How to Include Soil Thermal Instability in Underground Cable Ampacity Calculations

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***Abstract*—Previous papers have described a method to calculate and model the extent of drying that will occur in soil due to the heat produced by underground cables. Up until now, the techniques presented to include soil thermal instability in cable ampacity calculations have been limited to single isolated conductors with 100% load factors. This paper provides more generalized techniques that permit the inclusion of soil thermal instability in any calculation that can be performed using the Neher-McGrath method. Computer programs designed to perform Neher-McGrath calculations are often limited in their versatility and restrict the user in the type of inputs that may be entered. This paper includes suggestions that will permit the computer user to include soil thermal instability information in calculations done using commercially available computer programs.**

***Index Terms*—Soil Moisture, Soil Properties, Thermal Conductivity, Thermal Stability, Thermoresistivity, Cable Ampacity, Neher-McGrath Method, Computer Modeling.**

I. Introduction

The heat produced by underground cables can cause the soil surrounding the cables to dry. This drying causes a change in the soil's thermal properties, which may ultimately lead to cable overheating. This phenomenon is known as soil thermal instability. A method was suggested in [1] to determine the diameter the soil layer dried by the heat produced by the cables so its effects could be included in cable ampacity calculations. A set of equations was developed to find this diameter which may be simplified to (1).

$$D = D_{probe}\left(\frac{q_{new}}{q_{NHR}}\frac{\omega_{measured}}{\omega_{dry}}\right) \qquad (1)$$

Where:
D=Diameter of dried soil area (cm)
D_{probe}=Diameter of the probe used to measure q_{NHR} (cm)
q_{new}=Maximum heat rate of the conductors within D (W/cm)
q_{NHR}=The non-drying heat rate measured in the field (W/cm)
ω_{dry}=% soil moisture content at driest expected soil conditions
$\omega_{measured}$=% soil moisture content when q_{NHR} was measured

The values of q_{NHR} and $\omega_{measured}$ are measured in the field. The value ω_{dry} is the driest moisture content that is expected at the site. While ideally this value would be determined by extensive field measurements done over long periods of time that included both wet and dry conditions, this is seldom practical. As an alternative, the driest expected soil moisture contents near many sites in the United States are available from the National Water and Climate Center [2].

To determine cable ampacity, the soil ambient thermal resistivity must be measured and corrected to the driest expected ambient soil conditions at the site to find the thermal resistivity ρ_{amb}. Also, the resistivity of the dry soil must be measured to get ρ_{dry}. Once these two values are known, the thermal properties of the soil outside the cable or conduits in question will be modeled as an area of dried soil immediately surrounding the cable with a resistivity of ρ_{dry}, surrounded by the ambient soil having thermal resistivity ρ_{amb} as shown in Fig. 1.

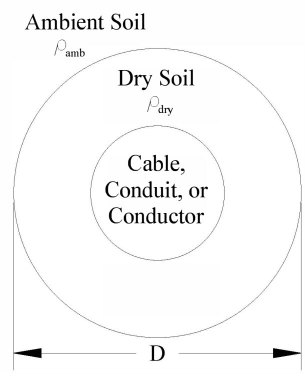

Fig. 1. Model of cable including dried soil caused by thermal instability.

II. Field versus Laboratory Tests

Since no laboratory test can replicate the natural flow of moisture through soil, the non-drying heat rate, q_{NHR}, must be measured in the field using the same equipment used for finding the soil *in situ* thermal resistivity [3]. A byproduct of measuring q_{NHR} is a measurement of thermal resistivity of the *in situ* soil at the soil moisture content that existed at the time

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of the measurement. However, the two resistivities needed to model the soil thermal properties around the cable are the resistivity at the driest ambient condition expected—ρ_{amb}, and the resistivity when the soil is completely dry—ρ_{dry}.

To find these two values, laboratory testing of the soil is needed [4]. The resistivity of a soil sample from the site is measured in the laboratory at various soil moisture contents to produce a soil dry-out curve. The soil dry-out curve for a sample of sand is shown in Fig. 2.

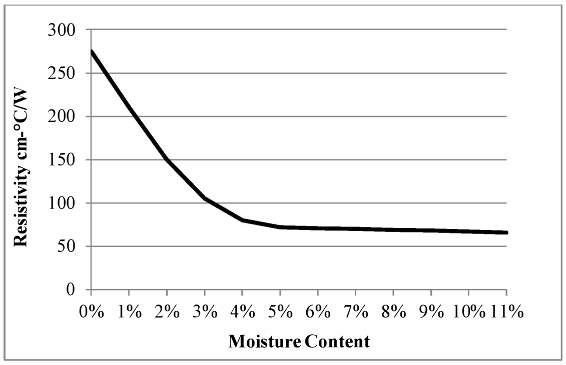

Fig. 2. Soil dry-out curve for sand.

While every effort should be made to reconstitute the soil sample in the lab to the same density as the *in situ* soil, it is seldom possible to make a laboratory sample match the undisturbed conditions found in the field. The result is that the resistivity of soil measured in the field will seldom match the resistivity measured in the lab at the same moisture content. It is commonly seen that the laboratory measurements produce higher values of resistivity than measurements *in situ*. It is suggested that the values of resistivity measured in the laboratory be corrected to match the value measured in the field.

This correction may be made in a way similar to the suggested method of calibrating the laboratory probe suggested in ASTM D5334. A correction factor C is determined and used to correct the laboratory values of resistivity in the dry-out curve. If, for example, the resistivity of the soil at a site was measured at 50 cm-ºC/W at a moisture content of 10% using the field test procedure [3], and a soil sample was then tested in the laboratory using laboratory test procedures [4] producing the dry-out curve shown in Fig. 2, it may be seen that value of resistivity found in the laboratory at a moisture content of 10% is 70 cm-ºC/W rather than the 50 cm-ºC/W found in the field. With this result it would be expected that all values on the laboratory curve would be higher than the actual field *in situ* values. The correction factor, C, is given in Equation (2)

$$C = \frac{\rho_{\text{field}}}{\rho_{\text{laboratory}}} = \frac{50}{70} = 0.714 \qquad (2)$$

This correction factor is multiplied by the values measured in the laboratory to get the estimated *in situ* values of resistivity.

If the driest soil conditions for this site were determined to result in 6% moisture content, Fig. 2 shows the resistivity would be 75 cm-ºC/W. This would be multiplied by the correction factor to produce an in-field resistivity at the driest soil conditions of (0.714)(75)=53.6 cm-ºC/W. This would be used as the resistivity value ρ_{amb}. Likewise, the resistivity of the soil when completely dry is given in Fig. 2 as 275 cm-ºC/W. Multiplied by the correction factor, this gives the value of ρ_{dry}=(0.714)(275)=196.4 cm-ºC/W for *in situ* soil resistivity with a water content of 0%.

III. Neher-McGrath Calculation

To account for the effects of thermal instability, the thermal resistance of the unstable dried soil layer must be included in Neher-McGrath calculations. The Neher-McGrath equation for calculating cable ampacity is [5]:

$$I = \sqrt{\frac{T_c - (T_a + \Delta T_d)}{R_{dc}(1 + Y_c)R_{ca}}}$$

For cables 35kV and below this may be simplified to:

$$I = \sqrt{\frac{T_c - T_a}{R_{ac}R_{ca}}}$$

Where:
I=Allowable current ampacity in (kA)
T_c=Allowable conductor temperature (ºC)
T_a=Soil ambient temperature (ºC)
R_{ac}=AC resistance of cable in (μΩ/ft)
R_{ca}=Effective thermal resistance of the thermal circuit (thermal ohm-ft)

The thermal resistance added by the dried layer of soil surrounding the cable or conduit will add to the value R_{ca}. The formerly suggested method given in [1] of adding this additional thermal resistance directly to R_{ca} is theoretically satisfactory as long as only a single, non-shielded direct buried conductor is being considered with a 100% load factor. To include the dried soil layer in standard Neher-McGrath ampacity calculations in a more generalized way, which may include load and loss factors and heating due to multiple conductors, a more general method is needed.

R_{ca} is made up of three components of thermal resistance (commonly measured in ohm-feet) that start from the conductor surface and move outward toward ambient earth.

$$R_{ca} = R_i + q_s R_{sd} + q_e R_e$$

The first term R_i is the thermal resistance of the conductor insulation (and jacket if present). The second term R_{sd} is the thermal resistance from the conductor insulation to the surrounding enclosure (conduit or outside of conductor cable jacket). R_{sd} is equal 0 for a direct buried, single-conductor cable. The final term, R_e, is the thermal resistance starting from where the earth path begins (and R_{sd} stops) and proceeding outward to ambient earth. It is this value that will be affected by the addition of a dried layer of soil. R_i and R_{sd} will be unaffected by the thermal resistance of the dried soil layer. The values q_s and q_e occur due to currents flowing in cable shields or conduit. These become unity for non-shielded cables (or cables with no shield currents) in non-metallic conduits.

Equation (3) is given by Neher-McGrath [5] to determine the value of R_e for a cable surrounded by two layers of soil with different resistivities. Where the cables are surrounded by a layer of dry soil of resistivity equal to ρ_{dry} and the resistivity of the surrounding ambient soil is ρ_{amb}, the value of R_e is found using (3) [5].

$$R_e = 0.012\rho_{dry} n\left[\log\frac{D_x}{D_e} + (LF)\log\left[\left(\frac{4L}{D_x}\right)F\right]\right] + 0.012(\rho_{amb}-\rho_{dry})nN(LF)\log\frac{L_b+\sqrt{L_b^2-\left(\frac{D}{2}\right)^2}}{\frac{D}{2}} \quad (3)$$

Where:

R_e=Thermal resistance between conduit or cable to ambient earth (Ohm-feet)

ρ_{dry}=Thermal resistivity of the dried soil layer (cm-°C/W)

ρ_{amb}=Thermal resistivity of the ambient soil (cm-°C/W)

D_e=Diameter of cable or conduit (inches)

D_x=Fictitious diameter found using (4) (inches)

D=diameter of dried soil found using (1) (inches)

n=Number of conductors in each cable or conduit

N=Number of cables or pipes surrounded by D

LF=Loss factor found using (6)

L_b=Distance below earth to the center of D (inches)

L=Depth of the reference cable below earth (inches)

F=Mutual heating factor found using (7)

Equation (4) is used to find the value of D_x [5].

$$D_x = 1.02\sqrt{\alpha\,(\text{length of cycle in hours})} \quad (4)$$

Where:

D_x=Fictitious diameter at which the loss factor commences (inches)

α=Soil thermal diffusivity (square inches/hour)

Soil thermal diffusivity can be found using (5).

$$\alpha = 7{,}165{,}910.\ 2\frac{1}{\rho_{amb}\,\gamma\,c} \quad in^2/hr \quad (5)$$

Where:

ρ_{amb}=Thermal resistivity of the ambient soil (cm-°C/W)

γ=soil density (lbs/ft)

c=soil specific heat (J/kg-°C)

The loss factor, LF, is found using (6).

$$LF = 0.3(lf) + 0.7(lf)^2 \qquad \text{Where } lf = \text{load factor} = \frac{\text{Average load}}{\text{Peak load}} \quad (6)$$

The mutual heating factor F is found using the method of images. For a set of cables, a mirror image is created mirrored about the surface of the earth. The distance between the reference cable and each other cable, and the reference cable and the image of each other cable, is calculated. F is then found using (7) [5].

$$F = \left(\frac{d_{12}'}{d_{12}}\right)\left(\frac{d_{13}'}{d_{13}}\right)\left(\frac{d_{14}'}{d_{14}}\right)\cdots\left(\frac{d_{1N}'}{d_{1N}}\right) \quad (7)$$

Where:

d_{12}=distance between the reference cable 1 and cable 2 (inches)

d_{12}'=distance between the reference cable 1 and the image of cable 2 (inches)

d_{13}=distance between the reference cable 1 and cable 3 (inches)

d_{13}'=distance between the reference cable 1 and the image of cable 3 (inches)

And so forth until N-1 terms are included.

Each cable is in turn made the reference cable and the value of F is recalculated for each reference cable. The reference cable or conduit resulting in the largest product of (F x L) will contain the conductors that will reach the highest temperature. Of course, it's usually possible to determine the cable that will results in the worst case F x L by inspection, so not every value must be calculated unless it's unclear what cable will be the hottest. These are the values that should be used in (3) to find the value of R_e needed to calculate the maximum cable ampacity.

IV. Example 1

To illustrate the procedure consider a simple example of three 500 kcmil, copper, single-conductor, low-voltage, non-shielded, direct buried cables. These three cables are spaced by their diameter center-to-center and buried 36" below the surface as shown in Fig. 3.

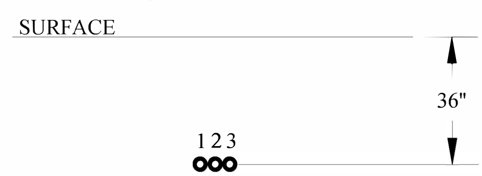

Fig. 3. Cables used in example 1.

The following properties were measured for the conductor and the soil:

- ρ_{dry}=196.4 cm-ºC/W
- ρ_{amb}=53.6 cm-ºC/W
- q_{NHR}=0.3 W/cm
- D_e=cable diameter=0.943 inch
- D_c=copper diameter =0.813 inch
- D_{probe}=1.59 cm
- lf=LF=1.0
- L_b=36 inches
- γ=soil density=90 lb/ft^3
- c=soil specific heat=800 J/kg°C
- T_a=30°C
- T_c=75°C
- Rac=AC Conductor resistance=28.86 μΩ/ft
- ω_{dry}=6%
- $\omega_{measured}$=10%

To find the effect of the cable heating on soil thermal stability, start by finding the cable ampacity and resulting heat rate q_{new} while ignoring any drying effects. The maximum value of (F x L) occurs when the center conductor (conductor 2) is used as the reference cable. The value of F can be found with the help of Fig. 4.

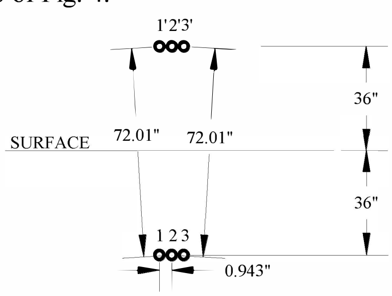

Fig. 4. Method of images.

$$F = \left(\frac{72.01}{0.943}\right)\left(\frac{72.01}{0.943}\right) = 5{,}831.25 \text{ inches}$$

To determine the effects of drying soil, the ampacity of the cable is first calculated in the absence of soil drying. Using the basic Neher-McGrath method with the measured data, the following values can be calculated [5]:

- R_e=3.38 Ωft
- R_{ca}=4.29 Ωft
- Allowable Ampacity= 605A.
- Heat Rate=0.347 W/cm per cable and 1.04 W/cm for all three combined.

Using (1), the expected dried soil diameter may be found. For the heat from each individual cable:

$$D = 1.59cm\left(\frac{0.347\text{W}}{0.3\text{W}}\frac{10\%}{6\%}\right) = 3.06\text{cm} = 1.21 \text{ inch}$$

Since this is larger than the individual conductor diameters there will be drying occurring outside the cables. If this diameter was determined to be less than the cable diameter, 0.943 inches, no soil drying would be expected and soil thermal instability would not have any effect on the ampacity of the cables in this installation.

A circle of dried soil 1.21 inch in diameter outside of each individual cable will intersect with each other. For this reason the circle of dried soil will be centered at the center of the middle cable and will surround all three cables. Therefore, the heat of all three cables must be considered to determine the exact diameter of dried soil since the heat from all three will contribute to the single area of dried soil. Including the heat from all three cables the diameter of dried soil can once again be found using (1).

$$D = 1.59cm\left(\frac{1.04\text{W}}{0.3\text{W}}\frac{10\%}{6\%}\right) = 9.19\text{cm} = 3.62 \text{ inch}$$

Fig. 5 shows the condition that will result after the expected soil drying occurs. The three cables are surrounded by a layer of dried soil of high resistivity, which is surrounded by the ambient soil.

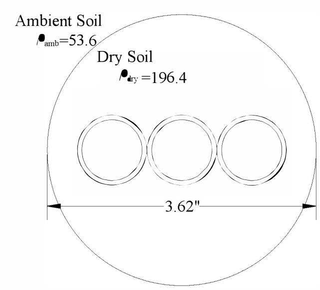

Fig. 5. Cables inside dried soil layer.

To find the new value of allowable cable ampacity with the conditions shown in Fig. 5, the new value of R_e must be calculated using (3).

$$R_e = 0.012(196.4)(1)\left[\log\frac{6.8}{0.943} + (1)\log\left[\left(\frac{4(36)}{6.8}\right)5831.25\right]\right] +$$
$$0.012(53.6-196.4)(1)(3)(1)\log\frac{36 + \sqrt{36^2-(3.62/2)^2}}{3.62/2} = 5.8$$

The addition of the dried soil layer will increase R_e from 3.38Ωft, calculated without the dried soil layer, to 5.8Ωft. R_{ca} will increase from 4.29Ωft to 7.4Ωft. This reduces the allowable cable ampacity from 605A to 499A. Reducing the current will also reduce the heat rate and the diameter of the dried area. So, several iterations may be needed to determine the exact allowable ampacity. At this point all that is known is that the ampacity will fall somewhere between 499A and 605A.

At 499A the heat rate for all three cables is 0.707W/cm and the diameter of the dried area becomes 2.46 inches. Using the process above with a dried soil diameter of 2.46 inches, results in an allowable ampacity of 537A. Several more iterations finally determine that the cable ampacity is 526A and the dried soil layer has a diameter of 2.73 inches. Since this diameter does not completely encompass all the cables, which have a combined width of 2.83 inches when laid side-to-side, it is suggested that to be conservative the dried soil diameter be considered no less than 2.83 inches. This results in a final ampacity of 522A for these cables including the effects of soil thermal instability. It should be noted that if the diameter of dried soil had been smaller than the diameter of any one cable, no soil drying would occur and soil instability can be ignored when calculating cable ampacity.

V. Including Dried Soil Layers Using a Computer Program

Many engineers use computer programs for calculating cable ampacity. While these programs have many advantages they have the disadvantage of being somewhat limited as to how information may be entered into the program. For example, some programs will not allow entering a circular area of soil that is different in resistivity from the ambient soil, and only permit entering rectangular areas such as would occur in a duct bank. This disadvantage can be overcome by modeling the circular layer of dried soil as a square area. Most programs permit surrounding the cables with a rectangular area of concrete or fill at a different resistivity from the surrounding soil. To enter the information into the program in this way it is necessary to determine the dimensions of a rectangular area of soil or concrete with a resistivity equal to ρ_{dry} that is equivalent in effect to a round area with a diameter D and resistivity ρ_{dry} . This equivalent square area can then be modeled in the computer program.

One possible way of determining this equivalent area is provided by Neher-McGrath [5]. If x is the longer dimension of a rectangular area and y is the shorter dimension, then a rectangular area equivalent to a circular area can be found using (8).

$$\log\left(\frac{D}{2}\right) = \frac{1}{2}\frac{x}{y}\left(\frac{4}{\pi} - \frac{x}{y}\right)\log\left(1 + \frac{y^2}{x^2}\right) + \log\left(\frac{x}{2}\right) \qquad (8)$$

If x is 3 inches and (8) is solved for a D=2.83 inches, y would then be approximately 2 inches. Therefore, a computer program's representation of the circular dried soil can be modeled by placing a rectangular area of fill or concrete, 3" x 2", with a resistivity of 193.4 cm°C/W, around the three cables. This will be equivalent in effect to surrounding the cables with a round area of dried soil as shown on Fig. 5. This permits the use of a computer program that accepts only rectangular inputs.

VI. Soil Thermal Instability and Concrete Duct Banks

When cables are contained in conduit encased in concrete, and the concrete duct bank is buried in the earth, the inclusion of the dried layer of soil may become more complex. If the dried soil diameter D from (1) falls within the concrete duct bank then no soil drying or thermal instability will occur since concrete is thermally more stable than soil. However, if diameter D falls outside the perimeter of the concrete duct bank the thermal circuit included in R_e has three parts: concrete, dried soil, and ambient soil.

The thermal resistivity of concrete in the duct bank can be measured if a sample can be taken, or calculated if the concrete mixture used in the duct bank is known [6]. The resistivity of the dried area of soil will be calculated as before; it is the soil resistivity when the soil is completely dry. The resistivity of the soil outside the dried soil area will be the ambient soil resistivity. Fig. 6 shows the concrete duct bank containing six conduits. The duct bank center is a distance L_b below the soil surface. The resistivity of the concrete is ρ_c. The duct bank is surrounded by a layer of dry soil of diameter D, centered at the duct bank center, and having a resistivity of ρ_{dry}. The dry soil layer is surrounded by soil at the natural resistivity ρ_{amb}.

As before, the value of R_e—the thermal resistance between the outside of the conduits and ambient earth—must be calculated and included in R_{ca} for the ampacity calculation. The first step in calculating the new R_e for this case is to calculate the radius of a circular area that is equivalent in effect to the concrete duct bank. This is done using (9).

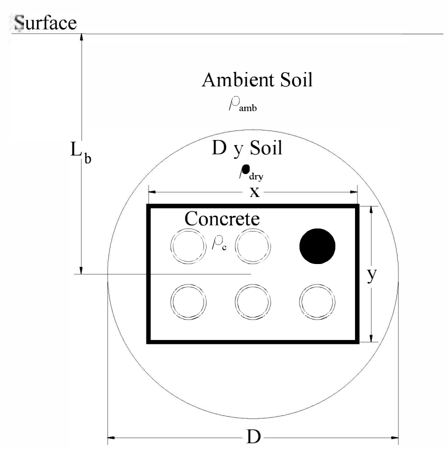

Fig. 6. Concrete duct bank enclosed in dried soil.

$$\log\left(r_c\right) = \frac{1}{2}\frac{x}{y}\left(\frac{4}{\pi} - \frac{x}{y}\right)\log\left(1 + \frac{y^2}{x^2}\right) + \log\left(\frac{x}{2}\right) \qquad (9)$$

Where:
r_c=The radius of the circular area equivalent in thermal effect to the duct bank (inches)
x=long dimension of the duct bank (inches)
y=short dimension of the duct bank (inches)

This method gives us an equivalent circular concrete duct bank with a radius r_b inscribed inside a circular area of dried soil of radius r_{dry}=D/2, which is in turn surrounded by the ambient soil. The next step is to calculate a geometric factor for each of the circular areas. These geometric factors will be determined by the value of the radii for each circle and the depth below the soil's surface. These two values G_c and G_{dry} are calculated using (10) [5].

$$G_c = \mathrm{Log}\left(\frac{L_b + \sqrt{L_b^2 - r_c^{\ 2}}}{r_c}\right) \qquad (10)$$

$$G_{dry} = \mathrm{Log}\left(\frac{L_b + \sqrt{L_b^2 - r_{dry}^{\ 2}}}{r_{dry}}\right)$$

Where:
r_c=radius of equivalent duct bank from (9) (inches)
r_{dry}=D/2 (inches)
L_b=depth of the center of the duct bank below the surface (inches)
G_b=Geometric factor for the duct bank
G_{dry}=Geometric factor for the dried soil layer

The value of R_e for the combined thermal resistances is then found using (11).

$$R_e = 0.012\rho_c n\left[\log\frac{D_x}{D_e} + (LF)\log\left[\left(\frac{4L}{D_x}\right)F\right]\right] + 0.012(\rho_{dry} - \rho_c)nN(LF)G_c + 0.012(\rho_{amb} - \rho_{dry})nN(LF)G_{dry} \qquad (11)$$

Where:
R_e=Thermal resistance between conduit to ambient earth (Ohm-feet)
ρ_{dry}=Thermal resistivity of the dried soil layer (cm-°C/W)
ρ_{amb}=Thermal resistivity of the ambient soil (cm-°C/W)
ρ_c=Thermal resistivity of the concrete (cm-°C/W)
D_e=Diameter of cable or conduit (inches)
D_x=Fictitious diameter found using (4) (inches)
F=Mutual heating factor found using (7)
n=Number of conductors in each conduit
N=Number of conduits in the duct bank
LF=Loss factor found using (6)
L_b=Distance below earth of the center of D (inches)
L=Depth below the surface of the reference cable used when calculating F (inches)
G_c=The concrete duct bank geometric factor calculated in (10)
G_{dry}=The dried soil area geometric factor calculated in (10)

This value of R_e is used to calculate R_{ca} in the ampacity equation.

If a computer program is used for these calculations it will be necessary to find a way to input this new thermal resistance into the program. Many computer programs do not permit inputting an additional resistivity layer between the outside of the duct bank and the ambient earth. Furthermore, they do not permit adding a circular area and restrict the user to rectangular areas only.

One way to include this more complex value of thermal resistance in a program is to determine an equivalent value of concrete resistivity that will produce the desired effect using the original duct bank dimensions. If this value of resistivity can be found then the computer program user only needs to change the resistivity of the concrete used in the program to a new equivalent value that includes the thermal resistance of the dried soil layer while leaving the duct bank dimensions untouched. This may be done using a form of (3).

In (12) we make R_e equal to the value of R_e calculated in (11). Then solve (12) for the new value of concrete resistivity ρ_c'. The concrete resistivity in the computer program is then changed to this new value while leaving the duct bank dimensions and all other inputs into the program unchanged.

$$R_e = 0.012\rho_c' n\left[\log\frac{D_x}{D_e} + (LF)\log\left[\left(\frac{4L}{D_x}\right)F\right]\right] + 0.012(\rho_{amb} - \rho_c')nN(LF)G_c \qquad (12)$$

For simplicity define two constants A and B.

$$A = 0.012n\left[\log\frac{D_x}{D_e} + (LF)\log\left[\left(\frac{4L}{D_x}\right)F\right]\right] \qquad (13)$$

$$B = 0.012\, nN(LF)G_c$$

Then the value of ρ_c' may be found using (14).

$$\rho_c' = \frac{R_e - B\rho_{amb}}{A - B} \qquad (14)$$

Where:
R_e=Thermal resistance between conduit to ambient earth (Ohm-feet)
ρ_c'=The equivalent resistivity of the concrete duct bank to be used in the computer program (cm-°C/W)
ρ_{amb}=Thermal resistivity of the ambient soil (cm-°C/W)

A and B=Constants defined in (13).

VII. Example 2

For this example a duct bank similar to that shown in Fig. 6 will be considered. The designer needs to determine cable ampacity, meaning that R_e must be calculated. Furthermore, the designer has determined that D is large enough to fall outside the duct bank. The following values have been measured or calculated.

- All conduits are 3.5" inner diameter Schedule 40
- Each conduit contains 3 conductors
- Clear distance between each conduit is 2 inches
- x=24 inches
- y=16 inches
- L_b=36 inches
- D=30 inches
- D_x=1.857 inches
- D_e=4 inches
- ρ_{dry}=196.4 cm-°C/W
- ρ_{amb}=53.6 cm-°C/W
- ρ_c=75 cm-°C/W

The largest value of (F x L) was calculated for the center conduit in the bottom of the duct bank. This will be the hottest location among the group of conduits. The values for F and L are:

- F=147,899 inches
- L=39 inches

Using (9) r_c was found to be approximately 11.25 inches. The value of r_{dry} is 15 inches, which is half of D. Making use of (10) to find G_c and G_{dry}:

$$G_c = \text{Log}\left(\frac{36+\sqrt{36^2-11.25^2}}{11.25}\right) = 0.795$$

$$G_{dry} = \text{Log}\left(\frac{36+\sqrt{36^2-15^2}}{15}\right) = 0.66$$

Using the above values (11) gives the final value of R_e.

$$R_e = 0.012(75)(3)\left[\log\frac{1.857}{4} + (1)\log\left[\left(\frac{4(39)}{1.857}\right)147{,}899\right]\right] +$$

$$0.012(196.4-75)(3)(6)(1)(0.795) + 0.012(53.6-196.4)(3)(6)(1)(0.66) =$$

$$18.25 + 20.85 - 20.36 = 18.74\ \text{Ohm - feet}$$

The calculated value of R_e without including the dried soil we be R_e=14.13Ωft. Including the effects of the dried soil yields R_e=18.74Ωft, reducing the allowable ampacity of the cables by approximately 13%.

To find the equivalent value of resistivity for this duct bank for use in a computer program, we would start with (13). From this equation we find that:

A=0.243 and B=0.172

Then solving (14):

$$\rho_c' = \frac{18.74 - 0.172(53.6)}{0.243 - 0.172} = 134.1\ \text{cm-}^\circ\text{C/W}$$

If the operator of the computer program calculating cable ampacity for this duct bank were to change the resistivity of the concrete from the actual value of 75 cm-°C/W to an effective value of 134.1 cm-°C/W, this would make possible the inclusion of the effects of the dried layer of soil on the ampacity of the cables. The programmer could then run the computer program as it would normally be used, except the value of the concrete resistivity would have changed to an equivalent value to include the effects of dried soil.

VIII. Conclusion

Past papers have described how to include the effects of soil thermal instability in cable ampacity calculations, but have been limited in providing a method only usable with isolated single-conductor direct buried cables with 100% load factors. This paper contains procedures to generalize the method for use in any underground cable ampacity calculation that can be performed using the Neher-McGrath method. This more generalized procedure makes it possible to include the effects of heating due to nearby cables, load and loss factors, concrete duct banks, and other conditions provided for in the Neher-McGrath method.

It may be particularly challenging to try to include the effects of soil thermal instability in calculations done using presently available computer programs based on the Neher-McGrath method. This is due to the limitations of these programs in including additional layers of thermal resistivities beyond merely ambient soil and concrete. The paper also included methods which may be used to include the effects of soil thermal instability while working with the limitations of presently available software.

IX. References

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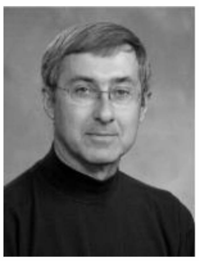
X. Biographies

Carson Bates (M'09) received the B.S. degree in engineering with electrical specialty Magna Cum Laude in 2010, and the M.S. in electrical engineering in 2013 both from the Colorado School of Mines, Golden, CO.

He worked as an intern while pursuing his B.S. degree at the National Renewable Energy Laboratory in the Advanced Power Electronics for Vehicles group. His work primarily involved investigating heat transfer through an IGBT package. He currently works as a full time engineer at NEI Electric Power Engineering, which he has been doing since 2010. While employed there, he has had the opportunity to design multiple substations and industrial facilities. He has also spent significant time troubleshooting problems in existing facilities and inspecting construction activities. Also, he is currently pursuing a doctor of philosophy from the Colorado School of Mines.



Keith Malmedal (M'91–SM'13) received his BSEET degree from Metropolitan State College of Denver in 1995, MSEE degree (Power), a MSCE degree (Structures) from the University of Colorado Denver in 1998 and 2002, respectively. In 2008 he received his PhD at Colorado School of Mines, Golden, CO.

He has over 24 years combined experience in electrical power system design and system study, teaching, and research, and is presently the President of NEI Electric Power Engineering, Arvada, Colorado, a consulting firm specializing in all aspects of power system engineering and design. He has published over 25 technical papers and taught university courses and short courses related to power systems, machines, protection, renewable energy, and energy policy issues.

Dr. Malmedal is also a member of the American Society of Civil Engineers (ASCE) and a registered professional engineer in 18 states, and Alberta, British Columbia, and Ontario, Canada.

David Cain received his Associates of Applied Science degree with two Certificates of Completion from the Community College of Aurora concurrent with his graduation from high school in 2011. Currently David is attending the Metropolitan State University of Denver majoring in Electrical Engineering Technology and expects to graduate with a BSEET by 2017. He is currently an engineering intern at NEI Electric Power Engineering.