Cable Ampacity Calculations: A Comparison of Methods

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***Abstract*—When designing electrical power systems, it is often necessary to determine underground cable ampacity. Various methods are in use today including computer simulation, ampacity tables, and a method that has recently been suggested that includes the effects of moisture migration through soil. Each of these methods can yield substantially different ampacity results for the same installation. Regardless of the method, using the correct value of soil thermal resistivity is critical and using the wrong value can result in cables that are incorrectly sized. This paper examines several commonly used methods and their underlying assumptions. Examples are provided to illustrate the differences in the results obtained from various methods and the consequences of using incorrect assumptions. It is hoped that these examples will provide guidance on the implementation of each method.**

***Index Terms*—cable ampacity, power cable installation, soil thermal resistivity, power distribution, soil thermal stability, solar power generation, underground power distribution lines, underground power transmission lines, wind power generation**

I. Introduction

Using accurate cable ampacities is critical to electrical power system design. An optimally sized cable results in minimum cost and high reliability. Wind and solar power plants, in particular, strive to optimize cable design by using ampacities that closely match maximum generation without including a growth factor or other safety factor.

Cable ampacities have been estimated over the years based on engineering assumptions and site conditions. Various configurations require different parameters and assumptions. Cables placed underground require information about the ambient earth temperature, cable separation distance, soil thermal resistivity, etc. If these parameters or assumptions are inaccurate, the resulting cable size will also be inaccurate. This may lead to cable overheating if the cable is undersized or increased cable cost if the cable is oversized.

Underground cable ampacity is difficult to estimate because a primary factor determining ampacity—soil thermal resistivity—varies substantially from moist to dry conditions, which may occur depending on cable loading [1]. This paper compares the difference in results obtained when using various methods including one recently proposed [1]. These methods will include cable ampacities calculated using the Neher-McGrath method, IEEE Cable Ampacity tables, and a commercially available computer program.

Each of these methods requires some values that must be collected at location where the cable will be installed. These include the soil thermal resistivity—also known as "rho" and measured in Kcm/W (°C*cm/W)—and the maximum expected ambient temperature, excluding cable heating, at the depth of the hottest cable. The soil thermal resistivity, while critical, may not be as readily available as the ambient temperature. IEEE Std. 835 states:

> "In the past, when the thermal resistivity of the earth was not known a rho of 90 was recommended for rating the cable. However, the ratings for buried cables are significantly affected by the earth's portion of the thermal circuit and therefore correct knowledge of the effective soil thermal resistivity and soil thermal stability is paramount in establishing the correct rating for a buried cable system"[2].

Measuring the *in situ* thermal resistivity is not a difficult process as described in [5], but it is frequently not performed. It is likely that a cable size will be selected that is either smaller or larger than optimal if this step is skipped.

II. Ampacity Calculation Methods

A. The Black Books

The "Black Books", which are entitled AIEE-IPCEA Power Cable Ampacities [3], were the first tabulated ampacities using the Neher-McGrath method and were published in 1962. This allowed an engineer to look up the appropriate cable size based on design current rather than calculating the cable size using Neher-McGrath calculations in [4]. Considering the number of calculations needed to determine ampacity using the Neher-McGrath method, it is obvious why engineers would prefer using this simplified tabular method. These same tables are still used by some engineers today as their primary method of sizing underground cables.

It is important to understand the assumptions used to create these tables. For example, one assumption used in the tables is that the ambient temperature of the earth is 20°C. Many locations in the Southwest USA experience maximum underground soil temperature of 25-30°C, which reduces the ampacity by 5-8% below the tabulated values. The tabular values must be adjusted using methods included in the introductory pages.

Another assumption is that the cable depth is 36" and the cable spacing is 7.5". If the burial depth was actually 18", this would increase the ampacity by approximately 10%, and doubling the spacing would increase it by approximately 6%. Adjustment factors for these assumptions are not given in the tables, so the Neher-McGrath calculations must be done if conditions of depth or spacing vary from the assumptions. Furthermore, modern cables use different insulation material and thickness than those used in these older tables. Also, these tables assume the cables are not jacketed. All of these assumptions may present difficulties for a modern user and, if differences are ignored, can result in cables that are sized too large or too small.

The key assumptions in these tables are listed below.

- 20°C ambient earth
- 90°C maximum conductor temperature
- Cable shields single point grounded
- 36” depth
- 7.5” spacing
- Generic rubber insulation
  - Thicker than modern insulations for equivalent voltage rating
  - Higher thermal resistivity (500 Kcm/W versus modern 350 Kcm/W)
  - Higher insulation power factor resulting in higher dielectric losses (3.5% versus modern 0.5%)

B. IEEE 835 Cable Ampacity Tables

In 1994, a new set of tabulated ampacities was issued by IEEE in order to: “update the cable constructions and design changes that had taken place since the original publication” [2]. While maintaining the fundamental calculations set forth by Neher-McGrath, the tables include updated information on cable properties and adjust some of the original assumptions. This includes assuming a 25°C ambient earth temperature and cable shields that are shorted (grounded at both ends) for most cable sizes. The standard also includes some step-by-step examples of the Neher-McGrath method with updates to address changes in assumptions of the original method. The steps given allow an engineer to develop a spreadsheet to calculate ampacity for any cable configuration, which eliminates the need for the tables except as a convenient check.

The key assumptions for these tables are given below.

- 25°C ambient earth
- 90°C maximum conductor temperature
- Cable shields shorted
- 36” depth
- 7.5” spacing

C. Computer Modeling

Commercially available computer software allows for the calculation of cable ampacity by modeling the cable properties and the physical configuration. The cables can be modeled with the intended design geometry and with the intended cable type. Programs utilize values of cable constituent thermal resistivity as specified by IEEE 835 [2] for each material type (e.g. EPR is 350 Kcm/W), allowing the thickness and order of the components to be adjusted. Programs are typically advertised as using the Neher-McGrath method to determine ampacity, meaning the only assumptions necessary are those inherent to the Neher-McGrath method.

D. Neher-McGrath Adaptation

The method proposed by [1] focuses on the thermal stability of the soil. All soils increase in resistivity as moisture content decreases. The suggested method addresses the issue of moisture migration with a simple procedure to approximate the effective thermal resistance to ambient earth including the effects of drying. The non-drying heat rate (NHR) and the completely dried soil resistivity must be known in addition to the *in situ* soil resistivity. These are used to calculate a dried soil diameter which is then included in the Neher-McGrath method. The cable ampacity may be calculated with the aid of a spreadsheet, by hand, or by using a computer program that includes the capability of adding concentric layers of thermal resistance surrounding the cable. Another notable feature of this method is that it does not assume that the only heat transfer mechanism of the cable is conduction to ambient earth. Rather, it includes the effects of heat transfer by moisture moving through the soil.

III. Comparison

In order to highlight the differences between these methods, some examples are provided. Each example involves three single, copper conductors that are directly buried 36” underground as shown in Fig. 1, which is the same configuration as figure “k” of IEEE 835 [2]. Also, each example involves single point grounded cables and the design requires an ampacity of at least 500A at 15kV with EPR insulation and tape shielding. A load factor of 100% is assumed.

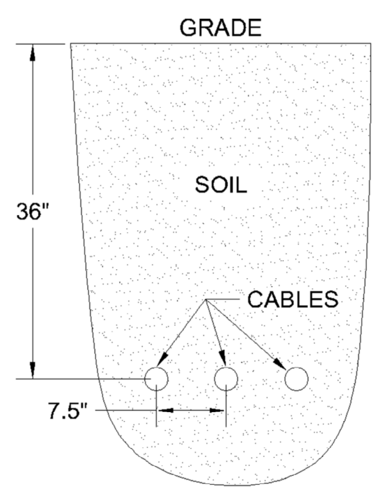

Fig. 1. Cable Configuration

A. *Site Specific Data Collection*

To begin the design for the first example, the *in situ* soil thermal resistivity and the moisture content must be measured. These can be found by following IEEE Std. 442 [5] and ASTM D4643 [6]. For this example, the *in situ* soil thermal resistivity has been measured at 90 Kcm/W at an *in situ* moisture content of 8%. It is important that the soil resistivity be measured at the minimum soil moisture content because it has a large effect on the soil resistivity. In addition, both the moisture content and the resistivity should be measured at the depth that the cables will be installed.

Determining the minimum moisture content is often difficult because it may occur at any point during the year and it is impractical to measure the moisture content throughout the year when sizing cables. Also, the minimum moisture content will vary from year to year and the year in which the soil resistivity is measured for the design may be an abnormally high level. This would result in a low soil resistivity and a cable size that is too small during a drought.

A practical method to determine the approximate minimum soil moisture content involves using the data provided by the Soil Climate Analysis Network (SCAN) operated by the National Water and Climate Center [7]. This publicly available data provides soil moisture content and soil temperature for various soil depths up to 40" at locations across the United States. From this data, the minimum soil moisture content and maximum soil temperature can be found over a period of several years. A plot of the minimum soil moisture and maximum soil temperature over a given year at a depth of 40" below grade for the soil used in this example is show in Fig. 2.

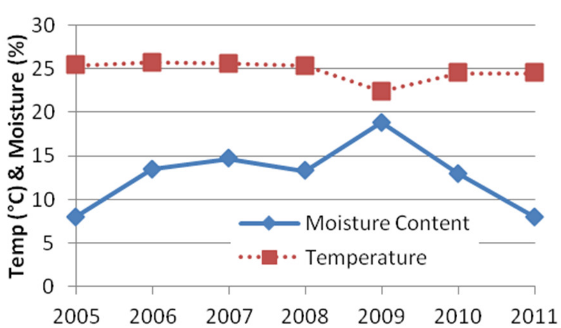

Fig. 2. Max. soil temperature and min. moisture content per year

The maximum soil temperature and the minimum soil moisture content are the conditions that result in the lowest cable ampacity. Using these extremes will result in a conservative design. In the case of Fig. 2, the lowest moisture content is 8% and the highest soil temperature is 25°C. Of course, the lowest moisture content may not occur concurrently with the highest soil temperature. A plot of the soil moisture content and the soil temperature over one year is shown in Fig. 3, which shows the maximum temperature occurring four months before the minimum moisture content.

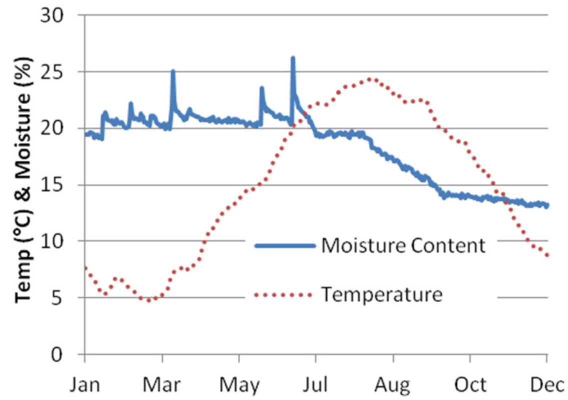

Fig. 3. Soil temperature and moisture content over one year

Using this information, it is possible to use the moisture content and temperature which occur simultaneously rather than the yearly minimum moisture content and yearly maximum temperature. Multiple cases would need to be examined for each moisture content and temperature. The case that resulted in the lowest ampacity would determine the required cable size. The *in situ* thermal resistivity is required for each moisture content used in the calculation. For example, after examining multiple cases, the minimum moisture content and maximum temperature that result in the minimum ampacity may occur in September compared with the maximum temperature occurring in July with the minimum moisture content in December. This is obviously more time consuming than using the minimum annual moisture content and maximum temperature, which will result in a more conservative design but may not differ significantly.

Another piece of information that is needed for the method proposed in [1] is the soil dry out curve, which is performed in a lab rather than *in situ*. The lab test of the soil is shown in Fig. 4.

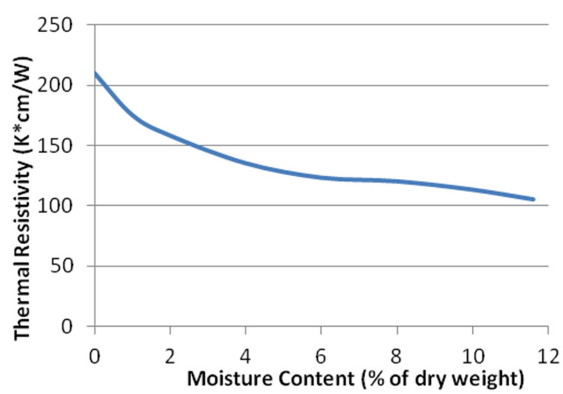

Fig. 4. Soil dry out curve

This curve provides information on the soil thermal resistivity over a range of moisture contents, but it should not be used to replace the *in situ* moisture content and thermal resistivity measurements. It is used for determining the dry soil resistivity. Laboratory tests allow for complete dehydration of the soil but do not permit ingress of moisture that would normally be experienced *in situ* and, therefore, do not produce accurate measurements of the expected resistivity in the field. These laboratory results may provide higher resistivity values than measured *in situ* because the surrounding soil moisture provides some cooling as it is heated by the cables [1].

B. Cable Sizing Example

After the soil data specific to the site has been determined, the ampacity can be found using various methods. Table 1 shows the calculated values of cable ampacity using four different methods, assuming the soil resistivity remains at 90Kcm/W, i.e. the soil does not dry out.

Table 1. Ampacity with RHO-90

Method	Ampacity	Cable Size
Neher-McGrath	**541A**	**350kcmil**
Black Book P.210	**534A**	**350kcmil**
IEEE 835 P.465	**519A**	**350kcmil**
Computer Program	**549A**	**350kcmil**

All of these methods result in an equivalent cable size though there are slight discrepancies in the resulting ampacity. These differences can be attributed to the different assumptions used by each method as described earlier in this paper.

C. Soil Drying Consideration

The effect of soil drying can be checked by measuring the non-drying heat rate (NHR) as described in [1]. This example will use a value of 0.53W/cm as the NHR measured using a standard probe diameter of 1.5875cm, as per IEEE 442 [5]. In order to determine if soil drying occurs, the NHR can be compared to the cable heat rate. The cable heat rate is a calculated value in the Neher-McGrath method and can also be found using a computer program. The Black Books and IEEE Std. 835 do not list the cable heat rate, but it could be calculated using the Neher-McGrath method if needed. The amount of heat a cable can generate before causing the soil to dry is a function of the diameter of the cable. The NHR found using the standard probe must be adjusted for the cable diameter before it can be compared to the actual cable heat rate. This can be accomplished by first calculating the conductive heat flow rate of the test probe at the NHR using (1), which is (7) in [1].

$$\dot{q}_{c,probe} = \frac{2\pi(T_1 - T_2)}{\rho \ln\left(\frac{4L}{D_{probe}}\right)} \tag{1}$$

where

$\dot{q}_{c,probe}$ is the conductive heat rate at the NHR for the test probe (W/cm)

L is the length of the test probe (cm)

T_1 is the maximum temperature of the NHR test (°C)

T_2 is the ambient temperature of the NHR test (°C)

ρ is the *in situ* soil thermal resistivity (using [5])

D_{probe} is the outside diameter of the test probe (cm)

The NHR for the cable diameter using the NHR measured with a test probe can be derived by beginning with (19) of [1], shown in the per unit length form in (2) below.

$$D_{cable} = \frac{D_{probe}(\dot{q}_{w,cable} + \dot{q}_{v,cable})}{\dot{m}_{NHR,probe}(h_v + C_w \Delta T_{cable})} \tag{2}$$

where

D_{cable} is the outside diameter of the cable (cm)

$\dot{q}_{w,cable}$ is the heat rate due to inflowing water (W/cm)

$\dot{q}_{w,cable}$ is the heat rate due to water vapor (W/cm)

$\dot{m}_{NHR,probe}$ is the mass flow rate of water at the probe diameter (lb/sec*cm)

h_v is the latent heat of vaporization of water (1025kJ/lb)

C_w is the specific heat of water (1.89kJ/lb°C)

ΔT_{cable} is the temperature difference between ambient earth and the dried soil interface, which is the cable diameter in the case of the NHR (°C)

The mass flow rate of water is given in (13) of [1] as shown in the per unit length form in (3) below.

$$\dot{m}_{NHR} = \frac{\dot{q}_{NHR,cable} - \dot{q}_c}{h_v + C_w \Delta T} \tag{3}$$

where

$\dot{q}_{NHR,cable}$ is the total heat rate at the NHR for the cable (W/cm)

The heat absorbed by inflowing water and the heat transferred by water vapor is shown in (4), which is the per unit length form of (12) in [1].

$$\dot{q}_{w,cable} + \dot{q}_{v,cable} = \dot{q}_{NHR,cable} - \dot{q}_{c,cable} \tag{4}$$

where

$\dot{q}_{c,cable}$ is the conductive heat rate at the NHR for the cable (W/cm)

The conductive heat rate at the NHR for the cable can be found in terms of the NHR using the same assumption as in (1)—that the increase in total heat rate from the NHR at the probe diameter to the NHR at the cable diameter will result in a proportional increase in each component of the heat rate, i.e. the heat transferred by conduction, water, and vapor. This is shown in (5), which is the per unit length form of (20) in [1].

$$\dot{q}_{c,cable} = \frac{\dot{q}_{NHR,cable}}{\dot{q}_{NHR,probe}} \dot{q}_{c,probe} \tag{5}$$

The NHR for the cable diameter can now be calculated using (2), (3), (4), and (5) as shown in the following derivation.

Begin by inserting (3) into (2).

$$D_{cable} = \frac{D_{probe}(\dot{q}_{w,cable} + \dot{q}_{v,cable})}{\frac{\dot{q}_{NHR,probe} - \dot{q}_{c,probe}}{h_v + C_w \Delta T_{probe}}(h_v + C_w \Delta T_{cable})} \tag{6}$$

The terms $h_v + C_w \Delta T_{cable}$ can be cancelled by $h_v + C_w \Delta T_{probe}$ if the same assumption is made as is made in [1]. Inserting (4) into (6) and cancelling the equivalent terms results in (7).

$$D_{cable} = \frac{D_{probe}(\dot{q}_{NHR,cable} - \dot{q}_{c,cable})}{\dot{q}_{NHR,probe} - \dot{q}_{c,probe}} \tag{7}$$

Inserting (5) into (7) results in (8).

$$D_{cable} = \frac{D_{probe}\left(\dot{q}_{NHR,cable} - \frac{\dot{q}_{NHR,cable}}{\dot{q}_{NHR,probe}}\dot{q}_{c,probe}\right)}{\dot{q}_{NHR,probe} - \dot{q}_{c,probe}} \quad (8)$$

Rearranging the terms in (8) completes the derivation, which is shown as (9).

$$\dot{q}_{NHR,cable} = \frac{D_{cable}(\dot{q}_{NHR,probe} - \dot{q}_c)}{D_{probe}\left(1 - \frac{\dot{q}_{c,probe}}{\dot{q}_{NHR,probe}}\right)} \quad (9)$$

Using test data of T_1 = 36°C, T_2 = 20°C, and the IEEE 442 [5] standard probe dimensions yields the following $\dot{q}_{c,probe}$ based on (1).

$$\dot{q}_{c,probe} = \frac{2\pi(36°C - 20°C)}{90\frac{Kcm}{W} * \ln\left(\frac{4 * 120cm}{1.5875cm}\right)} = 0.196W/cm$$

Using a cable diameter of 3.2 cm (compact stranded 350kcmil) yields the following NHR that is corrected for the cable diameter using Equation (9).

$$\dot{q}_{NHR,cable} = \frac{3.2cm(0.53W/cm - 0.196W/cm)}{1.5875cm\left(1 - \frac{0.196W/cm}{0.53W/cm}\right)} = 1.06W/cm$$

Now that the NHR is known for the cable diameter in question, a direct comparison can be made to the calculated cable heat flow rate needed in the design. The Neher-McGrath method yields values for the cable heat "W" that are the sum of the losses developed in a cable [4]. The value W is the sum of all of the other losses (W_c, W_s, W_p, and W_d), the most important of which will be the I^2R losses. For a direct buried cable operating at 15kV, the conduit losses (W_p) and dielectric losses (W_d) are zero. For this particular example, the cable heat rate, W or $\dot{q}_{cable}$, is equal to 0.373W/cm. This is well under the 1.06W/cm calculated for this soil, so soil drying is not expected to occur and no modification is needed to the calculations due to soil thermal instability [1].

D. *Laboratory Testing Versus In situ Testing*

A common concern when sizing cables is that the cable will heat up the surrounding soil enough to dry the soil. This would increase the temperature of the cable that would cause further drying of the soil that would cause an additional increase in temperature until the temperature rating of the insulation was exceeded. This is sometimes referred to as *thermal runaway*, but dramatic increases in temperature commonly associated with thermal runaway are not required in order to exceed the temperature rating of the cable. To avoid this problem, an engineer might choose to use a value of resistivity that is higher than the value measured *in situ*.

If *in situ* measurements are unavailable, the laboratory thermal measurements similar to those in Fig. 4 may need to be relied upon. These are commonly higher than *in situ* measurements and the designer may choose the highest value shown on the graph for safety.

For this example, a value of resistivity will be selected from the lab test based on the minimum moisture content of 8%. The other values are the same as those used in the first example. The value of resistivity found from laboratory was approximately 120 Kcm/W. Using the same methods used in Table 1 results in the ampacities and cable sizes show in Table 2.

Table 2. Ampacity with RHO-120

Method	Current	Cable Size
Neher-McGrath	**483A**	**350kcmil**
Neher-McGrath	**569A**	**500kcmil**
Black Book P.210	**485A**	**350kcmil**
Black Book P.210	**588A**	**500kcmil**
IEEE 835 P.465	**462A**	**350kcmil**
IEEE 835 P.465	**536A**	**500kcmil**
Computer Program	**489A**	**350kcmil**
Computer Program	**591A**	**500kcmil**

Comparing Table 1 and Table 2 shows that all of the cables had to be increased in size from a 350kcmil to a 500kcmil cable in order to carry the desired 500A design current. Using a cost of $9,900/1000ft for 350kcmil and $12,600/1000ft for 500kcmil, increasing the size from 350kcmil to 500kcmil would result in approximately 25% higher costs or $2,700 per 1000 feet. It is clear that if an *in situ* test resulted in rho=90 and laboratory tests resulted in rho=120 (or the designer used an arbitrarily high value for rho) that the costs of the installation would be significantly affected. The higher cost of the *in situ* measurement could easily be paid for in a situation such as this, and the desirability of accurate soil resistivity data is evident.

E. *Sand Backfill Cable Sizing Example*

Sand is often used to backfill cable trenches in a direct buried configuration. This protects the cables from damage that might otherwise occur if native backfill were used containing rocks or other debris. Protection against cable damage is required by section 300.5 of the National Electrical Code, which states, "Where necessary to prevent physical damage to the raceway or cable, protection shall be provided in the form of granular or selected material" [8]. Also, some cable manufacturers recommend that "sand or stone-free earth" be used "within 4 inches of the cable" [9].

Sand has poor thermal properties compared with many native soils when it is dry, and it dries with relatively low heat rates if the surrounding soil does not have high moisture content. For the next example, a value of resistivity equal to 90Kcm/W is used for the *in situ* soil with a moisture content of 8%. All other values are the same as in the first two examples. In addition, a dry resistivity of 350Kcm/W is used for the surrounding sand layer and a NHR of 0.1W/cm will be assumed. Converting the NHR at the test probe diameter to the cable diameter using Equation (1), based on test data in sand, yields the following:

$$\dot{q}_{c,probe} = \frac{2\pi(25°C - 20°C)}{90\frac{Kcm}{W} * \ln\left(\frac{4*120cm}{1.5875cm}\right)} = 0.061W/cm$$

Note that this equation uses the maximum temperature reached during the NHR test for sand as well as the thermal resistivity of sand.

$$\dot{q}_{NHR,cable} = \frac{3.2cm(0.1W/cm - 0.061W/cm)}{1.5875cm\left(1 - \frac{0.061W/cm}{0.1W/cm}\right)} = 0.20W/cm$$

Because the cable heat rate is 0.37W/cm and the NHR of the sand surrounding the cable is 0.2W/cm, soil drying will occur. Equation (8) can be used to determine the extent of drying.

$$D_{dry\,soil} = \frac{1.5875cm * 0.373W/cm\left(1 - \frac{0.061W/cm}{0.1\,W/cm}\right)}{0.10W/cm\ - 0.061W/cm} = 5.9cm$$

This diameter of dried soil can be accounted for by adding its resistance to R_{CA}' as stated by [1] using (34) in the same reference and shown in (5) below.

$$R_{dry\,soil} = 0.012\rho_{dry\,soil}\log\left(\frac{D_{dry\,soil}}{D_{cable}}\right) \quad (10)$$

where

$R_{dry\,soil}$ is the resistance of the dried soil (thermal ohms)

$\rho_{dry\,soil}$ is the resistivity of the dry sand (Kcm/W)

Solving for the resistance added by the dried sand yields:

$$R_{dry\,soil} = 0.012 * \frac{350Kcm}{W} * \log\left(\frac{5.9cm}{3.2cm}\right) = 1.12\Omega_{thermal}$$

The effective resistance of the earth portion of the circuit, R_e' in [4], must be recalculated for the new diameter of the dried soil. It can then be added to R_{ca}'. This yields a new ampacity of 504A rather than the 541A previously calculated in Table 1, which did not include the dried sand. It confirms that a 350kcmil will be adequate to handle the design current of 500A but is much less than the ampacities calculated in Table 1. This result is stated in Table 3.

Table 3. Ampacity with dried soil included

Method	Current	Cable Size
Adapted Neher-McGrath	**504A**	**350kcmil**

This method addresses the issue of soil drying and the possibility of thermal runaway by calculating an expected dried soil diameter rather than assuming the surrounding soil all dries to a larger resistivity, which would result in installing larger than necessary cables. The engineer may still include a factor of safety when sizing cables because of the large impact slight variations of soil resistivity have on the ampacity. However, this factor of safety no longer needs to include the risk of thermal runaway.

IV. CONCLUSIONS

The assumptions in several methods for determining underground cable ampacity have been shown. The older Black Books use an ambient earth temperature of 20°C while the IEEE 835 tables use an ambient earth temperature of 25°C. However, the IEEE tables assume the cable shields are shorted while the Black Books assume the shields are single point grounded. Overall, IEEE 835 results in a lower ampacity than the Black Books.

Using the Neher-McGrath method, or a software program using that method, allows for calculating cable ampacities using various soil resistivities, ambient temperatures, and shield grounding configurations. This reduces the error in the calculated ampacity by eliminating the assumptions used in the tables.

Regardless of the method, it is often economical to perform an *in situ* soil thermal resistivity measurement rather than attempting to utilize the lab thermal resistivity measurements. Performing an *in situ* test also allows for the measurement of the NHR, which can be used in thermal stability calculations. Using a higher value of resistivity, whether because the actual value is uncertain or because of concerns for thermal instability, can result in a larger cable size and a significant cost increase when compared to using measured *in situ* values.

The method proposed in [1] calculates an effective dried soil diameter rather than assuming a complete thermal runaway. This allows for a more accurate assessment of the cable size while including the risk of drying soil. These effects of soil thermal stability are otherwise not included in the Neher-McGrath method or the tabulated ampacities. The result is a design that includes all factors relevant to determining cable ampacity and that minimizes cost by preventing oversized cables due to unknown or poorly defined parameters.

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VITA

Keith Malmedal received his BSEET degree from Metropolitan State College of Denver in 1995, a 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 25 states (US), Alberta and British Columbia, Canada.

Carson Bates (M'09) received a B.Sc. degree in engineering with an electrical specialty Magna Cum Laude in 2010, and an M.Sc. in electrical engineering in 2013 both from the Colorado School of Mines in Golden, CO. He worked as an intern while pursuing his B.Sc. degree at the National Renewable Energy Laboratory in the Advanced Power Electronics for Vehicles group 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 2011. While employed here, he has had the opportunity to design multiple substations and industrial electrical power systems. He has also spent significant time commissioning substations and electrical installations. Mr. Bates is a registered professional engineer in multiple states.

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. He is a registered electrical apprentice, with three years of field experience; one year of industrial, one year of commercial, and one year of residential. Currently David is attending the University of Colorado at Denver majoring in Electrical Engineering and expects to graduate with a BSEE by 2016.