Journal of the Nigerian Association of Mathematical Physics
***Volume* 18 (May, 2011), pp 439 – 444**
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Optimal Safety Earthing – Earth Electrode Sizing Using A Deterministic Approach

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Abstract

In this paper a deterministic approach in the sizing of earth electrode using the permissible touch voltage criteria is presented. The deterministic approach is effectively applied in the sizing of the length of earth rod required for the safe earthing of residential and facility buildings. This approach ensures that the earthing design is not only safe and effective but also reduces wastages in both material and labour.

Keywords: step voltage, touch voltage, soil enhancer, earth electrode resistance, embedded earth electrode.

1.0 Introduction:

Safe earthing according to [10] is (1) to provide means to carry electric currents into the earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity in service. (2) to assure that a person in the vicinity of the earthed equipment is not exposed to the danger of critical electric shock.

By properly earthing the metallic frames of electrical equipments, voltages that may be hazardous to persons are eliminated. And this may require that the earthing systems of the equipment be designed and constructed in a manner to limit exposure voltages to safe levels and duration. . The effects of an improper or faulty earthing system can range from erratic operation of electronic devices to minor physical harm or damage to electrical equipment. An effective earthing system that limits hazardous voltages and electromagnetic disturbances is essential to ensure personnel safety, protection and stable operation of microelectronic equipments such as computers, medical instruments and communication facilities [8 and 9].

Several models and methods (numerical and analytical) has been employed in several literatures in the analysis of earthing systems. These methods include the finite element method (FEM) [13], the boundary element method (BEM) [5], the charge simulation method (CSM) [1] and the finite difference time domain (FDTD) [14]. These methods are used in the analysis of large (grid) earthing systems and are time consuming. None of these can be used in the sizing of micro-earthing systems (a system comprising of either a single earth rods or group of at most five earth rods) where the size of the earth electrode to be used is a function of the touch potential, earth resistivity and the sensitivity of the earth fault interrupting system.

In this paper, a deterministic approach is used in the sizing of micro-earthing systems. In this method we include the factors responsible for personnel safety in the final expression for the designing of an effective micro-earthing system. The determining expression used is obtained from a group of well tested empirical expressions [10]. It is simple and the required number of earth rods for the earthing of a particular facility can be computed using a calculator.

The deterministic approach is very useful method in the sense that it not only gives an earthing system design that protects personnel and electric equipments, but also brings about considerable saving in the material and labour.

2. Touch and Step Potential

Figure 1 is an illustration of the inherent danger of an electric shock to a person in contact with faulty electrical equipment during an earth fault. The two most dangerous electric shock phenomena are the touch and step potential. Touch Potential as illustrated in figure 1 is the voltage between the energized object and the feet of a person in contact with the object [11]. It is equal to the difference in voltage between the energized object and a point some distance away. It should be noted that the touch potential could be nearly the full voltage across the earthed object if that object is earthed at a point remote from the place where the person is in contact with it. Touch potential of a person weighing 50 kg and that weighing 70 kg respectively can be expressed as

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$$V_{touch50} = \frac{0.116}{\sqrt{t_s}}\left[R_B + \frac{1}{2}\left(R_{foot} + R_{mfoot}\right)\right] \quad (1)$$

$$V_{touch70} = \frac{0.157}{\sqrt{t_s}}\left[R_B + \frac{1}{2}\left(R_{foot} + R_{mfoot}\right)\right] \quad (2)$$

where R_B is the resistance of a human body from hand-to-both-feet and also from hand-to-hand, or from one foot to the other foot, t_s is the duration of electric shock. R_{foot} is the self resistance of each foot to remote earth and is expressed as

$$R_{foot} = \frac{\rho_{soil}}{4b} \quad (3)$$

R_{mfoot}, is the mutual resistance between the feet and is express as

$$R_{mfoot} = \frac{\rho_{soil}}{2\pi d_{foot}} \quad (4)$$

ρ_{soil}, b and d_{foot}, are the soil resistivity, the equivalent radius of a foot and the separation distance of the feet respectively Step Potential as illustrated in figure1 is the voltage between the feet of a person standing near an energized earthed object. It is equal to the difference in voltage given by the voltage distribution curve between two points at different distances from the earth electrode. A person could be at risk of injury during a fault simply by standing near the earthing system point. The step potential of a person weighing 50 kg and that weighing 70 kg respectively can be expressed as

$$V_{step50} = \frac{0.116}{\sqrt{t_s}}\left[R_B + 2\left(R_{foot} - R_{mfoot}\right)\right] \quad (5)$$

$$V_{step70} = \frac{0.157}{\sqrt{t_s}}\left[R_B + 2\left(R_{foot} - R_{mfoot}\right)\right] \quad (6)$$

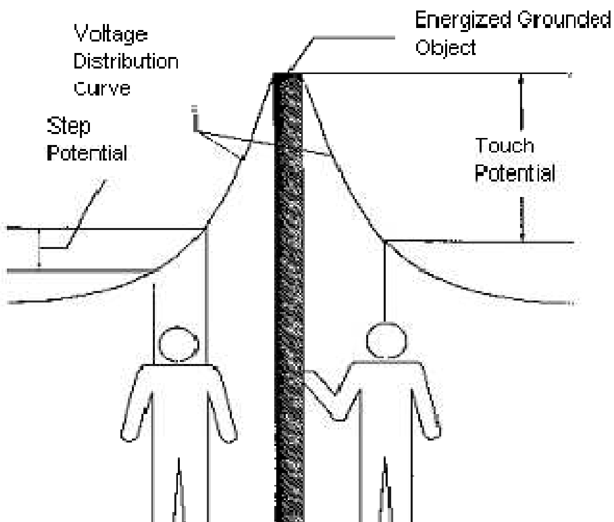

Figure 1: Step and Touch Potential [COS&HSB (1998)]

Modern earthing system design is based on the touch and step potential criteria as it helps in attaining an efficiently designed earthing system which limits earth voltages due to earth potential rises (EPR) within earthed equipment during earth faults. The earth potential rise (EPR) of an earthed equipment under earth fault conditions must be limited so that touch and step potential limits are not exceeded, and is controlled by keeping the earth electrode resistance (R_c) of the equipment earthing system as low as possible.

3. Choice of Earth Fault Interrupter

Many homes have fuses and circuit breakers as interrupting system against short circuits. Incidentally they also serve as interrupting system during earth faults. If they are to provide protection against faults to exposed metal frame, the wiring must be such that the earth fault produces the same conditions as a short circuit, namely a large excess current in the line conductor. This will happen only if the impedance of the path taken by the earth fault current is low enough. The policy of protecting against earth faults by making sure that they produce a short circuit and, therefore operate the fuse or circuit breaker has been described as 'chasing the ampere'. With ever increasing demand for electricity, circuit ratings and their fuse rating are becoming ever higher and the short circuit current needed to operate the fuse or circuit breaker becomes higher. Thus ever lower values are required for earth loop impedances and the earth fault currents which the fuses have to break become higher [12].

The magnitude of the earth fault current needed to setup an interruption depends on the earth fault impedance z_c, the faulted equipment earthing system resistance R_c, the soils impedance z_s, the transformer's solidly earthed neutral impedance z_t and the line impedance z_l and the transformer's secondary voltage V_{ph}. The earth fault current I_f is given as,

$$I_f = \frac{V_{ph}}{Z_T} = \frac{V_{ph}}{z_c + R_c + z_s + z_t + z_l} \qquad (7)$$

Once the earth fault current is obtained the voltage drop V_E in the safety earthing conductor can be calculated.

$$V_E = R_c I_f \qquad (8)$$

The magnitude of the earth fault current is the determining factor on the choice of an interrupting system. If the total impedance Z_T of the earth-loop path on a 240 volt installation is of the order of 20 ohms, the maximum possible earth fault current, even assuming a direct earth fault, would only be 12 amps. This current would, of course, be carried indefinitely by a 15 amps sub-circuit fuse and the metallic frame of the faulted equipment would now be permanently connected to the live circuit of 240 volts.

In such circumstances fuses can offer no protection against earth fault conditions. Some alternative form of protection, such as an earth-leakage circuit breaker or residual current devices (RCDs) must be adopted. These devices operate to provide protection with a leakage current of the order of 3 amps to 50mAmps or at 24 volts to 40 volts.

5. Deterministic Earthing

The earthing system designer is normally faced with two tasks: - to achieve a required earth electrode resistance value and to ensure that the touch and step potentials are satisfactory. The factors which influence the earth electrode resistance of an earthing system are the physical dimensions (length, diameter, area etc) and attributes of the earth electrode system and the soil conditions (composition, water content etc) [10].

The deterministic approach to safety earthing involves the use the touch potential expression of equation (1) and some basic earth electrode resistance expressions to determine the size and length of earth electrode that will be required to keep the earth potential rise (EPR) of faulted equipment at a predetermined value. The predetermined earth potential rise is that of the permissible touch potential which is 50 volts and 25 volts for dry and wet premises respectively. The soil resistivity the most predominant factor is seasonal dependant and the worse case value which is February value is used in the deterministic approach [15].

Earth electrodes are of various sizes, shape and configuration and this includes the following [10].

- Simple surface earth electrode in the form of horizontally placed strip or wire, either as a single ended strip or a ring. The earth electrode resistance R of such electrodes are expressed as

$$R = \frac{\rho_{soil}}{\pi l}\left(\ln\frac{2l}{\sqrt{2ah}} - 1\right) \qquad (9)$$

where, l, a and h are the strip or wire length, the radius of the wire and the depth of burial of the wire respectively.

- Meshed electrodes, constructed as a grid placed horizontally at a shallow depth. the expression of the earth electrode resistance is

$$R = \rho_{soil}\left[\frac{1}{l} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] \tag{10}$$

where, A is the area covered by the grid.

- Foundations or embedded earth electrodes formed from conductive structural parts embedded in concrete foundation providing a large area contact with the earth and has the following earth electrode resistance expression

$$R = \frac{1}{2\pi l}\left[(\rho_{soil} - \rho_c)\left(\ln\frac{8l}{D} - 1\right) + \rho_c\left(\ln\frac{8l}{d} - 1\right)\right] \tag{11}$$

where, ρ_c, D and d are the resistivity of concrete, the diameter of the concrete foundation and the diameter of the earth rod respectively.

- Rod electrodes which can consist of a pipe, rod, etc. and are driven or buried to a depth greater than 1 m and usually from 3 m to 30 m or more and its earth electrode resistance can be express as

$$R = \frac{\rho_{soil}}{2\pi l}\left(\ln\frac{8l}{d} - 1\right) \tag{12}$$

The adoption of any of these earth electrode configurations depends on the availability of surface area and soil topology. The most commonly used earth electrode is the deep driven earth rod and as such the deterministic earthing calculations will be based on the earth rod. The function of an earthing system is the protection of life against electric shock, the fundamental requirement being that the earthing potential, V_E, at a prospective short circuit current, I_E, does not exceed the permissible touch voltage V_{touch} that is:

$$V_E \le V_{touch} \tag{13}$$

Thus, the maximum permitted value of earthing resistance is

$$R = \frac{V_{touch}}{I_E} = \frac{0.116}{\sqrt{t_s}\, I_E}\left[R_B + \frac{1}{2}\left(R_{foot} + R_{mfoot}\right)\right] \tag{14}$$

From equations (12) and (14), the length of earth rod required to maintain the criteria of equation (1) and (2) is,

$$l \ge \frac{\sqrt{t_s}\, I_E\, \rho_{soil}\left[\ln l + \ln\frac{8}{d} - 1\right]}{0.232\pi\left[R_B + 0.5\left(R_{foot} + R_{mfoot}\right)\right]} \tag{15}$$

Assuming $R_B = 1000\Omega$, $\rho_{soil} = 200\Omega m$, $\rho_{dryfloor} = 1000\Omega m$, $\rho_{wetfloor} = 300\Omega m$, $R_{footdry} = 3125\Omega$, $R_{mfootdry} = 159\Omega$, $R_{footwet} = 938\Omega$, $R_{mfootwet} = 48\Omega$ and using a earth rod of diameter d of 0.02 metre, Table 1 shows the effective earth rod length for various interrupting systems using an interrupting time duration of three seconds. I_{cc} is the maximum current that can set the device into the interrupting mode. l_{wet} and l_{dry}, are the effective earth-rod length requirement for wet and dry environments respectively.

TABLE 1: Computation of the Effective Earth-Rod Length in both wet l_{wet} and dry l_{dry} environments for Various Interrupting Devices, using equation (15) with $\rho_{soil} = 200\Omega m$ $R_{footdry} = 3125\Omega$, $R_{mfootdry} = 159\Omega$, $R_{footwet} = 938\Omega$, $R_{mfootwet} = 48\Omega$ respectively and an earth rod of diameter d of 0.02 metre.

	Residual Current Device			Fuses			Circuit Breaker	
I_{rated}	$3A$	$1A$	$500mA$	$15A$	$20A$	$30A$	$15A$	$20A$
$I_{cc} = I_E$	$3A$	$1A$	$500mA$	$45A$	$60A$	$90A$	$23A$	$30A$
l_{wet} (m)	9.18	3.06	1.53	137.77	183.69	275.54	70.42	91.85
l_{dry} (m)	5.18	1.73	0.86	77.64	103.52	155.29	39.69	51.76

6. Improving and Minimizing the Sizing

In highly resistive soil environments, attaining the required earth electrode resistance consumes a lot of earth electrodes which increases the cost of installation. In an attempt to improve on the earth electrode resistance, designers have added various chemicals. Chemical electrodes are often proposed to accomplish this reduced resistance. However, the maintenance requirements and expense make this also a less than preferred option [4, 6].

Conductive concrete ($\rho = 30 - 90\Omega m$) and other soil enhancing material like bentonite ($2.5\Omega m$), carbon-based backfill material ($0.1 - 0.5\Omega m$) and clay-based backfill material ($0.2 - 0.8\Omega m$) are effective media for fill around earth electrodes. They have high moisture retention ability and the alkalinity in them provides free ions.

The earth electrode resistance of a reinforced concrete or any of the soil enhancing material is as given in equation (11). Using this with equations (1) or (8), the effective length is given as,

$$l \geq \frac{\sqrt{t_s}\, I_E \left[(\rho_{soil} - \rho_c)\left(\ln l + \ln \frac{8}{D} - 1 \right) + \rho_c \left(\ln l + \ln \frac{8}{d} - 1 \right) \right]}{0.232\pi \left[R_B + 0.5\left(R_{foot} + R_{mfoot} \right) \right]} \qquad (16)$$

Using the same parameters as that of Table 1 computation, but with a conductive concrete ($\rho_c = 30\Omega m$) as a soil backfill of a 1.2 metre diameter pit. Table 2 shows the resulting effective length requirements for an embedded earthing system.

TABLE 2: Computation of the Effective Earth-Rod Length in both wet l_{wet} and dry l_{dry} environments for Various Interrupting Devices, using equation (16) with $\rho_{soil} = 200\Omega m$ $R_{footdry} = 3125\Omega$, $R_{mfootdry} = 159\Omega$, $R_{footwet} = 938\Omega$, $R_{mfootwet} = 48\Omega$, $\rho_c = 30\Omega m$ and an earth rod of diameter d of 0.02 metre.

	Residual Current Device			Fuses			Circuit Breaker	
I_{rated}	$3A$	$1A$	$500mA$	$15A$	$20A$	$30A$	$15A$	$20A$
$I_{cc} = I_E$	$3A$	$1A$	$500mA$	$45A$	$60A$	$90A$	$23A$	$30A$
l_{wet} (m)	5.84	1.95	0.97	87.54	116.72	175.09	44.74	58.36
l_{dry} (m)	3.30	1.10	0.55	49.47	65.96	98.95	25.28	32.98

7. Discussions

From Table1 and 2, the best choice of interrupting devices is the residual current device (RCD). As shown in the computation in Table 1, in a wet environment an RCD of 3A requires an earth rod length l_{wet} of 9.18 metres only while on dry environment it only requires 5.18 metres to provide a means for the fault current to flow into earth in order to interrupt the circuit within 3 seconds during an earth fault on electrical equipment. The computation in Table 1 also shows that the more sensitive the RCD (sensitivity of an RCD increases with decrease in rated current I_{rated}) the shorter the required length of the earth electrode. The computation in Table 2 with conductive concrete of resistivity 30 ohm metre reduces the earth rod length requirement for both wet and dry environment to 5.84 metres and 3.30 metres respectively. A comparison Table 2 with Table 1 for RCD's shows a length reduction of about 38%. Further reduction in length is possible if the effective area of the soil conductive concrete is increased.

8. Conclusions

In this paper, the sizing earth electrodes using the deterministic approach based on the touch voltage criteria is discussed. The method is simple and can be used in the design of micro-earthing systems employed in facility buildings where other earthing analysis methods could not be used due to their complexity and the difficulty of including safety and sensitivity criteria in their formulations.

9. References

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