	cork oak [ha]]	port. oak[ha]
Algarve	6670.7	25355.8	423.5	23432.5	0.0
Baixo Alentejo	760.0	13659.0	0.0	47632.0	0.0
Alentejo Litoral	26543.5	47247.5	0.0	131655.8	0.0
Alentejo Central	2168.3	24574.4	0.0	112030.1	0.0
Alto Alentejo	11871.2	43111.2	0.0	129958.3	0
A.M. Lisboa	23026.0	13630.5	0.0	23409.7	2047.9
Ribatejo	54434.0	100634.0	0.0	118306.0	6784.0
Oeste	25187.7	26401.1	0.0	830.2	909.2
Centro Litoral	324100.0	254450.0	2750.0	150	6225.0
Centro Interior	91625.0	52675.0	1000.0	24075.0	7900.0
Pinhal Int. Norte	69669.0	45916.0	0.0	136.0	7123.0
Pinhal Int. Sul	97463.0	16291.0	0.0	0.0	201.0
Beira Int. Sul	49975.0	51538.0	0.0	25599.0	2586.0
Beira Int. Norte	85765.0	7357.0	0.0	2120.0	30795.0
Dão/Lafões	100895.0	32440.0	0.0	0.0	10286.0
Douro	46617.0	1827.0	0.0	7239.0	10423.0
Tâmega	38588.0	3093.0	0.0	0.0	0.0
A.M.Porto	47029.0	28087.0	0.0	0.0	0.0
Baixo Minho	48960.0	25884.0	0.0	0.0	6273.0
Alto Minho	40111.0	4077.0	0.0	0.0	0.0
Barroso/Padrela	51363.0	553.0	0.0	572.0	15801.0
Nordeste	29188.0	3265.0	0.0	26857.0	31920.0

TABLE V
DISTRIBUTION OF TREES SPECIES BY REGION

Region	$\mu_1[\Omega]$	σ_1 $[\Omega]$	μ_2 $[\Omega]$	$\sigma_2[\Omega]$	Neg. Log Likelihood	$\mathrm{w}_1[\%]$	$\mathrm{w}_2[\%]$
Algarve	13594.7	1.30e+07	56942.9	1.21e+09	975.3	67.8	32.2
Baixo Alentejo	14778.6	5.49e+05	40650.1	1.20e+09	991.1	61.3	38.7
Alentejo Litoral	14796.4	4.47e+05	38217.80	9.66e+08	2410.6	61.3	38.7
Alentejo Central	14876.0	4.64e+05	31373	7.84e+8	1652.3	27.8	72.2
Alto Alentejo	34175.6	9.18e+08	14749.8	4.77e+05	2163.6	34.5	65.5
A.M. Lisboa	14526.3	1.08e+06	48327.0	1.22e+09	1071.7	40.1	59.9
Ribatejo	14735.1	6.54e+05	34587.0	7.88e+08	3313.5	48.8	51.2
Oeste	14185.2	1.71e+07	54985.0	1.08e+09	1007.5	42.2	57.8
Centro Litoral	219442.6	4.6e+10	38444.5	7.95e+08	7319.7	2.0	98.0
Centro Interior	13257.4	9.73e+06	56082.3	1.08e+09	2427.3	40.2	59.8
Pinhal Int. Norte	12815.2	1.3e+07	53779.0	7.51e+08	1804.8	34.8	65.2
Pinhal Int. Sul	62857.0	9.01e+08	22750.0	1.15e+9	1723.8	58.0	42.0
Beira Int. Sul	13467.0	1.10e+07	55230.5	1.67e+09	1888.4	47.1	52.9
Beira Int. Norte	48135.9	7.31e+08	14821.21	4.06e+05	1799.4	74.6	25.4
Dão/Lafões	14378.6	1.5e+07	55257.1	7.06e+8	2042	30.7	69.3
Douro	14534.6	6.29e+05	54986.8	7.81e+08	1130.9	27.9	72.1
Tâmega	165960.4	1.18e+10	34114.7	6.46e+08	1274.0	3.1	96.9
A.M.Porto	38300.9	7.05e+08	147582.5	9.08e+09	1292.9	95.8	4.2
Baixo Minho	57267.3	1.2e+09	14880.7	2.28e+07	1336.4	58.6	41.4
Alto Minho	14604.7	6.08e+6	53232.8	7.32e+08	9039.6	25.9	74.1
Barroso/Padrela	14902.8	4.30e+05	52379.9	7.72e+08	1165.2	25.7	74.3
Nordeste	47474.2	6.03e+08	14723.2	4.67e+05	1283.0	44.9	55.1

impedance of each grounding connection was based on the equations stated in Chapter I.

TABLE VI
PARAMETERS OF THE MV GRID CONSIDERED

		Un[kV]	
		15	30
Upstream Network	S_{cc}	500 MVA	500 MVA
Substation Transformer	S_n	20 MVA	20 MVA
	V_{cc} [%]	8	8
Overhead Lines	Number	10	5
	$Extension$ [km]	30	60
	Capacitance [nF/km]	12.97	11.74

A. Natural Asymmetries

One of the constrains of the Electrical Network is their inherent natural asymmetry. Here the zero sequence current originated by it, imposes as the minimum pickup current of earth fault protections. Considering this, Pedro Aleixo simulated the Natural asymmetries of Network, when the electrical grid is operating on the normal conditions [8], for the same parameters considered on this study. The results obtained are shown in Figure 8

It is easily noted that the Natural Asymmetries play a prominent role on the Resonant neutral system. In contrast, the presence of Asymmetries in the Isolated System is almost

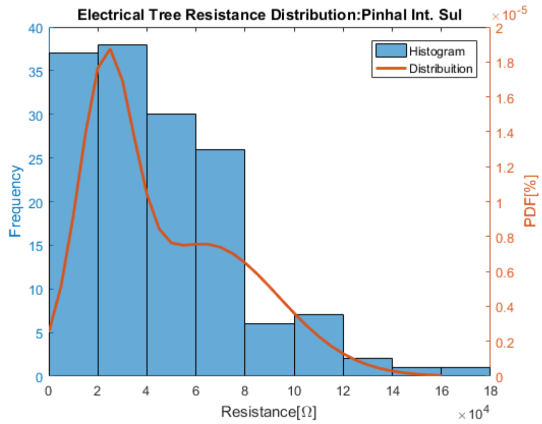

Fig. 7. Electrical Tree Resistance Distribution of Pinhal Interior Sul

RESULTS OF WORST CASE SCENARIO OF NATURAL ASYMMETRIES

Confidence level 99,5%	Voltage level [kV]	V_{res} [%]	I_{res} [A]	Characteristic angle [°]
Isolated	10	0,184	5,85E-05	undefined
	15	4,907	1,26E-04	undefined
	30	4,935	3,15E-04	undefined
Resonant	10	4,378	6,06E-01	-92,344
	15	18,8	2,3E-01	-92,257
	30	37,9	1,65E+00	-92,222
Resistance to 300A	10	0,096	2,21E-02	-179,243
	15	0,235	4,97E-02	-152,913
	30	0,409	2,00E-01	-164,778
Reactance to 300A	10	0,095	3,85E-02	-102,411
	15	0,289	5,15E-02	-102,433
	30	0,459	2,14E-01	-102,048
Reactance to 1000A	10	0,028	2,95E-02	-104,043
	15	0,159	5,02E-02	-103,295
	30	0,197	2,03E-01	-102,946

Fig. 8. Results of the Natural Asymmetries obtained by Pedro Aleixo, [4]

negligible.

B. *Zero Sequence current in healthy lines*

The zero sequence current in healthy lines, during a fault in other line, is other parameter necessary to obtain in order to guarantee and preserve the selectivity of the Protection System.
For the Network and for the impedances considered on the grounding connections, the zero sequence current in healthy lines were obtained by and are presented in Table VII.

TABLE VII
THE ZERO SEQUENCE CURRENT IN HEALTHY LINE, $3I_{0_h}$

		U_n [kV]	
		15	30
Neutral System	Isolated	3.18 A	11.87 A
	Resonant	3.17 A	11.85 A
	Resistance to 300 A	3.19 A	12.00 A
	Reactance to 300 A	3.09 A	11.29 A
	Reactance to 1000 A	2.88 A	9.61 A

Considering the electrical tree resistances obtained on the experiments and applying the equation 7, which could be simplified, due to the highly resistance magnitude of the tree, by

$$I_d = \frac{E_a}{R_{def}} \tag{14}$$

it is easy to infer that the residual current of the contact is smaller than the residual current of healthy lines. This fact forces the use of a directional overcurrent or inverse time current function, in order to preserve the selectivity of the Protection System.

VI. RESULTS

As stated before, the residual current of the natural asymmetries of the networks is imposed as the minimum pickup current value defined to operate- if the pickup current is set up to a value below, the electrical network will not operate.
In Table VIII refers to the probability of detection trees in each region for the $I_{op} = I_{res_h}$. It is noticeable that only for the Isolated System, the probability of detect a contact is certain, this implies the necessity of setting the current pickup to the minimum value above the residual current of the natural asymmetries allowed by the Unit Protection.

However, as seen in the chapterV there is a need of using a directional function or an inverse time earth fault overcurrent function. The latter is excluded, due to the importance of detecting and of the circuit breakers to actuate in the smallest amount of time.

A. *Directional Earth Fault Function*

In [8], it was obtained the optimal operation characteristic for the directional overcurrent function, in which, besides the results of the natural asymmetries, the errors of the measuring elements and of the Unit Protection were accounted. Since is the optimal operation characteristic, the settings considered in [4] were adopted for the sake of security, This results in the detection of a maximum number of contacts. In Figure 9 is shown the optimal operation characteristic applied for the directional earth fault overcurrent protection.
Comparing with the residual currents of natural asymmetries, the defined pickup current has a higher value. To ensure the maximum security possible surge the necessity of using a Define time earth fault overcurrent function, defined for a pickup currrent near to the residual current, in coordination with the directional earth fault protection.

B. *Define Time Earth Fault Function*

To obtain the minimum pickup current $I_{op}$for the Define Time Earth Fault function without losing the selectivity, it is important to obey to the following condition

$$I_{op} \geq max(I_{res_{ass}}; I_{res_{MIHD}}) \tag{15}$$

where $I_{res_{MIHD}}$ corresponds to the maximum residual current in a healthy feeder without the actuation of the directional earth fault protection on the faulty line. On Table IX is presented the $I_{res_{MIHD}}$ for each grounding system and each

TABLE VIII
PROBABILITY OF DETECT A CONTACT FOR A $I_{op} = I_{res_h}$ BY REGION

	Neutral System									
	Isolated		Resonant		Resistance to 300 A		Reactance to 300 A		Reactance to 1000 A	
Region	15 kV	30 kV	15 kV	30 kV	15 kV	30 kV	15 kV	30 kV	15 kV	30 kV
Algarve	100	100	78	31	100	94	100	92	100	93
Baixo Alentejo	100	100	81	8	100	96	100	95	100	96
Alentejo Litoral	100	100	90	7	100	99	100	99	100	99
Alentejo Central	100	100	82	8	100	98	100	97	100	97
Alto Alentejo	100	100	86	8	100	99	100	98	100	98
Centro Litoral	100	100	53	18	99	94	99	92	99	94
Dão/Lafões	100	100	51	14	100	92	100	88	100	91
Beira Int. Norte	100	100	55	7	100	94	100	92	100	94
Beira Int. Sul	100	100	66	27	100	88	100	86	100	88
Douro	100	100	50	5	100	91	100	87	100	90
Alto Minho	100	100	50	11	100	92	100	89	100	91
A.M. Lisboa	100	100	65	11	100	92	100	89	100	91
A.M.Porto	100	100	64	17	99	85	99	83	99	84
Baixo Minho	100	100	60	19	100	88	100	86	100	88
Barroso/Padrela	100	100	51	6	100	92	100	89	100	91
Nordeste	100	100	73	4	100	98	100	96	100	97
Oeste	100	100	61	21	100	90	100	87	100	90
Pinhal Int. Norte	100	100	56	21	100	92	100	89	100	92
Pinhal Int. Sul	100	100	53	10	100	88	100	84	100	87
Tâmega	100	100	59	20	99	96	98	94	99	95
Ribatejo	100	100	79	11	100	98	100	97	100	98
Centro Interior	100	100	59	23	100	89	100	87	100	89

Confidence level 99,5%	Voltage level [kV]	V_{res} [%]	I_{res} [A]	Characteristic angle [°]	$R_{def} max$ [Ω]
Isolated	10	0,5	1	90	6350
	15	5	1	90	9490
	30	5	1	90	16623
Resonant	10	6	1	10	18651
	15	47	2	5	5037
	30	25	2	5	19338
Resistance to 300A	10	0,5	1,5	45	4215
	15	0,5	1,5	45	6319
	30	0,5	1,5	45	12638
Reactance to 300A	10	0,833	2,5	9	2534
	15	0,833	2,5	11	3800
	30	0,833	2,5	11	7600
Reactance to 1000A	10	0,5	5	11	1267
	15	0,5	5	11	1902
	30	0,5	5	11	3805

Fig. 9. Settings of the directional earth fault protection defined by Pedro Aleixo, [4]

voltage level. Taken the defined settings (Figure 9) into account it could be seen that for the Resonant Grounded System on the 30 kV grid, there is no need of using a define time earth fault function. Given that the I_{op} of this function will be greater than of the directional one. Regarding the Isolated Neutral System, the minimum pickup current will be imposed by the $I_{res_{MIHD}}$ and by its corresponding setting. On the large fault currents grounding connections, the minimum threshold will be imposed by the residual current due to natural asymmetries.

TABLE IX
THE RESIDUAL CURRENT IN HEALTHY LINE FOR ID=$I_{op_{MIHD}}$

Neutral System	Un [kV]	$I_{res_{MIHD}}$ [A]
Isolated	15	0.1
	30	0.2
Resonant	15	0.747
	30	2.850
Resistance to 300 A	15	0.029
	30	0.104
Reactance to 300 A	15	0.030
	30	0.112
Reactance to 1000 A	15	0.025
	30	0.08

For obtaining the real I_{op} is important to consider the errors introduced by the zero sequence current transformers used and of the Protection Unit. In this case, the specification of the CT's are imposed by the setting defined for the directional overcurrent function and are presented in Table X For the

TABLE X
SPECIFICATION OF CURRENT TRANSFORMER

Neutral System	Un [kV]	CT [$I_1 : I_2$]
Isolated	15	50:1
	30	50:1
Resonant	15	10:1
	30	10:1
Resistance to 300 A	15	50:1
	30	50:1
Reactance to 300 A	15	50:1
	30	50:1
Reactance to 1000 A	15	100:1
	30	100:1

error introduced by the CT,ϵ_{CT}, it was considered the worst scenario for low current CT errors obtained by [9], regarding the maximum errors specified by the standards IEC 60255-3 standard.In Figure 10 is presented the magnitude errors introduced by CT for the worst case scenario.

The specification of CT will limit the choice of the Protection

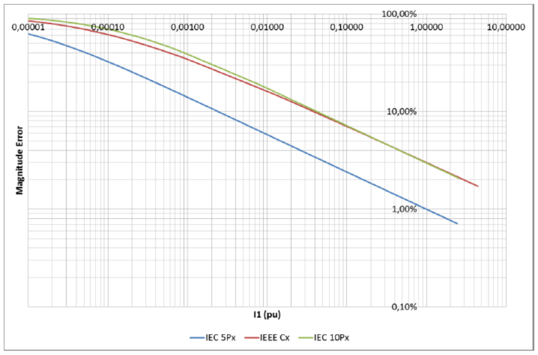

Fig. 10. the magnitude errors introduced by CT for the worst case scenario, [9]

Unit, once not all Units allow for reduced pickup currents and have an sensitive entry. For the scope of this project, the Protection Unit chosen was the SIPROTEC 4 7SJ64 made by Siemens [6], which allow a minimum pickup current of 0.001 A for the sensitive input. The tolerance error defined by the manufacturer for this relay is of $\epsilon_{PU} = 3 \times I_{op}$ or 1 mA. Finally, the pickup current accounting the errors introduced by the current transformer and the Protection Unit is given by

$$I_{op} = (max(I_{res_{ass}}; I_{res_{MIHD}}) \times (1 + \epsilon_{CT}))(1 + \epsilon_{PU}) + k_{saf} \tag{16}$$

where k_{seg} is a safety margin for other errors not accounted, that could arise.

C. Temporal coordination

In order to preserve the sensibility of the Protection System is necessary to define a temporal coordination between over-current functions.

The use of three stages for the protection against earth fault currents were considered. For the first stage, consists on the use of Define time Earth Fault overcurrent function with a time of operation, $t_{op} = 0.1s$. This extinguishes the fault current in the quickest amount of time possible, ensuring the security of the people and of the grid equipment. Regarding the other stages, the t_{op} will have to account the time of operation of the previous stage and the time of tripping of the circuit breaker and a security margin.

$$t_{op_i} = t_{max_{op_{i-1}}} + \Delta t \tag{17}$$

were $t_{max_{op_{i-1}}}$) is the maximum time of operation, which includes the operation time of the previous stage, the opening time of the circuit breaker and the time of signal processing of the relay. Δt represents the reset time of the circuit breaker and a safety margin to fulfill unequivocally the requirements of the temporal coordination. In Table **??**s presented the operation time of each stage.

TABLE XI
SPECIFICATION OF CURRENT TRANSFORMER

i	$t_{max_{op_{i-1}}}$	Δt	t_{op_i}
1			0.1
2	0.23	0.17	0.4
3	0.53	0.17	0.7

D. Suggested settings for detection of contacts between overhead lines and trees

Based on the previous consideration, the settings suggested for the detection of contacts between overhead lines and trees are shown in Table XII. This setting proposal should be considered for days where there is high temperatures and relatively low humidity in the air and also when in presence of a high risk of wildfires. For "normal" days, it could be used the usual setting defined by the utility.

TABLE XII
PROPOSED SETTINGS FOR THE DETECTION OF CONTACTS BETWEEN OVERHEAD LINES AND TREES

	15 kV			30 kV		
	Function	I_{op}	T_{op}	Function	I_{op}	T_{op}
Isolated	time def.		0.1	time def.		0.1
	directional	1	0.4	directional	1	0.4
	time def.	0.3	0.7	time def.	0.45	0.7
Resonant	time def.		0.1	time def		0.1
	directional	2	0.4	directional	2	0.4
	time def.	0.9	0.7			
Resistance to 300 A Reactance to 300 A	time def.		0.1	time def.		0.1
	directional	2.5	0.4	directional	2.5	0.4
	time def.	0.25	0.7	time def.	0.45	0.7
Reactance to 1000 A	time def.		0.1	time def.		0.1
	directional	8	0.5	directiona	8	0.4
	time def.	0.25	0.7	time def	0.45	0.7

The first stage pickup current was left in blank, in all neutral systems, for a free setting above the residual current of healthy lines present in Table VII.

In Table XIII is presented the probability of detecting tree contacts in each region for the setting proposal and also for an usual setting used by utilities. Note that in the majority of the regions the probability is around 50 %, however if the setting applied refers to the usual pickup current, the probability, at the initial time, is approximately zero, which could lead to the formation of wildfires without the knowing of the utility about the contact. Other aspect to be accounted is that although the probability of detection is of 50 %, if the contact is permanent, the fault current will arise, due to carbon path formation, which could make the relay to trip before the ignition of the branch.

VII. CONCLUSION

The experimental measurements of the electrical tree resistance on situ demonstrated that most of the trees have an electrical resistance of 20-80 $k\Omega$, which corroborates results of previous studies. Regarding to Portugal's tree species, it could be seen that the most hazardous tree to be in touch with overhead lines is the maritime pine, which on average have a resistance tree times greater than the other species measured.

TABLE XIII
PROBABILITY OF DETECT A CONTACT FOR THE SETTING PROPOSAL

CDF [%]	$I_{op}[A]$					
	0.3	0.9	0.25	3	0.45	3
	15 kV				30 kV	
Algarve	74.6	12.0	76.2	0.5	77.4	0.8
Baixo Alentejo	75.5	7.2	78.0	1.0	79.7	1.1
Alentejo Central	85.1	6.1	87.4	1.0	88.9	1.1
Alentejo Litoral	76.1	6.9	78.9	0.4	80.8	0.5
Alto Alentejo	80.4	7.2	83.0	0.2	84.7	0.3
Centro Litoral	36.4	15.4	44.1	0.0	49.5	0.0
Dão Lafões	41.8	6.3	45.9	0.1	49.0	0.1
Beira Int. Norte	43.2	5.8	48.5	0.0	52.3	0.0
Beira Int. Sul	60.8	12.8	63.3	0.1	65.1	0.2
Douro	40.5	3.8	44.7	0.1	47.9	0.1
Alto Minho	39.5	4.5	44.1	0.1	47.6	0.1
A.M. Lisboa	57.4	8.0	60.9	0.2	63.4	0.0.2
A.M.Porto	46.6	12.6	56.3	0.1	61.4	0.2
Baixo Minho	53.3	10.4	56.3	0.1	58.5	0.2
Barroso Padrela	40.4	4.6	45.1	5.2	48.6	5.7
Nordeste	65.2	2.8	68.6	0.0	71.2	0.1
Oeste	54.0	10.5	57.2	0.2	59.5	0.3
Pinhal Int. Norte	46.7	10.1	50.6	0.1	53.6	0.1
Pinhal Int. Sul	37.4	6.8	46.3	0.1	51.0	0.2
Tamega	40.8	16.5	49.6	0.1	55.4	0.3
Ribatejo	70.3	9.6	74.5	0.2	77.3	0.3
Centro Interior	52.3	9.6	55.5	0.1	57.9	0.2

This effect worsen in case the tree is infected by the pine wood Nematode, here the tree resistance could be of Megaohms, which could not be detected with any Protection Unit. This results enhance the need of trimming trees in the maintenance clearance zone, especially the maritime pine species.

For the model of electrical tree resistance, the results are in accordance with the obtained for the same heights and it shows that trees with largest diameters have a lower electrical resistance, however the model should be optimized by increasing the number of samples at different diameters.

Regarding the probability distribution function of electrical tree resistances by region, it could be seen differences between Southern Regions and Northern Regions, due to the different distribution of tree species in Portugal. Nevertheless, for a more realistic fit, the data collection of trees near overhead lines with the information of the tree species and the height of the tree should be included. This will adjust the fit to the location of the line and not only to the region where it is located.

In relation to the setting proposal, the major constrain is the minimum current admitted by the Unit Protection and the primary current of the CT used, which could imply an higher pickup current set than proposed one. Furthermore, we need to consider that the residual current for healthy lines and natural asymmetries were based on the parameters of the MV Grid present onVI, and could differ from real Networks, especially the number of lines and the extension of each line. For that reason, this proposal should be considered only for days with high risk of occurrence of wildfires.

REFERENCES

[1] B. William, B. Most, and S. Weissman, ''Trees and Power Lines: Minimizing Conflicts between Electric Power Infrastructure and the Urban Forest", 2012.

[2] J. Mitchell, '‘Power lines and catastrophic wildland fire in Southern California", Fire Mater. Conf. San Fr. CA, no. October 2007, 2009.

[3] E. M. Gora, P. M. Bitzer, J. C. Burchfield, S. A. Schnitzer, and S. P. Yanoviak, "Effects of lightning on trees: A predictive model based on in situ electrical resistivity," Ecol. Evol., vol. 7, no. 20, pp. 8523–8534, 2017

[4] J. L. Pinto de Sá," Textos de apoio à cadeira de Proteções e Automação em Sistemas de Energia"', Lisboa, 1993.

[5] EFACEC Sistemas de Electrónica, S.A.," TPU S420 Edição 1", Moreira Maia, 2005

[6] P. Aleixo,'‘Características operacionais ótimas de proteções direcionais de sobre-intensidade homopolar", Instituto Superior Técnico, 2017

[7] Instituto da Conservação da Natureza e das Florestas;Ministério da Agricultura do Mar do Ambiente e do Ordenamento do Território, '‘6o Inventário Florestal Nacional", 2013.

[8] SIEMENS, '‘SIPROTEC 4 Multi-Functional Protec- tive Relay with Local Control 7SJ62/64 Manual", 2016.

[9] M. Louro, '‘On CT errors at low currents", Lisboa, 2008.