Including Soil Drying Time in Cable Ampacity Calculations

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***Abstract* –Previous papers proposed a method to find the maximum possible dried area of soil expected due to heating by underground cables. A method was also proposed to include this dried soil area in cable ampacity calculations. This assumed cables would be loaded 100% of the time. To dry soil to the maximum possible extent may take very long time periods, and in many installations the cables actually carry current for a limited time. In these cases the soil may never dry to its maximum extent. This paper proposes a method to approximately determine the radius of dried soil that will occur due to cable heating for limited periods of time. It similarly proposes a method to approximate the time it will take for the dried soil to be replenished to its original moisture content after heating by the cables has ceased.**

***Index Terms*—Power Cables, Power Cable Thermal Factors, Thermoresistivity, Soil Thermal Stability, Underground Power Distribution, Underground Power Transmission, Soil,**

I. INTRODUCTION

Buried cables heat the surrounding soil, decreasing its moisture content, increasing the soil's thermal resistance. This gradual drying may eventually cause cable overheating. Previous papers have proposed a method for determining the maximum diameter of the dried soil area and described how this dried area may be included in Neher-McGrath cable ampacity calculations [1][2][3]. This method was based upon the worst-case assumption that the buried cables would provide a constant heat rate 100% of the time.

Many installations have a load factor that provides for cable heating far less than this worst-case condition. Many photovoltaic installations deliver power only six to eight hours a day, with very little output the remaining 16-18 hours. This type of heating pattern will allow the soil to dry for a few hours followed by a longer period of time where surrounding soil moisture can be replenished. Using the maximum possible diameter of dried soil is overly conservative, causing cables to be unnecessarily oversized, resulting in increased cost.

Soil will be subject to drying only during the time the cable is carrying current. A method is proposed to calculate the radius of soil that will dry during the time period the cable is heating the soil. This paper proposes an approximate method to determine the radius of dry soil that will occur during any arbitrary time period and heat rate. Once this dried soil radius is known, it can be used in cable ampacity calculations in lieu of the maximum possible dried radius. Since the radius of soil around a cable that will dry during a limited time will be less than the maximum possible radius, the result will be an increase in allowable cable ampacity compared to the worst possible case.

II. SOIL DRYING

Fig. 1 shows the model for soil drying around a cable. The dry soil will have a thermal resistivity of ρ_{dry} and the ambient soil thermal resistivity is ρ_{amb}. The maximum possible diameter dry soil, D, that will occur due to the heat produced by a cable, is given by Equation (1) [2].

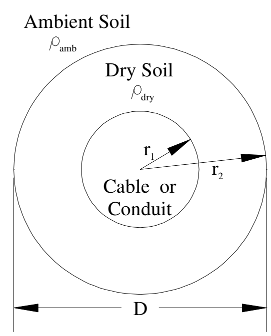

Fig. 1. Model of soil drying.

$$D = D_{probe}\left(\frac{q_{new}}{q_{NHR}}\right) \tag{1}$$

Where:
D=Maximum dried soil diameter (cm)
q_{NHR}=Non-drying heat rate measured at the site (W/cm)
q_{new}=Heat rate of the cable under consideration (W/cm)
D_{probe}=Diameter of the probe used to measure q_{NHR} (cm)

The non-drying heat rate, q_{NHR}, is the highest heat rate at which the soil will not begin to dry using a probe of diameter D_{probe}. At any higher heat rate drying will occur. This value is determined by field testing [1]. If the cable is loaded 100% of the time, the soil will eventually dry to the diameter calculated from Equation (1). If the cable is not loaded 100% of the time, the diameter of dried soil may be much less.

A cable loaded only a few hours a day will dry the soil for those hours. Once heating ceases, the moisture in the surrounding will replenish the dried area. If the soil can return to its original moisture content before the next heating cycle begins, the soil will never dry to its maximum possible diameter. If the soil moisture cannot be completely replenished during the time the cable is not heating, then the dried area will continue to expand until it reaches the maximum possible diameter D calculated in Equation (1).

If the dried moisture can be completely replenished during the time the cable is not heating, the maximum extent of dried soil will only reach the diameter that will dry during the time the cable is heating. An approximate method will be developed to determine the dried radius of soil, r_2 inFig. 1, that will occur at any given time, t.

When a cable produces heat, the heat is carried away to ambient earth in two main ways. The first is direct conduction through the soil. The second is by vaporizing water. This vapor leaves the vicinity of the cable carrying heat with it. There is also a small amount of heat absorbed by water flowing in to replace the vapor that is heated from ambient temperature to the temperature of the cable surface.

Using the results of field testing for soil resistivity and non-drying heat rate, the value of heat being lost due to conduction under steady-state conditions may be found. A heated cylinder is inserted into the ground as shown in Fig. 2 and the heat rate into the cylinder is set to the non-drying heat rate. The two temperatures T_1, the temperature of the surface of the heated probe, and the ambient soil temperature are measured. Assuming that T_2 is equal to the average soil ambient temperature and the earth is equivalent to a semi-infinite medium of constant resistivity, the heat conduction through the soil can be found using Equation (2) [1][4].

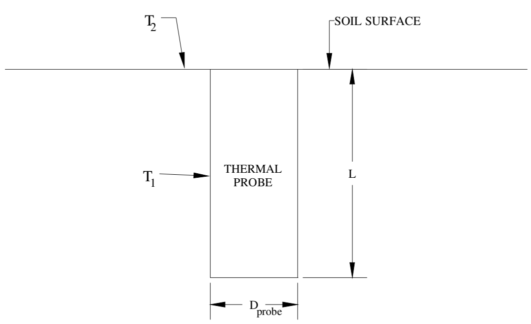

Fig. 2. Thermal probe test for non-drying heat rate.

$$q_{cNHR} = \frac{2\pi(T_1 - T_2)}{\rho \ln\left(\frac{4L}{D_{probe}}\right)} \quad (2)$$

Where:

q_{cNHR}=Conduction through the soil at the NHR (W/cm)

T_1= Surface temperature of the probe at the NHR measured during field testing (°C)

T_2= Ambient soil temperature (°C)

ρ = Soil thermal resistivity cm-°C/W

L=Length of probe below the earth's surface (cm)

D_{probe}=diameter of the probe (cm)

The heat rate produced by the cables, q_{new}, in most designs will often be greater than the non-drying heat rate q_{NHR}. Assuming that the heat conducted through the earth, q_{cnew}, at a new heat rate, q_{new}, will be proportional to the conduction q_{new} divided by q_{NHR}, the conduction at the new heat rate may be found using Equation (3).

$$q_{cnew} = \frac{q_{new}}{q_{NHR}} q_{cNHR} \quad (3)$$

Where:

q_{cnew}= Heat carried away by conduction (W/cm)

q_{new}=The heat rate of the heat source being considered (W/cm)

q_{NHR} =Non-drying heat rate (W/cm)

q_{cNHR}=Heat conducted away by conduction at the non-drying heat rate (W/cm)

As the radius of dried soil increases there will be some radius at which the heat rate of conduction to ambient earth will remain constant at the wet/dry soil interface, at the heat rate q_{cnew}. This implies that the temperature at the wet/dry soil interface will also stay constant at the temperature T_1. It is this radius that is calculated and considered to be the boundary of dried soil. Equation (2) implies that as the diameter of the cylinder of dried soil increases either the heat rate of conduction will slightly increase, or the wet/dry soil interface temperature, T_2, will slightly decrease. For a constant heat rate from the source this would mean the rate of heat carried away by soil moisture would decrease. As a result, making the assumption that the heat of conduction remains constant will overestimate the amount of drying that will occur, resulting in a conservative design.

Former experiments show that as the diameter of the heat source increases there is a slight increase in the time it takes to dry soil [5]. This implies that the rate of evaporation decreases as the source diameter increases. If the drying cylinder of soil surrounding the heated source is considered as one composite heat source slowly expanding in diameter, then experimentation also suggests that the time it takes to dry the soil would slowly increase as the diameter of dried soil increases. The proposed method, which assumes that the drying rate and heat of conduction will remain constant as the soil dries, should overestimate the time it takes to dry the soil.

When the heat rate of the source is increased to q_{new}, the heat rate of conduction increases to q_{cnew}. Equation (4) may be used to find the difference in temperature between ambient soil temperature and the temperature of the heated source when the rate of heat leaving the heat source by conduction is equal to q_{cnew}.

$$\Delta T_{cnew} = \frac{q_{cnew}\ \rho \ln\left(\frac{4L}{D_{probe}}\right)}{2\pi} \quad (4)$$

Where:

ΔT_{cnew}=Change in temperature between the heated source and ambient soil temperature, T_2, at the new heat conduction rate q_{cnew} (°C)

q_{cnew}=heat carried away by conduction from Equation (3) (W/cm)

ρ = Soil thermal resistivity cm-°C/W

L=Length of probe below the earth's surface (cm)

D_{probe}=diameter of the probe (cm)

III. Calculating Maximum Dried Soil Radius

Equation (5) will be used to calculate the maximum diameter of dried soil that will occur during any given length of time at the heat rate of interest.

$$(\text{Rate of water flow out of a volume of soil})(\text{Drying time}) - (\text{Rate of water flow into a volume of soil})(\text{Drying time}) = (\text{Water contiained in a volume of soil before drying}) \quad (5)$$

If this relationship is satisfied, the volume of soil in question will become dry during the drying time. The volume of soil in Equation (5) is the cross sectional area of an annulus of soil between radii r_1 and r_2 as shown in Fig. 1, one centimeter in depth, surrounding a heated cable or other cylindrical heat source.

Soil testing in the field typically measures the unit weight of the soil and the soil moisture content. If these two values are available, the mass of water within a volume of soil can be calculated using Equation (6) [1].

$$\gamma_w = \frac{\gamma\omega}{1+\omega} \quad (6)$$

Where:

γ_w = Unit weight of water per volume of soil (g/cm^3)

γ = Unit weight of soil (g/cm^3)

ω = water content in per unit (%/100)

Once γ_w is found, the mass of water contained within an volume of soil bounded by radius r_1 and r_2 as shown in Fig. 1, and one centimeter thick, may be found using Equation (7).

$$M = (\pi r_2^2 - \pi r_1^2)\gamma_w = \pi\gamma_w (r_2^2 - r_1^2) \quad (7)$$

Where:

M=Mass of water in a volume one cm thick bounded by r_1 and r_2 (g)

r_1 = Radius of from the center of the heat source to the beginning of the earth path (cm)

r_2= Radius from the center of the heat source to the outer boundary of the soil area (cm)

γ_w = Unit weight of water per volume of soil (g/cm^3)

The rate of water flow out of the area of soil surrounding the heated source may be found using Equation (8) [1].

$$M_{out} = \frac{q_{new} - q_{cnew}}{h_v + C_w \Delta T_{cnew}} \quad (8)$$

Where:

M_{out}= Rate of water flow out of the dried area one cm thick caused by the heat source (g/sec)

q_{new} =The heat rate of the heat source being considered (W/cm)

q_{cnew} = Heat carried away by conduction found using Equation (3) (W/cm)

h_v = Heat of vaporization of water (2,260 J/g)

C_w=Specific heat of water (4.18 J/g-°C)

ΔT_{cnew}= Change in temperature between the heated source and ambient soil temperature at the new heat conduction rate q_{cnew} found using Equation (4) (°C)

This equation applies when a state of equilibrium has occurred where the soil temperature is not increasing. This would be the condition obtaining when the soil had dried to its maximum extent and the water flow into the dried area of the soil would equal the vapor flow out of the dried area. For the transitional condition where the soil is drying, and continuing to increase in temperature, use of this equation ignores the heat absorbed by the soil particles. This will result in overestimating the amount of soil that will dry. For most cases, the error resulting will be small compared in the time periods considered in most loading cycles. For simplicity the heat absorbed by the soil particles is ignored in the suggested procedure, resulting in a conservative estimate for the area of dried soil.

The rate of water flow from the surrounding soil back in to the dried soil layer at the wet/dry interface may be found using Equation (9) [1].

$$M_{in} = \frac{q_{NHR} - q_{cNHR}}{D_{probe}(h_v + C_w \Delta T_{NHR})} D_2 = \frac{2(q_{NHR} - q_{cNHR})}{D_{probe}(h_v + C_w \Delta T_{NHR})} r \quad (9)$$

Where:

M_{in}=Rate of water flow into a dried area one cm thick (g/sec)

q_{NHR}=Non-drying heat rate from field measurements (W/cm)

q_{cNHR}= Heat carried away by conduction at the non-drying heat rate Equation (2) (W/cm)

D_{probe}=Diameter of the probe used in measuring the non-drying heat rate (cm)

h_v=Heat of vaporization of water (2,260 J/g)

C_w=Specific heat of water (4.18 J/g-°C)

ΔT_{NHR}=Change in temperature between the heated source and ambient soil temperature at the non-drying heat rate,

q_{NHR}, measured during field testing. T_1-T_2 in Equation (2) (°C)
D_2=Diameter of the dried area of soil (cm)
r= Radius from the center of the heat source to the wet/dry soil interface (cm)

For simplicity, part of Equation (9) is set equal to a constant, Z.

$$Z = \frac{2(q_{NHR} - q_{cNHR})}{D_{probe}(h_v + C_w \Delta T_{NHR})} \quad \text{g/sec-cm}^2 \tag{10}$$

So Equation (9) becomes Equation (11).

$$M_{in} = Z\,r \tag{11}$$

The average flow rate of water flowing into an area bounded by any two radii, r_1 and r_2, may be found using Equation (12).

$$M_{inavg} = \frac{1}{r_2 - r_1} Z \int_{r_1}^{r_2} r\,dr = \frac{Z(r_2 + r_1)}{2} \tag{12}$$

Where:
M_{inavg}=Average flow rate of water into a dried area 1 cm thick bounded by r_1 and r_2 (g/sec)

Equation (5) may now be written as Equation (13) using the pieces developed in Equations (7), (8), and (12).

$$M_{out}\,t - \frac{Z(r_2 + r_1)}{2} t = \pi \gamma_w \left(r_2^2 - r_1^2\right) \tag{13}$$

Where:
t=time (sec)
M_{out}=Rate of water flow out of the area of soil one cm thick (g/cm)
Z=Constant calculated in Equation (10) (g/sec-cm^2)
r_1=Radius of from the center of the heat source to the beginning of the earth path (cm)
r_2= Radius from the center of the heat source to the outer boundary of the soil area (cm)
γ_w = Unit weight of water per volume of soil (g/cm^3)

Solving this equation for r_2 as a function of time t results in Equation (14).

$$r_2^2 + \frac{Z\,t}{2\pi\gamma_w} r_2 - \frac{M_{out}\,t}{\pi\gamma_w} - r_1^2 + \frac{Z r_1\,t}{2\pi\gamma_w} = 0 \tag{14}$$

Equation (14) may then be solved for r_2, for any time, t, using the positive solution to the quadratic formula, Equation (15).

$$r_2 = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \tag{15}$$

$$A = 1$$

$$B = \frac{Z\,t}{2\pi\gamma_w}$$

$$C = -\frac{M_{out}}{\pi\gamma_w} - r_1^2 + \frac{Z r_1\,t}{2\pi\gamma_w}$$

The radius r_2 would then be the radius of soil that would dry during time t.

IV. Returning Soil Moisture to its Original Value

If a cable carries load less than 100% of the time, the soil moisture will have time to become replenished during the time the cable is not generating heat. If the soil moisture is brought back to its natural content before the next heating cycle begins then the dried soil diameter will never reach the maximum possible extent described by Equation (1) and will be limited to the radius calculated in Equation (14). This value could then be used for cable ampacity calculations.

Once an area of soil has dried, the average flow rate at which the water from the surrounding soil will flow back into the dry area bounded by radii r_1 and r_2 may be found using Equation (16).

$$M_{return} = \frac{Z(r_2 + r_1)}{2} \tag{16}$$

Where:
M_{return}=Rate water will return to the dried area of soil one cm thick (g/sec)
Z=Constant found in Equation (10)
r_1 = Radius of from the center of the heat source to the inner boundary of the dried soil (cm)
r_2= Radius from the center of the heat source to the outer boundary of the dried soil area (cm)

The mass of water necessary to replenish the dried area to its original moisture content can be found using Equation (7). The time in seconds, t_{return}, necessary to return the moisture content of the dried area of soil back to its natural value may be found using Equation (17).

$$\pi\gamma_w\left(r_2^2 - r_1^2\right) = \frac{Z(r_2 + r_1)}{2} t_{return}$$

$$t_{return} = \frac{2\pi\gamma_w(r_2 - r_1)}{Z} \tag{17}$$

V. EXAMPLE

To demonstrate how this method might be applied, consider the case where the following criteria have been measured in the field or determined by design restrictions.

- Cable loading cycle= 0.8 W/cm for 6 hours then 0.0 W/cm for 18 hours
- Direct buried cable diameter = 1 inch (2.54 cm)
- Soil density γ=100 lbs/ft^3 =1.602 g/cm^3
- Soil moisture Content ω=14%=0.14pu
- Non-drying heat rate q_{NHR}=0.15 W/cm
- Surface temperature of probe at NHR T_1=34°C
- Probe diameter D_{probe}=1.59 cm
- Length of probe L=120 cm
- Ambient soil temperature T_2=29°C
- Soil thermal Resistivity ρ=100 cm°C/W
- Dry soil thermal resistivity ρ_{dry}=300 cm°C/W
- Specific heat of soil particles C_s=0.8 J/g°C

Equation (1) is used to find the maximum possible diameter of dried soil at the new heat rate of 0.8 W/cm.

$$D = 1.59\left(\frac{0.8}{0.15}\right) = 8.48 \text{ cm}$$

If the load factor of the cable was 100%, then the soil would be expected to dry to a diameter of 8.48 cm. However, since the load cycle of the cable is only 6 hours, the amount of soil that will dry during that time period and then be replenished during the remaining 18 hours may be less than this maximum amount.

Using Equation (2), the heat of conduction at the non-drying heat rate is found.

$$q_{cNHR} = \frac{2\pi(34-29)}{100\ln\left(\frac{4(120)}{1.59}\right)} = 0.055 \text{ W/cm}$$

The expected heat of conduction at the new heat rate is found using Equation (3).

$$q_{cnew} = \frac{0.8}{0.15}0.055 = 0.2934 \text{ W/cm}$$

The difference in temperature between the heat source and the ambient soil at the new heat rate is found using Equation (4).

$$\Delta T_{cnew} = \frac{0.2934(100)\ln\left(\frac{4(120)}{1.59}\right)}{2\pi} = 26.67\,°\text{C}$$

The unit weight of water per volume of soil is found using Equation (6).

$$\gamma_w = \frac{(1.602)0.14}{1+0.14} = 0.1967 \text{ g/cm}^3$$

The rate of water flow out of the dried area is found using Equation (8).

$$M_{out} = \frac{0.8-0.2934}{2{,}260+(4.18)(26.67)} = 0.0002136 \text{ g/sec}$$

The constant, Z, is then found using Equation (10).

$$Z = \frac{2(0.15-0.055)}{1.59(2{,}260+4.18(34-29))} = 0.0000524 \text{ g/sec-cm}^2$$

All the values needed to solve Equation (14) are now available.

$$A = 1$$

$$B = \frac{0.0000524\,t}{2\pi(0.1967)} = 0.0000424\,t$$

$$C = -\frac{0.0002136}{\pi(0.1967)}t - \left(\frac{2.54}{2}\right)^2 + \frac{(0.0000524)\left(\frac{2.54}{2}\right)t}{2\pi(0.1967)} =$$

$$-0.000346t - 1.613 + 0.0000538t$$

The time the cable will be heating the soil is 6 hours, or 21,600 seconds. Substituting this value for t results in the following equation. The solution to this equation will be the radius, r_2, of soil that will dry in 6 hours.

$$A = 1$$

$$B = 0.0000424(21{,}600) = 0.915$$

$$C = -0.000346(21{,}600) - 1.613 + 0.0000538(21{,}600) = -7.92$$

$$r_2^2 + 0.915r_2 - 7.92 = 0$$

$$r_2 = 2.39 \text{ cm}$$

The results are shown in Fig. 3. In a 6 hour drying period at a heat rate of 0.8 W/cm it would be expected that a radius of 2.39 cm of soil would have dried. The result is that the 2.54 cm cable is surrounded by a layer of dried soil with a diameter of 4.78 cm. This area is then surrounded by natural soil of natural moisture content.

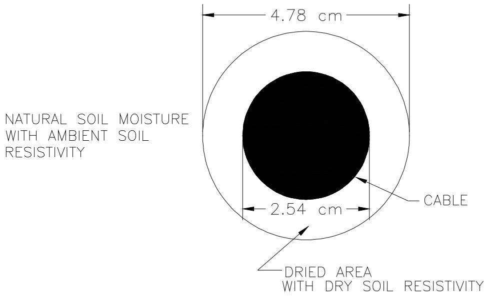

Fig. 3. Cable surrounded with dried soil.

It is also important to know if the dried area will be replenished back to its natural moisture content in the 18 hours during which the cable will not be producing heat. Equation (17) is used to find the time it will take to replenish the moisture.

$$t_{return} = \frac{2\pi(0.1967)\left(2.39 - \frac{2.54}{2}\right)}{0.0000524} = 26{,}416\,\text{sec} = 7.34\,\text{hours}$$

Since the moisture in the dried area can be replenished in less than 18 hours, the maximum extent of soil drying should be a dried soil diameter of 4.78 cm rather than the maximum possible extent of 8.48 cm as calculated using Equation (1). 4.78 cm will then be used in cable ampacity calculations for this cable. Using this smaller diameter of dried soil will result in a larger cable ampacity and will prevent overdesigning the cable size, thus avoiding unnecessary cost.

VI. Assumptions and Errors

To derive a method of calculating the time and extent of dried soil, that is simple enough to be used in everyday engineering problems, it is necessary to make simplifying assumptions. Each assumption may be a source of error, and the exact impact of these errors is difficult to assess.

Before heating begins, the heat source is surrounded by soil at ambient resistivity and ambient soil moisture. When the heat source is energized, it will take a period of time for its surface to temperature to increase to the point that the difference in temperature between the surface of the heat source and ambient soil temperature is ΔT_{cnew}. The time needed will depend upon the thermal time constant of the heat source, and this time period is ignored in this procedure.

It is assumed that all moisture movement out of the dried area is due to vapor movement. Some sources claim that some moisture movement out of the dried area occurs due to water movement [6]. Some water movement may occur during the time when the soil is still relatively wet; however, it is reported that as the soil dries, vapor movement becomes the most important component. The proposed method ignores any movement of heat out of the dried area due to water movement.

The procedure assumes that the amount of heat at the NHR can be calculated during a steady state condition, and the heat lost due to conduction at all other heat rates will be proportional to the heat lost due to conduction at the NHR. The magnitude of the error that will result from this assumption, if any, is unknown, and will require further experimentation to determine.

When the surface of the heat source increases to a temperature where its surface is equal to the soil ambient temperature plus ΔT_{cnew}, soil drying will begin. At this point a dry/ambient moisture boundary will progress out from the surface of the heat source and become progressively larger until the maximum extent is reached during the time of interest. It is assumed that the thermal resistance from the surface of this growing cylinder of dried soil, to ambient earth, will remain constant. The size of the cylinder of dried soil will be controlled by the rate that moisture can flow into the dried area from the surrounding soil, and the rate water will be evaporated and leave the dried area. As the cylinder grows larger, the amount of moisture that can return to the dried area increases.

The temperature at the dry/wet soil interface of the dried cylinder of soil is assumed to be the ambient temperature plus ΔT_{cnew}, and the radius of dried soil will be measured to the point where this temperature occurs. While a sudden transition of moisture content and temperature at the wet/dry interface is assumed, it is likely that there will be a gradual transition of both in the wet soil.

Some error will result from ignoring the heat absorbed by the soil particles as the soil heats up from ambient conditions. This error can be estimated.

In the example, after a 6 hour period the radius of dried soil progressed to a distance of 2.39 cm from the center of the source. The temperature at this radius would be 55.67°C (ambient temperature, 29°C, plus ΔT_{cnew}, 26.67°C). The soil between this boundary layer and the surface of the heat source would have a resistivity equal to the dry soil thermal resistivity, ρ_{dry}=300 cm°C/W.

Solving the exponential differential equations for transient heat flow through a semi-infinite medium shows that it would take approximately 12 minutes for the 0.8 W/cm heat source to raise the temperature of a point 2.39 cm from the center of the heat source—in a semi-infinite medium with resistivity=300 cm°C/W—by 26.67°C [7]. So in the six hour time period in the example, the temperature of the boundary layer would be controlled by moisture flow rather than by the time needed for heat conduction. A quasi-steady state, from the point of view of heat conduction, has developed. Since the dried layer contains no moisture, all the heat flow through it must be due to conduction. Using the steady state equations for conduction, the temperature of the surface of a heat source of radius 1.27 cm can be determined assuming the soil temperature at a radius of 2.39 cm is being held constant. Using Equation (18) the temperature of the surface of the heat source was found to be 79.82°C.

$$T_1 = \frac{\rho_{dry} q_{new}(\ln r_2 - \ln r_1)}{2\pi} + T_2 \tag{18}$$

$$T_1 = \frac{(300)(0.8)(\ln 2.39 - \ln 1.27)}{2\pi} + 55.67 = 79.82°C$$

Using Equation (19) the temperature at any point a distance r from the center of the heat source (assuming $r>r_1$) may be found.

$$T_2 = -\left(\frac{\rho_{dry} q_{new} (\ln r - \ln r_1)}{2\pi} - T_1 \right) \quad (19)$$

Fig. 4 shows a plot of the solution to Equation (19) from the surface of the heat source to a radius of 2.39 cm from the center of the heat source.

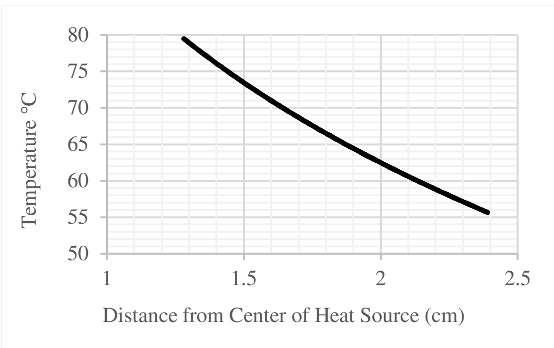

Fig. 4. Temperature from heat source surface to extent of dried area.

Assuming the specific heat of the soil particles is 0.8 J/g°C and a soil particle density of 1.405 g/cm^3 (total soil g/cm^3 minus water g/cm^3), a 1 cm depth of soil around the source, heated to the heat gradient shown in Fig. 4, would absorb approximately 523 Joules. At a heat rate of 0.8 W/cm it would take slightly over 10 minutes to generate 523 J. Ten minutes in a 6 hour cycle is less than 10%. Furthermore, since 10 minutes of the heat produced by the heat source during the 6 hour heating cycle would be absorbed by the soil particles rather than by the vapor leaving the dried area and the water flowing back into the dried area, the radius of dried soil would be slightly less than the 2.39 cm calculated using this method. The error due to ignoring the heat absorbed by the soil will always be conservative and result in a larger estimation for dried area than should actually occur.

VII. Conclusions

While using the maximum possible extent of dried soils in Neher-McGrath cable ampacity calculations will result in cables that should not overheat in the presence of soil thermal instability, it is unlikely that the soil will ever dry to this extent in many installations. The soil will dry to the maximum extent only if the time the cable is energized and drying the soil is greater than the time it takes for moisture from surrounding soil to replenish the dried soil during the time the cable is not energized. This is a common condition on many projects such as solar and other renewable energy installations with low capacity factors.

A method was proposed to determine the extent of soil drying when a cable is loaded less than 100% of the time. The diameter of dried soil determined using this method may then be used in cable ampacity calculations to account for the effects of thermal instability of the soil due to drying effects.

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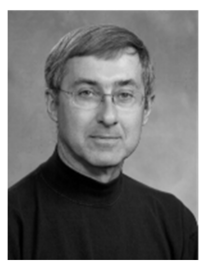
VIII. Vita



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Including Soil Drying Time in Cable Ampacity Calculations

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***Abstract* –Previous papers proposed a method to find the maximum possible dried area of soil expected due to heating by underground cables. A method was also proposed to include this dried soil area in cable ampacity calculations. This assumed cables would be loaded 100% of the time. To dry soil to the maximum possible extent may take very long time periods, and in many installations the cables actually carry current for a limited time. In these cases the soil may never dry to its maximum extent. This paper proposes a method to approximately determine the radius of dried soil that will occur due to cable heating for limited periods of time. It similarly proposes a method to approximate the time it will take for the dried soil to be replenished to its original moisture content after heating by the cables has ceased.**

***Index Terms*—Power Cables, Power Cable Thermal Factors, Thermoresistivity, Soil Thermal Stability, Underground Power Distribution, Underground Power Transmission, Soil,**

I. Definition of Variables

ΔT_{cnew} = Change in temperature between the heated source and ambient soil temperature at the new heat conduction rate q_{cnew} found using Equation (4) (°C)

ΔT_{NHR} = Change in temperature between the heated source and ambient soil temperature at the non-drying heat rate, q_{NHR}, measured during field testing. T_1-T_2 in Equation (2) (°C)

γ = Unit weight of soil (g/cm^3)

γ_w = Unit weight of water per volume of soil (g/cm^3)

ρ = Soil thermal resistivity cm-°C/W

ω = water content in per unit (%/100)

C_w = Specific heat of water (4.18 J/g-°C)

D = Maximum dried soil diameter (cm)

D_2 = Diameter of the dried area of soil (cm)

D_{probe} = Diameter of the probe used in measuring the non-drying heat rate (cm)

h_v = Heat of vaporization of water (2,260 J/g)

L = Length of probe below the earth's surface (cm)

M = Mass of water in a volume one cm thick bounded by r_1 and r_2 (g)

M_{in} = Rate of water flow into a dried area one cm thick (g/sec)

M_{inavg}= Average flow rate of water into a dried area 1 cm thick bounded by r_1 and r_2 (g/sec)

M_{out} = Rate of water flow out of the dried area one cm thick caused by the heat source (g/sec)

M_{return} =Rate water will return to the dried area of soil one cm thick (g/sec)

q_{new} = Heat rate of the cable under consideration (W/cm)

q_{cnew} = Heat carried away by conduction found using Equation (3) (W/cm)

q_{NHR} = Non-drying heat rate from field measurements (W/cm)

q_{cNHR} = Heat carried away by conduction at the non-drying heat rate Equation (2) (W/cm)

r = Radius from the center of the heat source to the wet/dry soil interface (cm)

r_1 = Radius of from the center of the heat source to the inner boundary of the dried soil (cm)

r_2 = Radius from the center of the heat source to the outer boundary of the dried soil area (cm)

t = time (sec)

T_1 = Surface temperature of the probe at the NHR measured during field testing (°C)

T_2 = Ambient soil temperature (°C)

Z = Constant found in Equation (10)

II. Introduction

Buried cables heat the surrounding soil, decreasing the soil's moisture content and increasing the soil's thermal resistance. This gradual drying may eventually cause cable overheating. Previous papers have proposed a method for determining the maximum diameter of the dried soil area and described how this dried area may be included in Neher-McGrath cable ampacity calculations [1][2]. This method was based upon the worst-case assumption that the buried cables would provide a constant heat rate 100% of the time.

Many installations have a load factor that causes cable heating far less than this worst-case condition. Many photovoltaic installations deliver power only six to eight hours a day, with very little output the remaining 16-18 hours. This heating pattern dries the soil for a few hours but allows moisture from surrounding soil to replenish the dry soil over a longer period of time. Using the maximum possible diameter of dried soil is overly conservative, causing cables to be unnecessarily oversized, resulting in increased cost.

Soil will be subject to drying only during the time the cable is carrying current. A method is proposed to calculate the radius of soil that will dry based on the heating duration. This paper proposes an approximate method to determine the radius of dry soil that will occur during any arbitrary time period and heat rate. Once this dried soil radius is known, it can be used in cable ampacity calculations in lieu of the maximum possible dried radius. Since the radius of soil around a cable that will dry during a limited time will be less than the maximum possible radius, the result will be an increase in allowable cable ampacity compared to the worst possible case.

III. Soil Drying

Fig. 1 shows the model for soil drying around a cable. The dry soil will have a thermal resistivity of ρ_{dry} and the ambient soil thermal resistivity is ρ_{amb}. The maximum possible diameter dry soil, D, that will occur due to the heat produced by a cable, is given by Equation (1) [1].

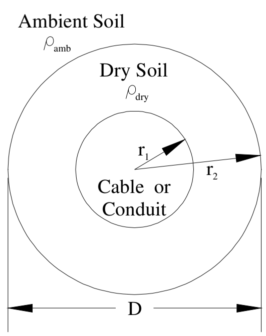

Fig. 1. Model of soil drying.

$$D = D_{probe}\left(\frac{q_{new}}{q_{NHR}}\right) \quad (1)$$

The non-drying heat rate, q_{NHR}, is the highest heat rate at which the soil will not begin to dry using a probe of diameter D_{probe}. At any higher heat rate drying will occur. This value is determined by field testing [1]. If the cable is loaded 100% of the time, the soil will eventually dry to the diameter calculated from Equation (1). If the cable is not loaded 100% of the time, the diameter of dried soil may be much less.

A cable loaded for only a few hours a day will dry the soil during those hours. Once heating ceases, the moisture in the surrounding will replenish the dried area. If the soil can return to its original moisture content before the next heating cycle begins, then the soil will never dry to its maximum possible diameter. If the soil moisture cannot be completely replenished during the time the cable is not heating, then the dried area will continue to expand until it reaches the maximum possible diameter D calculated in Equation (1). If the dried moisture can be completely replenished during the time the cable is not heating, the maximum extent of dried soil will only reach the diameter that will dry during the time the cable is heating.

When a cable produces heat, the heat is carried away to ambient earth in two main ways. The first is direct conduction through the soil. The second is by vaporizing water. This vapor leaves the vicinity of the cable carrying heat with it. There is also a small amount of heat absorbed by water flowing in to replace the vapor that is heated from ambient temperature to the temperature of the cable surface.

Using the results of field testing for soil resistivity and non-drying heat rate, the value of heat being lost due to conduction under steady-state conditions may be found. A heated cylinder is inserted into the ground as shown in Fig. 2 and the heat rate into the cylinder is set to the non-drying heat rate. The two temperatures T_1, the temperature of the surface of the heated probe, and the ambient soil temperature are measured. Assuming that T_2 is equal to the average soil ambient temperature and the earth is equivalent to a semi-infinite medium of constant resistivity, the heat conduction through the soil can be found using Equation (2) [1][3].

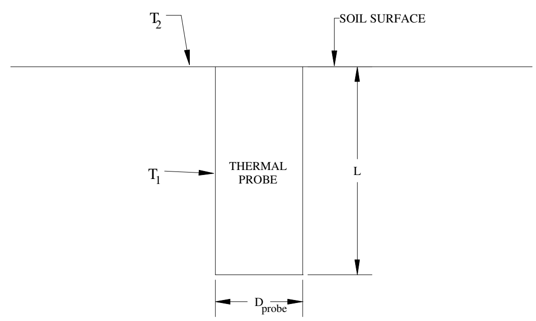

Fig. 2. Thermal probe test for non-drying heat rate.

$$q_{cNHR} = \frac{2\pi\left(T_1 - T_2\right)}{\rho \, \ln\left(\frac{4L}{D_{probe}}\right)} \quad (2)$$

The heat rate produced by the cables, q_{new}, may be greater than the non-drying heat rate q_{NHR}. Assuming that the heat conducted through the earth, q_{cnew}, at a new heat rate, q_{new}, will be proportional to the conduction q_{new} divided by q_{NHR}, the conduction at the new heat rate may be found using Equation (3).

$$q_{cnew} = \frac{q_{new}}{q_{NHR}} q_{cNHR} \quad (3)$$

As the radius of dried soil increases, there will be some radius at which the heat rate of conduction to ambient earth will remain constant. This radius is termed the wet/dry soil interface and represents a dry soil annulus from the cable jacket to this radius and ambient soil beyond that point. It occurs for a given cable heat rate, q_{cnew}. This implies that the temperature at the wet/dry soil interface will also stay constant at the temperature T_1. It is this radius that is calculated and considered to be the boundary of dried soil. Equation (2) implies that as the diameter of the cylinder of dried soil increases, either the heat rate of conduction will slightly increase, or the wet/dry soil interface temperature, T_2, will slightly decrease. For a constant heat rate from the source this would mean the rate of heat carried away by soil moisture would decrease. As a result, making the assumption that the heat of conduction remains constant will overestimate the amount of drying that will occur, resulting in a conservative design.

Former experiments show that as the diameter of the heat source increases there is a slight increase in the time it takes to dry soil [4]. This implies that the rate of evaporation decreases as the source diameter increases. If the drying cylinder of soil surrounding the heated source is considered as one composite heat source slowly expanding in diameter, then experimentation also suggests that the time it takes to dry the soil would slowly increase as the diameter of dried soil increases. The proposed method, which assumes that the drying rate and heat of conduction will remain constant as the soil dries, should overestimate the time it takes to dry the soil.

When the heat rate of the source is increased to q_{new}, the heat rate of conduction increases to q_{cnew}. Equation (4) may be used to find the difference in temperature between ambient soil temperature and the temperature of the heated source when the rate of heat leaving the heat source by conduction is equal to q_{cnew}.

$$\Delta T_{cnew} = \frac{q_{cnew}\,\rho \ln\left(\frac{4L}{D_{probe}}\right)}{2\pi} \qquad (4)$$

IV. Calculating Maximum Dried Soil Radius

Equation (5) will be used to calculate the maximum diameter of dried soil that will occur during any given length of time at the heat rate of interest.

$$\begin{aligned}&(\text{Rate of water flow out of a volume of soil})(\text{Drying time}) - \\ &(\text{Rate of water flow into a volume of soil})(\text{Drying time}) = \\ &(\text{Water contiained in a volume of soil before drying})\end{aligned} \qquad (5)$$

If this relationship is satisfied, the volume of soil in question will become dry during the drying time. The volume of soil in Equation (5) is the cross sectional area of an annulus of soil between radii r_1 and r_2 as shown in Fig. 1, one centimeter in depth, surrounding a heated cable or other cylindrical heat source.

Soil testing in the field typically measures the unit weight of the soil and the soil moisture content. If these two values are available, the mass of water within a volume of soil can be calculated using Equation (6) [1].

$$\gamma_w = \frac{\gamma\omega}{1+\omega} \qquad (6)$$

Once γ_w is found, the mass of water contained within a volume of soil bounded by radii r_1 and r_2 as shown in Fig. 1, and one centimeter thick, may be found using Equation (7).

$$M = \left(\pi r_2^2 - \pi r_1^2\right)\gamma_w = \pi\gamma_w\left(r_2^2 - r_1^2\right) \qquad (7)$$

The rate of water flow out of the area of soil surrounding the heated source may be found using Equation (8) [1].

$$M_{out} = \frac{q_{new} - q_{cnew}}{h_v + C_w \Delta T_{cnew}} \qquad (8)$$

This equation applies when a state of equilibrium has occurred where the soil temperature is not increasing. This would be the condition when the soil has dried to its maximum extent and the water flow into the dried area of the soil equals the vapor flow out of the dried area. For the transitional condition where the soil is drying and continuing to increase in temperature, use of this equation ignores the heat absorbed by the soil particles. This will result in overestimating the amount of soil that will dry. For most cases, the error resulting will be small compared in the time periods considered in most loading cycles. For simplicity the heat absorbed by the soil particles is ignored in the suggested procedure, resulting in a conservative estimate for the area of dried soil.

The rate of water flow from the surrounding soil back in to the dried soil layer at the wet/dry interface may be found using Equation (9) [1].

$$M_{in} = \frac{q_{NHR} - q_{cNHR}}{D_{probe}\left(h_v + C_w \Delta T_{NHR}\right)} D_2 = \frac{2\left(q_{NHR} - q_{cNHR}\right)}{D_{probe}\left(h_v + C_w \Delta T_{NHR}\right)} r \qquad (9)$$

For simplicity, part of Equation (9) is set equal to a constant, Z.

$$Z = \frac{2\left(q_{NHR} - q_{cNHR}\right)}{D_{probe}\left(h_v + C_w \Delta T_{NHR}\right)} \quad \text{g/sec-cm}^2 \qquad (10)$$

So Equation (9) becomes Equation (11).

$$M_{in} = Z\,r \qquad (11)$$

The average flow rate of water flowing into an area bounded by any two radii, r_1 and r_2, may be found using Equation (12).

$$M_{inavg} = \frac{1}{r_2 - r_1} Z \int_{r_1}^{r_2} r\,dr = \frac{Z\left(r_2 + r_1\right)}{2} \qquad (12)$$

Equation (5) may now be written as Equation (13) using the pieces developed in Equations (7), (8), and (12).

$$M_{out}\,t - \frac{Z(r_2 + r_1)}{2}t = \pi\gamma_w\left(r_2^2 - r_1^2\right) \quad (13)$$

Solving this equation for r_2 as a function of time t results in Equation (14).

$$r_2^2 + \frac{Z\,t}{2\pi\gamma_w}r_2 - \frac{M_{out}\,t}{\pi\gamma_w} - r_1^2 + \frac{Zr_1\,t}{2\pi\gamma_w} = 0 \quad (14)$$

Equation (14) may then be solved for r_2, for any time, t, using the positive solution to the quadratic formula, Equation (15).

$$r_2 = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \quad (15)$$

$$A = 1$$

$$B = \frac{Z\,t}{2\pi\gamma_w}$$

$$C = -\frac{M_{out}\,t}{\pi\gamma_w} - r_1^2 + \frac{Zr_1\,t}{2\pi\gamma_w}$$

The radius r_2 would then be the radius of soil that would dry during time t.

V. Returning Soil Moisture to its Original Value

If a cable carries load less than 100% of the time, the soil moisture will have time to become replenished during the time the cable is not generating heat. If the soil moisture is brought back to its natural content before the next heating cycle begins then the dried soil diameter will never reach the maximum possible extent described by Equation (1) and will be limited to the radius calculated in Equation (14). This value could then be used for cable ampacity calculations.

Once an area of soil has dried, the average flow rate of water from the surrounding soil that will flow back into the dry area bounded by radii r_1 and r_2 may be found using Equation (16).

$$M_{return} = \frac{Z(r_2 + r_1)}{2} \quad (16)$$

The mass of water necessary to replenish the dried area to its original moisture content can be found using Equation (7). The time in seconds, t_{return}, necessary to return the moisture content of the dried area of soil back to its natural value may be found using Equation (17).

$$\pi\gamma_w\left(r_2^2 - r_1^2\right) = \frac{Z(r_2 + r_1)}{2}t_{return}$$

$$t_{return} = \frac{2\pi\gamma_w(r_2 - r_1)}{Z} \quad (17)$$

VI. Example

To demonstrate how this method might be applied, consider the case where the following criteria have been measured in the field or determined by design restrictions.

- Cable loading cycle = 0.8 W/cm for 6 hours then 0.0 W/cm for 18 hours
- Direct buried cable diameter = 1 inch (2.54 cm)
- Soil density γ=100 lbs/ft^3=1.602 g/cm^3
- Soil moisture content ω=14%=0.14pu
- Non-drying heat rate q_{NHR}=0.15 W/cm
- Surface temperature of probe at NHR T_1=34°C
- Probe diameter D_{probe}=1.59 cm
- Length of probe L=120 cm
- Ambient soil temperature T_2=29°C
- Soil thermal resistivity ρ=100 cm°C/W
- Dry soil thermal resistivity ρ_{dry}=300 cm°C/W
- Specific heat of soil particles C_s=0.8 J/g°C

Equation (1) is used to find the maximum possible diameter of dried soil at the new heat rate of 0.8 W/cm.

$$D = 1.59\left(\frac{0.8}{0.15}\right) = 8.48 \text{ cm}$$

If the load factor of the cable was 100%, then the soil would be expected to dry to a diameter of 8.48 cm. However, since the load cycle of the cable is only 6 hours, the diameter of dry soil during those 6 hours will be less than this maximum amount.

Using Equation (2), the heat of conduction at the non-drying heat rate is found.

$$q_{cNHR} = \frac{2\pi(34 - 29)}{100\ln\left(\frac{4(120)}{1.59}\right)} = 0.055 \text{ W/cm}$$

The expected heat of conduction at the new heat rate is found using Equation (3).

$$q_{cnew} = \frac{0.8}{0.15}0.055 = 0.2934 \text{ W/cm}$$

The difference in temperature between the heat source and the ambient soil at the new heat rate is found using Equation (4).

$$\Delta T_{cnew} = \frac{0.2934(100)\ln\left(\frac{4(120)}{1.59}\right)}{2\pi} = 26.67\,°C$$

The unit weight of water per volume of soil is found using Equation (6).

$$\gamma_w = \frac{(1.602)0.14}{1+0.14} = 0.1967\ \text{g/cm}^3$$

The rate of water flow out of the dried area is found using Equation (8).

$$M_{out} = \frac{0.8-0.2934}{2{,}260+(4.18)(26.67)} = 0.0002136\ \text{g/sec}$$

The constant, Z, is then found using Equation (10).

$$Z = \frac{2(0.15-0.055)}{1.59(2{,}260+4.18(34-29))} = 0.0000524\ \text{g/sec-cm}^2$$

All the values needed to solve Equation (14) are now available.

$$A = 1$$

$$B = \frac{0.0000524\ t}{2\pi(0.1967)} = 0.0000424\,t$$

$$C = -\frac{0.0002136}{\pi(0.1967)}t - \left(\frac{2.54}{2}\right)^2 + \frac{(0.0000524)\left(\frac{2.54}{2}\right)t}{2\pi(0.1967)} =$$

$$-0.000346t - 1.613 + 0.0000538t$$

The time the cable will heat the soil is 6 hours, or 21,600 seconds. Substituting this value for t results in the following equation. The solution to this equation will be the radius, r_2, of soil that will dry in 6 hours.

$$A = 1$$

$$B = 0.0000424(21{,}600) = 0.915$$

$$C = -0.000346(21{,}600) - 1.613 + 0.0000538(21{,}600) = -7.92$$

$$r_2^2 + 0.915r_2 - 7.92 = 0$$

$$r_2 = 2.39\ \text{cm}$$

The results are shown in Fig. 3. In a 6 hour drying period at a heat rate of 0.8 W/cm it would be expected that a radius of 2.39 cm of soil would have dried. The result is that the 2.54 cm cable is surrounded by a layer of dried soil with a diameter of 4.78 cm. This area is then surrounded by natural soil of natural moisture content.

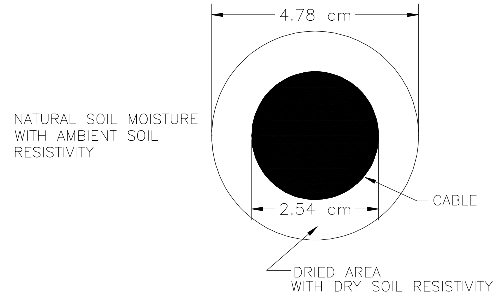

Fig. 3. Cable surrounded with dried soil.

It is also important to know if the dried area will be replenished back to its natural moisture content in the 18 hours during which the cable will not be producing heat. Equation (17) is used to find the time it will take to replenish the moisture.

$$t_{return} = \frac{2\pi(0.1967)\left(2.39-\frac{2.54}{2}\right)}{0.0000524} = 26{,}416\,\text{sec} = 7.34\,\text{hours}$$

Since the moisture in the dried area can be replenished in less than 18 hours, the maximum extent of soil drying should be a dried soil diameter of 4.78 cm rather than the maximum possible extent of 8.48 cm as calculated using Equation (1). 4.78 cm will then be used in cable ampacity calculations for this cable. Using this smaller diameter of dried soil will result in a larger cable ampacity and will prevent overdesigning the cable size, thus avoiding unnecessary cost.

VII. Assumptions and Errors

To derive a method of calculating the time and extent of dried soil, that is simple enough to be used in everyday engineering problems, it is necessary to make simplifying assumptions. Each assumption may be a source of error, and the exact impact of these errors is difficult to assess.

Before heating begins, the heat source is surrounded by soil at ambient resistivity and ambient soil moisture. When the heat source is energized, it will take a period of time for its surface temperature to increase to the point that the difference in temperature between the surface of the heat source and ambient soil temperature is ΔT_{cnew}. The time needed will depend upon the thermal time constant of the heat source, and this time period is ignored in this procedure.

It is assumed that all moisture movement out of the dried area is due to vapor movement. Some sources claim that some moisture movement out of the dried area occurs due to liquid water movement [5]. Some liquid water movement may occur during the time when the soil is still relatively wet; however, it is reported that as the soil dries, vapor movement becomes the most important component. The proposed method ignores any movement of heat out of the dried area due to liquid water movement.

The procedure assumes that the amount of heat at the NHR can be calculated during a steady state condition, and the heat lost due to conduction at all other heat rates will be proportional to the heat lost due to conduction at the NHR. The magnitude of the error that will result from this assumption, if any, is unknown and will require further experimentation to determine.

When the surface of the heat source increases to a temperature where its surface is equal to the soil ambient temperature plus ΔT_{cnew}, soil drying will begin. At this point a dry/ambient moisture boundary will progress out from the surface of the heat source and become progressively larger until the maximum extent is reached during the time of interest. It is assumed that the thermal resistance from the surface of this growing cylinder of dried soil to ambient earth will remain constant. The size of the cylinder of dried soil will be controlled by the rate that moisture can flow into the dried area from the surrounding soil and the rate water will evaporate away from the dried area. As the cylinder grows larger, the amount of moisture that can return to the dried area increases.

The temperature at the dry/wet soil interface of the dried cylinder of soil is assumed to be the ambient temperature plus ΔT_{cnew}, and the radius of dried soil will be measured to the point where this temperature occurs. While a sudden transition of moisture content and temperature at the wet/dry interface is assumed, it is likely that there will be a gradual transition of both in the wet soil.

Some error will result from ignoring the heat absorbed by the soil particles as the soil heats up from ambient conditions. This error can be estimated.

In the example, after a six hour period the radius of dried soil progressed to a distance of 2.39 cm from the center of the source. The temperature at this radius would be 55.67°C (ambient temperature, 29°C, plus ΔT_{cnew}, 26.67°C). The soil between this boundary layer and the surface of the heat source would have a resistivity equal to the dry soil thermal resistivity, ρ_{dry}=300 cm°C/W.

Solving the exponential differential equations for transient heat flow through a semi-infinite medium shows that it would take approximately 12 minutes for the 0.8 W/cm heat source to raise the temperature of a point 2.39 cm from the center of the heat source—in a semi-infinite medium with resistivity=300 cm°C/W—by 26.67°C [6]. So in the 6-hour time period, the temperature of the boundary layer would be controlled by moisture flow rather than by the time needed for heat conduction. A quasi-steady state, from the point of view of heat conduction, has developed. Since the dried layer contains no moisture, all the heat flow through it must be due to conduction. Using the steady state equations for conduction, the temperature of the surface of a heat source of radius 1.27 cm can be determined assuming the soil temperature at a radius of 2.39 cm is being held constant. Using Equation (18), the temperature of the surface of the heat source was found to be 79.82°C.

$$T_1 = \frac{\rho_{dry} q_{new} (\ln r_2 - \ln r_1)}{2\pi} + T_2 \qquad (18)$$

$$T_1 = \frac{(300)(0.8)(\ln 2.39 - \ln 1.27)}{2\pi} + 55.67 = 79.82°C$$

Using Equation (19), the temperature at any point a distance r from the center of the heat source (assuming $r>r_1$) may be found.

$$T_2 = -\left(\frac{\rho_{dry} q_{new} (\ln r - \ln r_1)}{2\pi} - T_1 \right) \qquad (19)$$

Fig. 4 shows a plot of the solution to Equation (19) from the surface of the heat source to a radius of 2.39 cm from the center of the heat source.

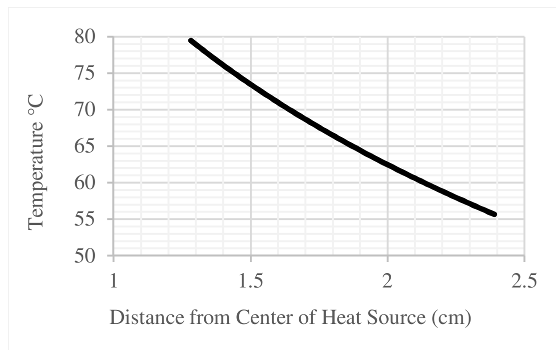

Fig. 4. Temperature from heat source surface to extent of dried area.

Assuming the specific heat of the soil particles is 0.8 J/g°C and a soil particle density of 1.405 g/cm^3 (total soil g/cm^3 minus water g/cm^3), a 1 cm depth of soil around the source, heated to the heat gradient shown in Fig. 4, would absorb approximately 523 Joules. At a heat rate of 0.8 W/cm, it would take slightly over 10 minutes to generate 523 J. Ten minutes in a 6-hour cycle is less than 10%. Furthermore, since 10 minutes of the heat produced by the heat source during the 6-hour heating cycle would be absorbed by the soil particles rather than by the vapor leaving the dried area and the water flowing back into the dried area, the radius of dried soil would be slightly less than the 2.39 cm calculated using this method. The error due to ignoring the heat absorbed by the soil will always be conservative and result in a larger estimation for dried area than should actually occur.

VIII. Conclusions

While using the maximum possible extent of dried soils in Neher-McGrath cable ampacity calculations will result in cables that should not overheat in the presence of soil thermal instability, it is unlikely that the soil will ever dry to this extent in many installations. The soil will dry to the maximum extent only if the time the cable is loaded is greater than the time it takes for moisture from surrounding soil to replenish the dried soil during the time the cable is not loaded. This is a common condition on many projects such as solar and other renewable energy installations with low capacity factors. Also, the same calculations can be used if the cable is loaded less than the non-drying heat rate, i.e. current does not have to be 0 Amps but can be any value less than the non-drying heat rate to begin rehydrating the soil.

A method is proposed to determine the extent of soil drying when a cable is loaded less than 100% of the time. This method provides an equation to calculate the diameter of dried soil caused by the cable heating above the non-drying heat rate and an equation to calculate the time required to rehydrate this same dried volume. The diameter of dried soil determined using this method may then be used in cable ampacity calculations to account for the effects of thermal instability of the soil due to drying effects. Many commercially available software packages have the ability to include this dried soil diameter by modeling user defined cable insulation or a surrounding duct bank with resistivity equal to the dried soil resistivity. For more details on including these effects, please refer to [2] and a paper to be published in the near future.

The proposed method is currently theoretical. Experimental validation is required and is currently in progress. The experiments must show a change in soil resistivity when the cable heating exceeds the non-drying heat rate and, based on this proposed method, should be time dependent.

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IX. VITA

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