Neher–McGrath Calculations for Insulated Power Cables

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Abstract—**The Neher–McGrath (NM) method for calculating temperature rises and current-carrying capacities of insulated nonshielded power cables rated 0–2000 V phase-to-phase is described. The concept of the thermal circuit is explained, NM equations for calculating thermal resistances are given and sample calculations are presented.**

INTRODUCTION

IN 1957 Neher and McGrath presented an outstanding technical paper [1] with numerous detailed mathematical equations which can be used to relate an insulated conductor's current loading to its operating temperature. The general calculation method is very broad and can be applied to a variety of cable constructions and installation conditions.

For simplicity the Neher–McGrath (NM) method uses steady-state equations; they are based on the assumption that radial heat flow has been constant for a long time. Transient heat flow is not addressed in this paper.

The NM equations also assume an infinitely long cable with heat uniformly distributed along its length and no end effects. Longitudinal heat transfer from cable to termination or vice versa is not addressed.

The NM method and equations have been used extensively and have received wide acceptance. They were used as the basis of [2] and [3].

The National Electrical Code® (NEC), which has included tables of ampacities for power cable [4] (based on technical studies that predate NM) [5], has published in its 1984 edition new ampacity tables based upon the NM method of calculation. This paper is intended to give readers not familiar with the NM equations a basic understanding of the NM method and how it is applied to the calculation of power cable ampacities.

GENERAL APPROACH

When current is carried by a cable's conductor, the heat (I^2R) generated within the conductor flows radially to ambient and is dissipated in the surrounding air, or earth in the case of buried cable. This causes a gradient temperature rise from the ambient air or earth through the cable's components. Because the maximum allowable conductor temperature is limited by the temperature rating of the cable's insulation, the temperature rise of the conductor above ambient must be calculated. To do this, the I^2R heat generated in the cable and the thermal resistances of the heat path (thermal circuit) must be determined (see Fig. 1).

The thermal circuit is analogous to an electrical circuit (see Fig. 2). For this analogy, the corresponding electric and thermal parameters (including symbols and dimensions) are summarized in Table I. Note that the NM thermal circuit quantities are always calculated on a per foot length basis.

NOTATION

In the NM equations, subscripts are used to identify thermal parameters according to their location in the thermal circuit and mathematical symbols for thermal resistances are differentiated from those for electrical resistances by diacritical marks. Some examples of subscripted symbols are listed in Table II.

THE THERMAL CIRCUIT

To apply the NM calculation method, the thermal circuit must be developed for each specific cable construction and installation. For example, a single cable installed in air has a thermal circuit as shown in Fig. 3.

Once the thermal circuit for a specific cable construction and installation has been developed, the value of each thermal resistance in the circuit must be calculated. Then all the thermal resistance values must be added to arrive at a total thermal resistance between conductor and ambient, since all the thermal resistances are in series.

NM equations for the calculation of the thermal resistances are summarized in Appendix I. They are applicable to both single- and three-conductor cables, and cover various installations: for example, cable in air, cable in conduit in air, cable in duct, and cable direct earth buried.

HEAT

The heat which flows from conductor to ambient is calculated by multiplying the total ac conductor resistance by the square of the conductor current. This yields the heat generated in the conductor, expressed in W/ft.

In some cable systems additional heat may be generated in the cable insulation and/or metallic shield and raceway; however, for 0–2000-V rated insulated power cable, dielectric loss is negligible, metallic shielding is not used, and metallic raceway effects are for the most part cancelled by the inclusion of all phases in the raceway. Mutual heating from adjacent cables is taken into account in the NM equations for thermal resistances.

CONCLUSION

The heat generated at the conductor (W/ft) times the total thermal resistance from conductor to ambient (°C·ft/W)

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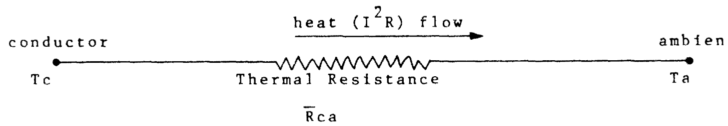


Fig. 1. Thermal resistance of heat path, or thermal circuit.

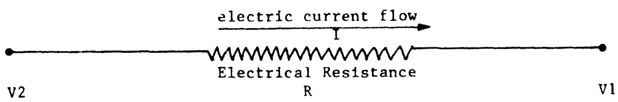


Fig. 2. Electric circuit.

TABLE I
ANALOGOUS THERMAL AND ELECTRICAL PARAMETERS

Electrical Circuit			Thermal Circuit		
Symbol	Parameter	Units	Symbol	Parameter	Units
V	voltage	V	T	temperature	°C
I	current	A	I^2R	heat flow	W/ft
R	resistance	Ω	R	thermal resistance	°C·ft/W

TABLE II

Symbol	Parameter	Unit
Tc	conductor temperature	°C
Ta	ambient temperature	in
Rc	conductor resistance	μΩ/ft
	Thermal Resistance °C·ft/W	
$\bar{R}i$	insulation	
$\bar{R}j$	jacket	
$\bar{R}sd$	between cable and surrounding enclosure	
$\bar{R}d$	duct wall	
$\bar{R}e$	between cable and ambient air	
$\bar{R}'e$	earth	
$\bar{R}ca$	total between conductor and ambient	

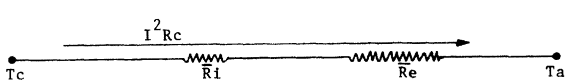


Fig. 3. Thermal circuit for single cable installed in air.

yields the temperature rise of the conductor above ambient:

$$(I^2Rac)\times \bar{R}ca = Tc - Ta \tag{1}$$

or

$$I = \sqrt{\frac{Tc - Ta}{Rac \times \bar{R}ca}}. \tag{2}$$

(I is in kA because Rac is in μΩ/ft.)

Equation (2) expresses conductor current as a function of conductor temperature for a specific cable construction and installation condition. Given the maximum allowable conductor temperature based on the cable insulation's temperature rating, the maximum current-carrying capacity of the conductor can be calculated with (2).

Note that ampacity is only one of several factors (including voltage drop, short circuit capability, and recently, the increasingly important cost of energy losses [6]) that must be considered in arriving at the most economic conductor size for a given set of conditions.

APPENDIX I

EQUATIONS FOR THE CALCULATION OF THERMAL RESISTANCE

Thermal Resistance of Insulation

$$\bar{R}i = 0.012\bar{p}i \log \frac{\mathrm{DI}}{\mathrm{DC}}$$

where

- DC conductor diameter
- DI diameter over insulation
- $\bar{p}i$ thermal resistivity of material, [1, table VI] (see Table III).

Thermal Resistance of Jacket

$$\bar{R}j = 0.0104\bar{p}jn' \frac{t}{D-t}$$

where

- $\bar{p}j$ thermal resistivity of material [1, table VI],
- t jacket thickness,
- D diameter over jacket,
- n' number of current carrying conductors within D,
- $\bar{R}d$ thermal resistance of duct wall can similarly be calculated with pd.

Thermal Resistance of Cables in Ducts

$$\bar{R}sd = \frac{n'A'}{Ds' + B'}$$

where

- n' number of current-carrying conductors within Ds',
- Ds' effective diameter of cable(s) in duct,
- $A' + B'$ constants (see Table IV).

Thermal Resistance from Cable(s), Conduit, or Duct Suspended in Air

$$\bar{R}e = \frac{9.5n'}{1 + 1.7D_s'(e + 0.41)}$$

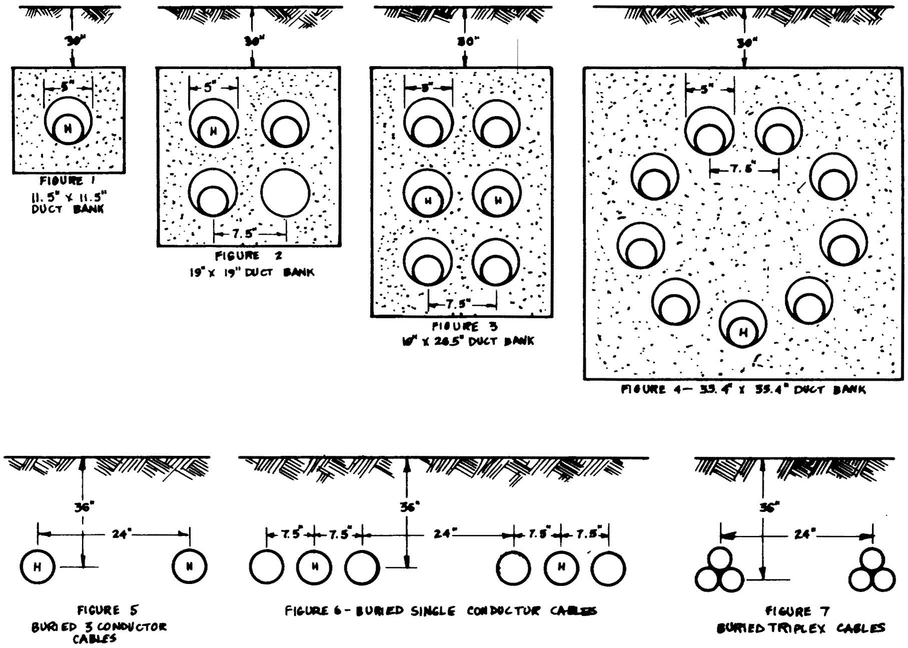


Fig. 4.

TABLE III[a]

Material	$\bar{\rho}i$, °C·cm/W
Paper insulation (solid type)	700
Varnished cambric	600
Paper insulation (other types)	500
Rubber and rubber-like	500
Jute and textile protective covering	500
Fiber duct	480
Polyethylene	450
Transite duct	200
Somastic	100
Concrete	85

[a] From [1, table VI].

TABLE IV
CONSTANTS FOR USE IN $\bar{R}sd$ EQUATION[a]

Condition	A'	B'
In metallic conduit	3.2	0.19
In fiber duct in air	5.6	0.33
In fiber duct in concrete	4.6	0.27
In transite duct in air	4.4	0.26
In transite duct in concrete	3.7	0.22
Gas-filled pipe cable at 200 lb/in^2	2.1	0.68
Oil-filled pipe cable	2.1	0.45

[a] Abstracted from [1, table VII].

where Ds' is the effective diameter of cable(s), conduit, or duct, and e is the effective diameter of surface emissivity.

Thermal Resistance of the Earth

$$\bar{R}e' = 0.012\bar{\rho}en' \left[\log \frac{8.3}{De} + \text{LF} \log \left[\frac{4L \times F}{8.3} \right] \right]$$

TABLE V[a]

Condition	Figure	n'	N	L	F
One three-conductor cable[b]	1	3	1	35.8	1
Three three-conductor cables[b]	2	3	3	35.8	102
Six three-conductor cables[b]	3	3	6	43.3	1.02×10^5
Nine three-conductor cables[b]	4	3	9	57.7	6.81×10^6
Three single-conductor cables	2	1	3	35.8	102
Six single-conductor cables	3	1	6	43.3	1.02×10^5
Nine single-conductor cables	4	1	9	57.7	6.81×10^6

[a] Abstracted from [2, table VI].
[b] Note: This applies to a conventional three-conductor or to a triplex assembly of three single-conductor cables.

where

- n' number of current carrying conductors within De,
- $\bar{\rho}e$ thermal resistivity of the earth,
- De diameter at start of the earth portion of the thermal circuit,
- LF loss factor,
- L depth of burial (inches),
- F mutual heating factor. (See Table V.)

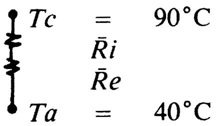
APPENDIX II

SAMPLE CALCULATIONS

1) Calculate the ampacity of a 1/0 AWG compact aluminum XHHW cable in 40°C ambient air.

Cable Buildup		DC	0.336
t	insulation thickness	$2t$	0.120
DI	$2t$ + DC	DI	0.456

Thermal Circuit



$$\bar{R}i = 0.012\bar{\rho}i \log \frac{\mathrm{DI}}{\mathrm{DC}} \quad \bar{\rho}i = 400$$

$$= 0.012(400) \log \frac{0.456}{0.336}$$

$$\underline{\bar{R}i = 0.637}$$

$$\bar{R}e = \frac{9.5n'}{1 + 1.7Ds'(e + 0.41)}$$

$$= \frac{9.1(1)}{1 + 1.7(0.456)(0.95 + 0.41)}$$

$$\underline{\bar{R}e = 4.625}$$

$$\bar{R}ca = \bar{R}i + \bar{R}e$$

$$\underline{\bar{R}ca = 5.262}$$

$$Rdc \text{ at } 25^\circ\mathrm{C} = 168\mu\Omega/\mathrm{ft}$$

$$Rdc \text{ at } 90^\circ\mathrm{C} = 168 \times \frac{228.1 + 90}{228.1 + 25}$$

$$\mathrm{ac/dc} = 1.00$$

$$Rac \text{ at } 90^\circ\mathrm{C} = 168 \times \frac{318.1}{253.1} \times 1.00$$

$$\underline{Rac \text{ at } 90^\circ\mathrm{C} = 211}$$

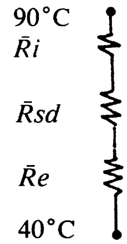
$$I = \sqrt{\frac{Tc - Ta}{Rac \times Rca}} \quad \mathrm{kA}$$

$$= \sqrt{\frac{90 - 40}{211 \times 5.262}}$$

$$\underline{I = 212 \quad \mathrm{A}}.$$

2) Calculate the ampacity of three 1/0 AWG compact aluminum XHHW cables in a 1¼ aluminum conduit in 40°C ambient air.

Thermal Circuit



$$\underline{\bar{R}i = 0.637}$$

$$\bar{R}ds = \frac{n'A'}{Ds' + B'}.$$

From [1, table VII],

$$A' = 3.2$$

$$B' = 0.19$$

1¼ aluminum conduit

$$\mathrm{ID} = 1.38$$

$$\mathrm{OD} = 1.66.$$

From [1, table VII],

$$Ds' = 216DI$$

$$\underline{Ds' = 0.984}$$

$$\bar{R}sd = \frac{3(3.2)}{0.984 + 0.19}$$

$$\underline{\bar{R}sd = 8.177}$$

$$\bar{R}e = \frac{9.5n'}{1 + 1.7Ds'(e + 0.41)}$$

$$Ds' = \text{conduit OD } (1.66 \text{ in})$$

$$e = 0.5$$

$$\bar{R}e = \frac{9.5(3)}{1 + 1.7(1.66)(.5 + .41)}$$

$$\underline{\bar{R}e = 7.987}$$

$$\bar{R}ca = \bar{R}i + \bar{R}sd + \bar{R}e$$

$$\underline{\bar{R}ca = 16.8}$$

$$I = \sqrt{\frac{90 - 40}{211(16.8)}}$$

$\underline{I = 119 \quad A}.$

3) Calculate the ampacity of three 1/0 AWG concentric copper type USE cables, each carrying equal current (three-phase operation), direct earth buried in triangular configuration, 36 in below the earth's surface. The earth ambient is 20°C, the loss factor is 0.75 and $\bar{p}e$ is 90°C cm/W.

Cable Buildup

$$\begin{aligned} DC &= 0.373 \\ 2t &= 0.160 \\ \hline DI &= 0.533 \end{aligned}$$

Thermal Circuit

90°C*

$\bar{R}i$

$\bar{R}e'$

20°C

$\underline{\bar{R}i = 0.744}$

$$\bar{R}e = 0.012\bar{p}en'\left[\log\frac{8.3}{De} + \text{LF}\log\left[\frac{4L\times F}{8.3}\right]\right]$$

$De = 1.6DI$ (from [2, Table VI)

$$\bar{R}e' = 0.012(90)(3)\left[\log\frac{8.3}{1.6(0.533)}\right.$$
$$\left. + 0.75\log\frac{(4\times 36)\times 1}{8.3}\right]$$

$\underline{Re' = 6.213}$

$\bar{R}ca = \bar{R}i + \bar{R}e'$

$\underline{\bar{R}ca = 6.957}$

R dc at $25°C = 106\ \mu\Omega/\text{ft}$

$$R \text{ dc at } 90°C^1 = 106\times\frac{234.5+90}{234.5+25}$$

[1] If the installation comes under the jurisdiction of the NEC, the maximum allowable conductor temperature would be limited to 75°C.

ac/dc = 1.00

$$Rac \text{ at } 90°C^* = 106\times\frac{324.5}{259.5}\times 1.00$$

$\bar{R}$ac at $90°C^* = 132.55$

$$I = \sqrt{\frac{90^* - 20}{132.55(6.957)}}$$

$\underline{I = 276 \text{ A}}.$

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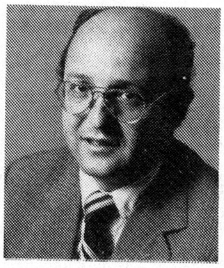

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