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Efficient Computation of Grounding Pit Optimum Dimensions in High Resistivity Soils

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ABSTRACT

Good grounding arrangement is very important for safe and reliable operation of a power system and to ensure safety of the power apparatus and operating personnel. In Kingdom of Saudi Arabia, the weather is dry and the soil resistivity varies significantly from area to area because the geodetic terrain varies from sea shore to the arid desert and dry mountains. In most of the inland desert areas, the soil resistivity is significantly high and it is difficult to get low earth resistance with conventional methods. Therefore, an economical and efficient grounding system design of the earthing pit is necessary which can be achieved by using a low resistivity material (LRM). When such material is used, it is important to optimize the pit design. The intent of this paper is to present a simple general computational technique for finding the optimum economical size of grounding pit when filled with LRM. The suggested method can be readily used by engineers to obtain a good earthing pit configuration for efficient grounding of the power system components in high resistivity soils.

KEY WORDS: Grounding resistance, ground resistivity, grounding rods, low resistivity material (LRM), grounding pit optimization.

1. INTRODUCTION

Over-voltages are induced in power transmission and distribution lines and are the most serious threats to components/insulation in power system. According to statistical results of power system failure in China, about 40 to 70% of high voltage transmission line failure was caused by lightning[1]. Thepower lines and substations are protected from such over-voltages by surge arresters which are provided with a low earth resistance connection to enable the large lightning and fault induced currents encountered to be effectively discharged to the earth. The earth resistance of a grounding system depends on grounding electrode arrangement and soil resistivity. The ground potential rise can cause problems such as electrical shock and can damage the equipment if it rises above a certain threshold. It can also causes interference with electronic equipment. Therefore, a lower grounding resistance is important for safety of the equipment and personnel. The first step to design an efficient grounding system is to obtain the surrounding soil resistivity data. Then the next step is to design an efficient low resistance grounding pit according to the surrounding soil structureand its resistivity. The soil resistivity depends on the type of soil, moisture content, the quantity of saltspresent in the soil and the ambient temperature. An increase of the moisture content and dissolved salts or the increase in temperature reduces the soil resistivity.

To reduce the grounding resistance different materials have been proposed. These include use of bentonite, drilling rig mud, steel furnace slag, ground water accumulation using deep wells, and a variety of other materials and techniques [1-7]. Most of these materials are also utilized in the formulation of LRM.

The resistance to ground of simple grounding electrodes can be easily calculated [8].Scale model tests with an electrolytic tank are also very useful for determining the ground resistance and surface potential distributions during ground faults in complex grounding arrangements where accurate analytical calculations may be difficult [9]. In recent years several publications have discussed the application of low resistivity materials and the performance of such and conventional materials under different conditions [1, 10-13]

In Saudi Arabia, the ground resistivity varies in a large range because the geodetic terrain varies from sea shore to the arid desert and dry mountains [14]. Therefore to get a low value of grounding resistance, a good design of the grounding pit is necessary. In some cases, LRM needs to be used in such pits. In such situations, it is important to make an efficient use of the LRM. Different parameters that affect the grounding resistance were studied in detail and an optimized pit design procedure was suggested. This paper presents a simple general computational technique for finding the optimum size of grounding pit that is commonly filled with LRM. The suggested method can be readily used by engineers to obtain a good earthing pit configuration for efficient grounding of the power system components.

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1. Expression for the Grounding Resistance

Consider a conductor extended along X axis between $x= -L$ and $x = L$, and a current I(*0*) is injected into the conductor as shown in Fig. 1. Assume that the conductor is buried in uniform soil of resistivity ρ Ω-m. Let *dl* be the conductor element at distance $x = l$ and I(*l*) be the conductor current at a distance $x = l$. The potential at a point *(x, y)* in the surrounding medium with resistivity *ρ* (Ω-m) due to the current leaving the conductor element *dl* is:

$$dV(x,y) = \frac{\partial I(l)}{\partial l}\frac{\rho}{4\pi a}dl \quad (1)$$

$$\text{where, } a = \left[(x-l)^2 + y^2\right]^{1/2} \quad (2)$$

Here, it is assumed that the potential due to the current leaving the conductor element is same as for a point source.

The potential at point P(*x,y*) due to the current flowing to the ground along the entire conductor is given as:

$$V(x,y) = \frac{\rho}{4\pi}\int_{-L}^{L}\left[(x-l)^2 + y^2\right]^{-1/2}\frac{\partial I(l)}{\partial l}dl \quad (3)$$

Assume constant current leakage $\frac{\partial I(l)}{\partial l}$ = *2I(0)/2L* = I_0/L along the conductor length, then evaluation of (3) gives:

$$V(x,y) = \frac{\rho I(0)}{4\pi L}\ln[u(x,y)] \quad (4)$$

$$\text{where } u(x,y) = \frac{\sqrt{(x+L)^2 + y^2} + (x+L)}{\sqrt{(x-L)^2 + y^2} + (x-L)} \quad (5)$$

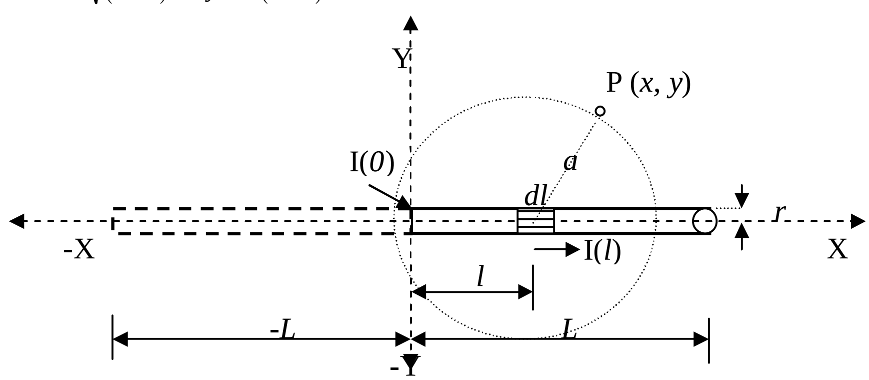

Figure 1. Method of Calculation of Grounding Resistance

The average potential along the conductor is obtained by substituting $y = r$ in (4) and integrating it between $x = 0$ and $x = L$. The following expression for the resistance of the conductor in a medium of infinite extent in all direction is obtained by dividing the average potential by *2I(0)* [5, 15, 16]:

$$R = \frac{\rho}{2\pi L}\left\{\ln\left(\frac{2L}{r}\left[1+\sqrt{1+\left(\frac{r}{2L}\right)^2}\right]\right) + \frac{r}{2L} - \sqrt{1+\left(\frac{r}{2L}\right)^2}\right\} \quad (6)$$

The value of resistance of vertical ground rod as shown in Fig. 2(a) can be calculated using (6).

2. Grounding techniques

In the low resistivity soils, a simple copper (Cu) or copper clad steel rod of suitable length *L*(m) and radius *r*(m) is inserted in the ground as shown in Figure1(a) for the grounding purpose. The grounding resistance R_1 (Ω) of such an earthing rod can be expressed as in (6).

After simplification by neglecting the term $\frac{r}{2L}$ and its high powers ($\because \frac{r}{2L} << 1$), eqn. (6) can be expressed as:

$$R_1 = \frac{\rho}{2\pi L}\left(ln(\frac{4L}{r}) - 1 \right) \quad (7)$$

where ρ is the soil resistivity (Ω-m). The volume of ground rod (Vol_1) is given as follow:

$$Vol_1 = \pi r^2 L \quad (8)$$

When the surrounding soil has very high resistivity, multiple parallel rods have to be used where the spacing between rods must be at least twice the rod depth in order to derive maximum benefit of using multiple rods. However, when the soil resistivity is either too high or the space is insufficient to construct the grounding network of required number of parallel grounding rods, one of the following two methods of employing LRM as shown in Figs. 2(b) & 2(c) can be used for reducing the high grounding resistance. It will provide a low impedance path for fault and lightning induced currents ensuring maximum safety from the internal system faults as well as the impact of lightning strokes.

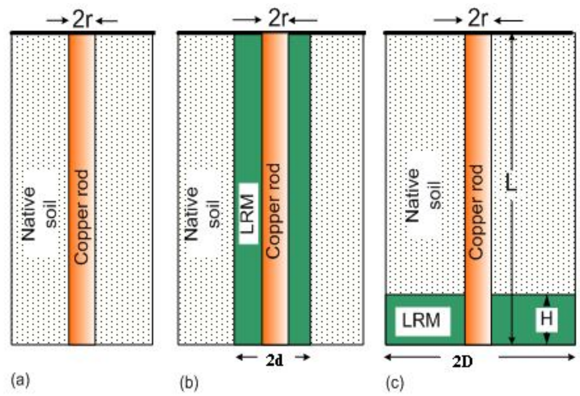

Figure 2. Grounding arrangement [15]:(a) Grounding rod in natural soil, (b) Grounding rod totally surrounded by LRM, (c) Grounding rod embedded partially in LRM placed in a circular pit

2.1. Method-A

In this method, a grounding rod is buried in an augured hole of some suitable diameter (2*d*) which is filled with the LRM. The buried electrode is fully surrounded by the LRM having resistivity (ρ_c) and a symmetrical thickness of *d-r* (m) as shown in Fig.2 (b). The LRM is surrounded by uniform high resistivity native soil of resistivity (ρ) (Ω-m). The grounding resistance R_2 (Ω) of the rod fully embedded in LRM arrangement of Fig. 2(b) can be derived from (6) and is expressed as:

$$R_2 = \frac{\rho_c}{2\pi L}\left\{ \ln\left(\frac{2L}{r}\left[1 + \sqrt{1 + \left(r/2L \right)^2} \right] \right) + \frac{r}{2L} - \sqrt{1 + \left(r/2L \right)^2} \right\} + \frac{\rho - \rho_c}{2\pi L}\left\{ \ln\left(\frac{2L}{d}\left[1 + \sqrt{1 + \left(d/2L \right)^2} \right] \right) + \frac{d}{2L} - \sqrt{1 + \left(d/2L \right)^2} \right\} \quad (9)$$

Neglecting the terms $\frac{r}{2L}, \frac{d}{2L}$ and their higher powers from (9), it is written as [7,15]:

$$R_2 = \frac{\rho_c}{2\pi L}\left(\ln(\frac{4L}{r}) - 1 \right) + \frac{\rho - \rho_c}{2\pi L}\left(\ln(\frac{4L}{d}) - 1 \right) \quad (10)$$

The volume of the LRM used in this arrangement will be:

$$Vol_2 = \pi(d^2 - r^2)L \quad (11)$$

2.2. Method-B

A pit of suitable dimensions (2D×L) is prepared and the vertical grounding rod of radius *r*(m) is embedded at the center of a horizontal layer of LRM having diameter 2*D*(m) and height H (m) as shown in Fig.2(c). This arrangement can also provide the desired ground resistance reduction. The equivalent resistivity $\rho_{eq.}$ of two soil layers is:

$$\rho_{eq.} = \frac{L}{H/\rho_c + (L-H)/\rho} = \frac{L.\rho.\rho_c}{[H\rho + (L-H)\rho_c]} \quad (12)$$

Replacing ρ_c with ρ_{eq} and *d* with *D* in (9), the grounding resistance R_3 for method-B can be expressed as:

$$R_3 = \frac{\rho_{eq}}{2\pi L}\left\{ln\left(\frac{2L}{r}\left[1+\sqrt{1+\left(r/_{2L}\right)^2}\right]\right)+\frac{r}{2L}-\sqrt{1+\left(r/_{2L}\right)^2}\right\} + \frac{\rho-\rho_{eq}}{2\pi L}\left\{ln\left(\frac{2L}{D}\left[1+\sqrt{1+\left(D/_{2L}\right)^2}\right]\right)+\frac{D}{2L}-\sqrt{1+\left(D/_{2L}\right)^2}\right\} \quad (13)$$

$$= \frac{\rho\rho_c}{2\pi\left[H\rho+(L-H)\rho_c\right]}\left\{\ln\left(\frac{2L}{r}\left[1+\sqrt{1+\left(r/_{2L}\right)^2}\right]\right)+\frac{r}{2L}-\sqrt{1+\left(r/_{2L}\right)^2}\right\} + \frac{H\rho(\rho-\rho_c)}{2\pi L\left[H\rho+(L-H)\rho_c\right]}\left\{\ln\left(\frac{2L}{D}\left[1+\sqrt{1+\left(D/_{2L}\right)^2}\right]\right)+\frac{D}{2L}-\sqrt{1+\left(D/_{2L}\right)^2}\right\} \quad (14)$$

Eliminating the terms $\frac{r}{2L},\frac{d}{2L}$ and their higher powers from (14), it is written as:

$$R_3 = \frac{\rho.\rho_c}{2\pi\left[H\rho+(L-H)\rho_c\right]}\left\{\ln\left(4L/_{r}\right)-1\right\}+\frac{H\rho\rho(-\rho_c)}{2\pi L\left[H\rho+(L-H)\rho_c\right]}\left\{\ln\left(4L/_{D}\right)-1\right\} \quad (15)$$

The volume of the LRM (Vol_3) used in this case will be:

$$Vol_3 = \pi(D^2 - r^2)H \quad (16)$$

In choosing methods-*A* and *B*, one has to consider the amount of resistance reduction achieved with certain volume of the LRM for given values of soil and LRM resistivities and other pit parameters as discussed next.

The ground resistance values for the grounding arrangements shown in Fig.2 above were evaluated using a range of data as shown in Table 1, for all the variables mentioned in equations (7) - (16).

TABLE 1.Input Data Ranges [14]

Specifications	Unit	Value range
Radius of the grounding rod (r)	m	0.0085
Grounding rod length (L)	m	1.2, 2.4, 3.6
Native soil resistivity □□□)	Ω-m	10 ~ 2000
LRM resistivity □□□$_c$)	Ω-m	1, 2, 5, 10
Diameter of the augured hole (2d)	-	2r ~ 50r
Diameter of the pit (2D)	m	0.1 ~ 3
LRM layer thickness (*H*)	-	0.001L ~ L

3. Problem formulation and Solution Technique

A general optimization problem refers to the selection of a best element from some set of available alternatives. It consists of an objective to be optimized and is associated with a number of equality and inequality constraints. Mathematically, it can be formulated as follows;

$$\text{Minimize } F(x) = f(x_1, x_2, ...x_n) \quad (8)$$

$$\text{Subject to } \begin{cases} g_i(x_1, x_2, ...x_n) & i = 1,2,......,I \\ h_j(x_1, x_2, ...x_n) & j = 1,2,......,J \\ l_k(x_1, x_2, ...x_n) & k = 1,2,......,K \end{cases} \quad (9)$$

where, (8) is the objective function and (9) constitutes the set of constraints imposed on the solution. The variables x_1, x_2, . . .,x_n, represent the set of decision variables, and f (x_1, x_2, . . ., x_n) is the objective function expressed in terms of

these decision variables.

Here, the main objective of the optimization is to make the most efficient use of the LRM, to achieve this, the pit size has to be optimized to achieve the minimum value of R_3. In other words, minimize the value of R_3 which is a function of pit dimensions D and H as given in (15) with given constraints.

The constraints which must be incorporated to find the optimum value of R_3 and corresponding values ofD and H are as follow;

- The LRM volume used for both method-*A* and method-*B* are same in order to ensure equal cost of LRM, i.e.
- $Vol_3 = Vol_2$(10)

- The pit dimensions should be realistic and therefore should be restricted by the possible volume of lower and the upper limits. Thus, diameter of the pit should be more than the diameter of the earth road and length of the pit should not exceed the length of the earth road, i.e.

- $D \geq r$ (11)

$0.01L \leq H \geq L$ (12)

The optimization problem can be formulated as follows:

Minimize $R_3 = f(H,D)$

(13)

$$\text{Subjected to} \begin{cases} Vol_3 = Vol_2 \\ D \geq r \\ 0.01L \leq H \leq L \end{cases}$$

The Solution of the above optimization problem with the given constraints is carried out using MATLAB with Sequential Quadratic Programming (SQP) algorithm since SQP algorithm having strict feasibility with bounds. The obtained results are discussed next.

4. RESULTSAND DISCUSSION

The grounding resistance for the three configurations shown in Figure 2(a) - 2(c) were calculated and based on the results, an optimized pit configuration was discussed and is presented next.

The grounding resistance *(R*$_1$) for the grounding rod in native soil without LRM as given by eqn. (1) clearly shows that $R_1$is directly proportional to the surrounding soil resistivity (□) and R_1 increases with the increase in soil resistivity.

In order to make the most efficient use of the LRM, the pit size has to be optimized. The optimized values of the grounding resistance as well as the pit dimensions were derived using the MATLAB simulation model.

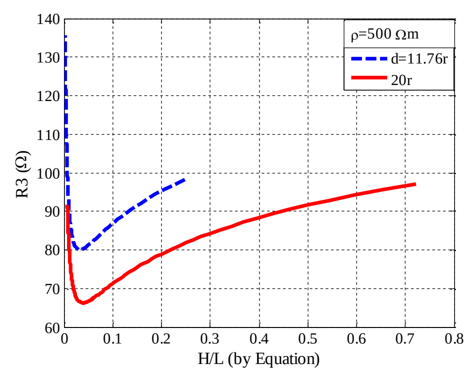

Figure 3. Variation in R_3vs*H/L* (Constant LRM volume)

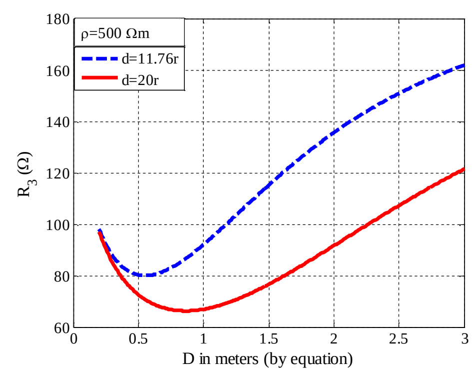

Figure 4. Variation in R_3 vs. *D* at *d*=11.76*r* and *d=20r*

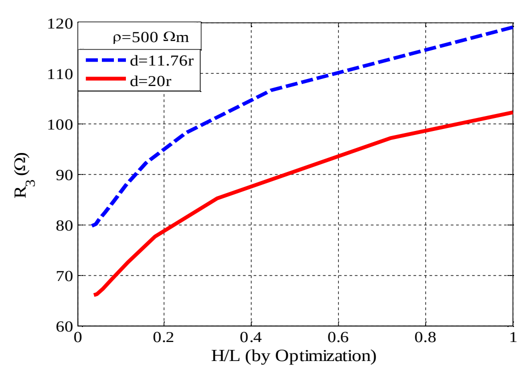

Figure 5. Optimized R_3vs*H/L* (using Optimization)

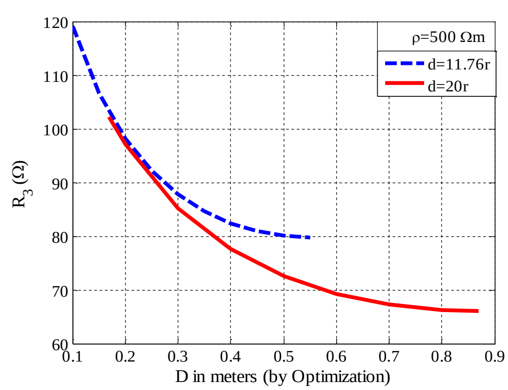

Figure 6. Optimized R_3vs*D*

These optimum values were obtained keeping the LRM volume the same for both method-*A* as well as for method-*B*. The LRM volumes used for the method-*A* i.e. (*Vol*$_2$) were the volumes corresponding to the augured hole having *d*=11.76*r* as well as *d*=20*r*. Thus *Vol*$_2$=0.063 m^3 when *d*=11.76*r* and *Vol*$_2$=0.1966 m^3 when *d*=20*r*. The pit radius *D* was varied from 0.2 m to 2 m and the respective variation in optimum R_3 vs. *H/L* is shown in Fig. 3 whereas R_3 vs. *D* is shown in Fig.4**.** It is important to note that for both of these fixed LRM volumes, the values of R_2 were bigger than the corresponding values of R_3. R_2 were 119.1 Ω and 102.2 Ω for *d*=11.76*r* and

d=20r, respectively which are much higher than corresponding values of R_3 as shown in Figures 3 and 4. Thus, the method B represents a more effective way of using the LRM in high resistivity soils for ground resistance reduction applications.

The optimum value of R_3, D and H were calculated using the above discussed optimization technique. The corresponding results are as shown in Figures 5 and 6. Here also, the volume of the LRM is fixed at value corresponding to the case when the conductor is fully covered and d=11.76r (i.e. Vol_3=Vol_2= 0.063m^3). From Figure 4, the optimum value of grounding resistance is 80.1 Ω at H/L ratio=0.032 (i.e. H=0.077 m when L=2.4 m) and from Figure 6, the corresponding pit radius D=0.5507 m.

4.1. Optimum values of R$_3$ and pit dimensions

Using the above discussed technique, optimum values of R_3, D and H were calculated for different values of LRM volumes and soil resistivity (□) and the results are shown in Figures 7 - 11.

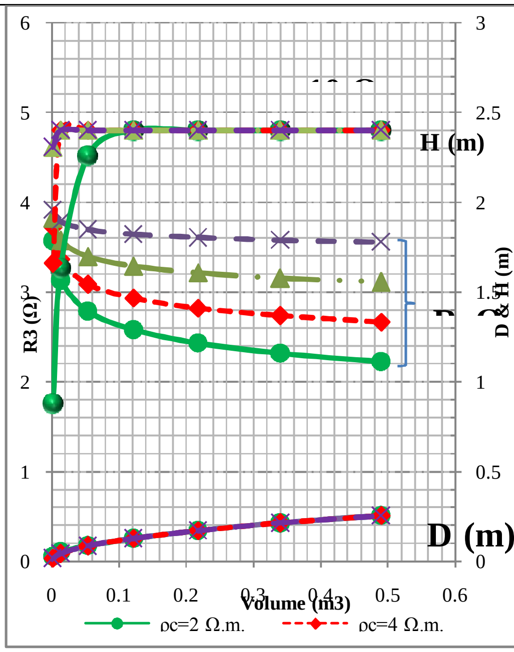

Fig. 7 Optimum values of R_3, H & D with Vol$_3$ (ρ=10 Ωm)

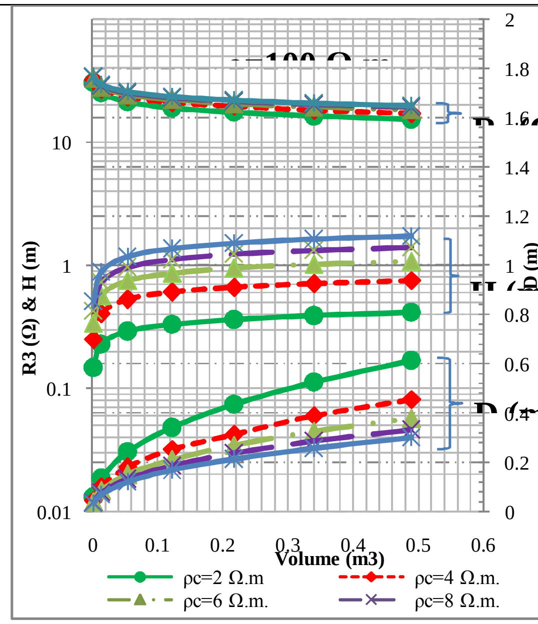

Fig. 8 Optimum values of R_3, H & D with Vol$_3$ (ρ=100 Ωm)

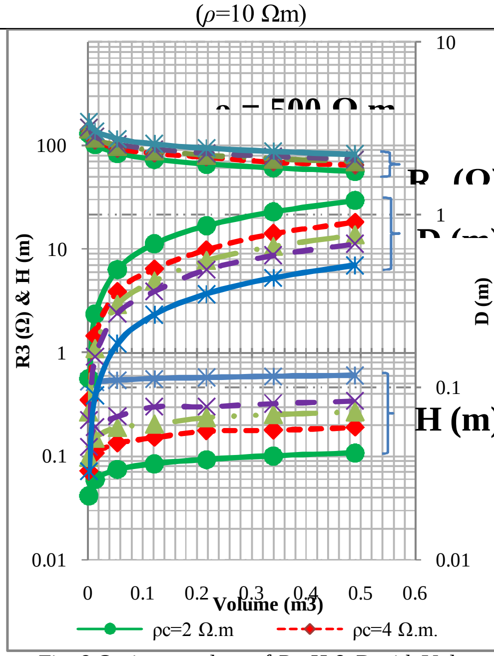

Fig. 9 Optimum values of R_3, H & D with Vol$_3$ (ρ=500 Ωm)

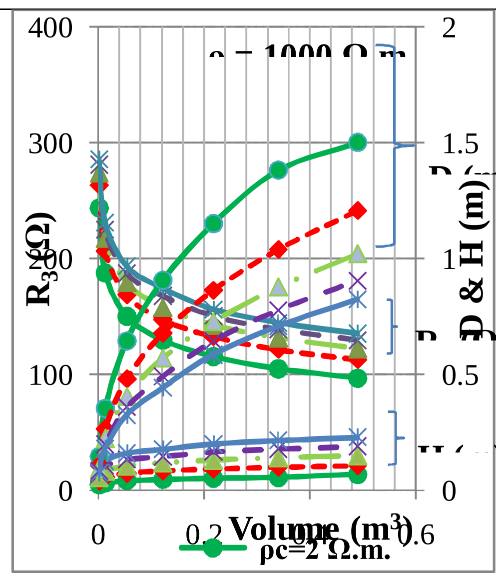

Fig. 10 Optimum values of R_3, H & D with Vol$_3$ (ρ=1000 Ωm)

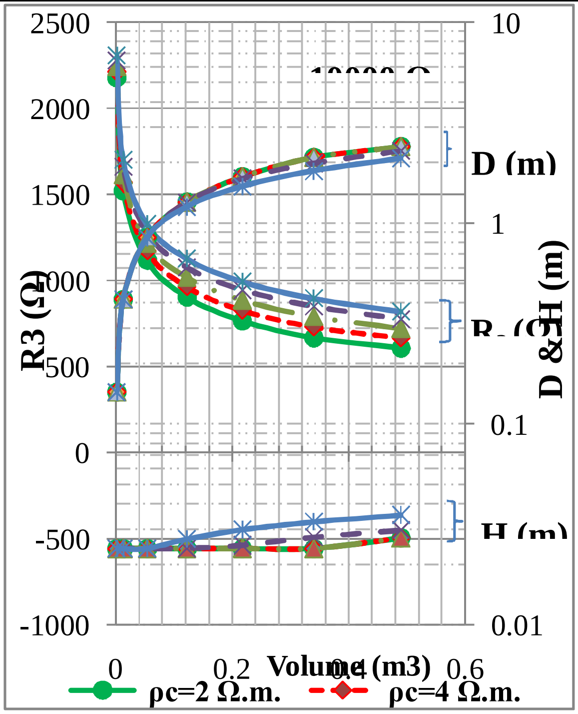

Fig. 11 Optimum values of R_3, H & D with Vol3 (ρ=10000 Ωm)

The optimum values of R_3 and pit dimensions at any value of ρ and ρ_c for a given volume of LRM is calculated as discussed next.

The optimum values of R_3, D and H for any value of $\rho_c$in the above mentioned rangecorresponding to a given ρ and volume can be determined using the following equation:

$$f(\rho_c) = f(\rho_{c0}) + \frac{f(\rho_{c1}) - f(\rho_{c0})}{\rho_{c1} - \rho_{c0}}(\rho_c - \rho_{c0}) \qquad \text{........(8)}$$

where $\rho_{c0}<\rho_c<\rho_{c1}$ and $f(\rho_{c0})$ and $f(\rho_{c1})$ are the optimum values of R_3 or pit dimensions at ρ_{c0} andρ_{c1}respectively. Similarly the optimum values at any value of ρ (10 -10000 Ω m) for a given value of $\rho_c$and volume can be estimated using eqn. (9).

$$f(\rho) = f(\rho_0) + \frac{f(\rho_1) - f(\rho_0)}{\rho_1 - \rho_0}(\rho - \rho_0) \qquad \text{........(9)}$$

where $\rho_0< \rho < \rho_1$ and $f(\rho_0)$ and $f(\rho_1)$ are the optimum values of R_3 or pit dimensions at ρ_0 and$\rho_1$respectively.

For example, the procedure is as followed in order to calculate the optimum values for R_3, *D&H* when ρ = 750 Ω m and ρ_c= 3 Ωm,.

The optimum values of R_3, *D&H* corresponding to ρ_{c0} = 2 Ω m and ρ_{c1} = 4 Ω m from the Fig. 7 (at ρ = 500 Ωm) and Fig. 8 (at ρ 1000 Ωm) were taken. Using eq.(8) above, R_3, *D&H* were calculated at ρ_c= 3 Ωm at ρ = 500 Ωm as well as 1000Ωm. Using the calculated values at ρ = 500 Ωm as well as 1000 Ωm from Table 2 the optimum values can be calculated at ρ = 750 Ωm as shown in Table 3.

TABLE 2.Optimum Values at ρ_c = 3 Ω m

Pit Volume (vol_3) = 0.22 m^3						
Ω m	Optimum Values at ρ = 500 Ω m			Optimum Values at ρ = 1000 Ω m		
	R_3 (Ω)	D (m)	H (m)	R_3 (Ω)	D (m)	H (m)
2	66.282	0.863	0.093	115.489	1.150	0.052
4	77.494	0.627	0.176	132.562	0.863	0.093
Calculated Optimum values using Eqn. (8) at ρ_c= 3 Ωm						
3	*71.888*	*0.745*	*0.135*	*124.056*	*1.007*	*0.073*

TABLE 3.Optimum Values at ρ= 750 Ωm and ρ_c = 3 Ω m

ρ_c= 3 Ωm and vol_3 = 0.22 m^3			
ρ (Ωm)	R_3 (Ω)	D (m)	H (m)
500	71.888	0.745	0.135
1000	124.056	1.007	0.073
Calculated Optimum values using Eqn. (9)			
750	*97.972*	*0.876*	*0.104*

TABLE 4.Variation in optimum pit dimensions and R_3 with ρ

Soil Resistivity ρ (Ωm)	Comparison of Values of Pit Dimensions (LRM Vol_3≈ 0.5 m^3)		Range of R_3 (Ω) **2 Ωm<ρ_c<8 Ωm**
	ρ_c= 2 Ωm	ρ_c= 8 Ωm	
10	H ≥ 215%D	H ≥ 215% D	2 to 4
100	H ≥ 20% D	H ≥105% D	15 to 20
500	D ≥ 110% H	D ≥ 33% H	56 to 83
1000	D ≥ 140% H	D ≥ 70% H	97 to 135
10000	D ≥235% H	D ≥ 225% H	608 to 820

The analysis of these figures clearly indicates that the surrounding soil resistivity ρ has significant impact on R_3 as well as pit dimensions. At lower values of ρ (Figure 7), the optimum value of H is more as compared to optimum value of D, while for high values of ρ (Figure10), the optimum H is less than that of D. The optimum values of H are almost 200% higher than that of D for ρ =11 Ωm whereas at ρ =1000 Ωm, the optimum values of D are almost 100% higher than that of H. Table 4 compares the variation in optimum pit dimensions (i.e. *D&H*) and range of optimum R_3 with *ρ*.

The optimum values of both R_3 and D are increased while the optimum H is reduced with the increase of values of LRM resistivity ρ_c. Moreover, for closer values of ρ and ρ_c (say ρ= 10 Ωm), the effect of ρ_c on optimum pit dimensions is negligible with increase in LRM volume as shown in Fig. 7. Also the values of H reach to its maximum permissible limit, i.e, the length of the grounding rod *L*=2.4 m. The figures 7-11 shows that the use of too high volume of LRM (large *H* for constant *D* and *L*) does not reduce the earthing resistance in a corresponding manner.

In order to test the analytical expressions (3) and (6), two augured holes, each of 0.1 m diameter and 2.5 m depth and an earth pit of 1 m×1 m and 1.2 m (deep) were prepared at King Saud University (KSU) campus. Average soil resistivity at this site was measured corresponding to a depth of 3.0 m using the four point method and was found to be about 40 Ω-m. Two copper earth rods, each of 2.4 m length and 17 mm diameter, were gently centered and placed inside these two holes as shown in Figure 12 whereas an earth electrode of *L*=1.2 m and diameter of 17 mm was placed vertically in the middle of the pit as shown in Figure 13. One of the hole (hole-1) was filled with sifted native soil while the second (hole-2) was filled with LRM of □$_c$=1 Ω-m.

Figure 12. Photograph of the augured hole

The earth resistance of each arrangement was measured using the fall of potential method on monthly basis for duration of one year to accommodate the impact of seasonal variations and effect of rainfall. Table 5, summarizes the calculated values of R_2 as function of different resistivities of the native soil when LRM with □$_c$=1 Ω-m is used. The calculated value of R_2 for □ =40 Ω-m in case of hole-1 is about 20 Ω, whereas, in case of hole-2, it corresponds to 9.64 Ω. The corresponding measured values in case of hole-1, were between 16-21 Ω. However, in case of hole-2, these were in the range of 7-8 Ω. These values are closer to but lower than the theoretical values. The difference can be attributed to the diffusion of wet LRM in the native soil surrounding the LRM rendering its effective diameter to be more than the drilled hole diameter. Moreover, LRM ingredients will be effective in acquiring and retaining the moisture from the surroundings during rainy spells which will tend to reduce the grounding resistance as well.

In case of earthing pit configuration LRM of $□_c$=1 Ω-m was filled up to height H=0.2 m. The rest of the pit was then refilled with the native soil. The measurement of its ground resistance (R_3) were carried out for a span of 12 months and was found to vary in a close range of 8-10 Ω. Table 6 exhibits the variations of R_3 as a function of native soil resistivity and also provides comparisons of calculated and measured values. It is gratifying to note that the measured values are close to calculated values. The small difference can be attributed to seasonal variations in the value of the resistivity of the native soil due to variations of moisture content, ambient temperature and the effect of LRM on surroundings as discussed earlier for method-A.

TABLE 5.Variation of R_2 as a function of soil resistivity with LRM in augured holes(rod length=2.4m, rod diameter=17mm, $□_c$=1 ω-m)

Native soil resistivity □□□Ωm)	***R*₂ in augured hole filled with native soil □Ω)**		***R*₂ in augured hole filled with LRM □Ω)**	
	Calculated	Measured	Calculated	Measured
20	8	-	*4.88*	-
40	20	16-21	9.64	7-8.5
100	40	-	23.76	-
200	80	-	47.36	-

Fig. 13Photograph of the earthing pit with grounding mesh

TABLE 6
Variation of R_3 as a function of soil resistivity with LRM filled in pit
(rod length=1.2m, rod diameter=17mm, d=0.5m, h=0.2 m,$□□_c$=1 ω-m)

Native soil resistivity □□□Ωm)	***R*₁ in native soil □Ω)**	***R*₃ in Pit filled with LRM □Ω)**	
	Calculated	Calculated	Measured
20	14.1	7.53	-
40	25.5	*11.77*	*8-10*
100	70.7	22.56	-
200	141.4	39.6	-

5. Conclusion

This paper presents different configurations of grounding pits commonly used with LRM applications. It also explains an easy way of computing the optimum dimensions of the grounding pit in high soil resistivity areas. The following are the main conclusions:

- In case of high soil resistivity, the earthing resistance decreases with the increase in LRM volume used.
- In the pit design, the use of too high volume of LRM (large H for constant D and L) does not reduce the earthing resistance in a corresponding manner.
- The optimum value of the grounding pit dimensions can be easily calculated for any surrounding soil resistivity by the proposed optimization method.

The suggested method can be readily used by engineers to obtain a good earthing pit configuration for efficient grounding of the power system components in high resistivity soils

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