Chapter 13
Cable ampacity studies

13.1 Introduction

The cables that network a power system together form the backbone of the system. It is only logical, therefore, that any complete analysis of a power system should include an analysis of its cable ampacities. This analysis is complicated since the ampacity of a conductor varies with the actual conditions of use. Ampacity is defined as "the current in amperes a conductor can carry continuously under the conditions of use (conditions of the surrounding medium in which the cables are installed) without exceeding its temperature rating." Therefore, a cable ampacity study is the calculation of the temperature rise of the conductors in a cable system under steady-state conditions. The purpose of this chapter is to acquaint the reader with the use of computer software systems in the solution of cable ampacity problems with emphasis on underground installations.

The ampacity of a conductor depends on a number of factors. Prominent among these factors and of much concern to the designers of electrical distribution systems are the following:

a) Ambient temperature
b) Thermal characteristics of the surrounding medium
c) Heat generated by the conductor due to its own losses
d) Heat generated by adjacent conductors

To account for the various items that affect ampacities of cables, the 1975 edition of the National Electrical Code® (NEC®) (see NFPA 70-1996[1]) accepted, for the first time, the Neher-McGrath method (Neher and McGrath [B10][2]) of determining the ampacities of conductors. Since then, the NEC has added new ampacity tables to account for some limited conditions of use. As an alternative to the ampacity tables, Section 310-15 (b) of NFPA 70-1996 permits, under engineering supervision, the use of an ampacity equation for determining ampacities. A discussion of this evolution and the origin of NEC Tables 310-16 through 310-19 is provided in Knutson and Miles [B1]. This equation is based on the Neher-McGrath method, which is the basis for the calculating procedures discussed in this chapter.

In subsequent paragraphs, various items that affect cable ampacities are discussed and quantified with the help of ampacity adjustment factor tables and actual computer runs. The computer program from which the ampacity adjustment factors were generated is based on the Neher-McGrath method of calculation and has been corroborated by a second, independently developed computer program of like kind. Under some specific and limited conditions, the ampacity adjustment tables were compared and verified with the NEC ampacity tables, including Appendix B of the NEC. Note that the tables provided here generally cover broader conditions of use with greater resolution than the NEC tables.

[1]Information on references can be found in 13.7.
[2]The numbers in brackets correspond to those of the bibliography in 13.8.

Since the ampacity adjustment tables have been developed for some specific conditions, they cannot be applied for all cases. In general, these tables can be used to size the cables in the initial stages of a design and to closely approximate ampacities. These preliminary cable sizes can then be used as the basis for a more rigorous computer analysis to determine actual conductor temperatures and to finalize the design.

13.2 Heat flow analysis

When designing a power distribution system, the cable ampacity is of primary concern. Once the size and location of electrical loads are determined, an adequate distribution system must be designed. The total number of required circuits, their sizes, and the method of routing are significant elements in the design problem. But in addition, accurate cable sizing becomes especially critical to ensure that the cables are adequate to carry the required load without being subjected to temperatures that exceed their temperature ratings.

As an electrical current flows through a cable, it generates heat. The type of cable and how it is connected and installed determines how many components of heat generation are present, e.g., I^2R losses, sheath losses, etc. The heat flows from these sources through a series of thermal resistances to the surrounding environment. The operating temperature that the cable ultimately reaches is directly related to the amount of heat generated and the net effective value of the thermal resistance through which it flows.

A detailed discussion of all the heat transfer complexities involved is beyond the scope of this subclause. However, the heat transfer process will be covered briefly in order to establish a basic background from which the discussion to follow can proceed.

The calculation of the temperature rise of cable systems involves the application of a series of thermal equivalents of Ohm's and Kirchoff's laws to a relatively simple thermal circuit, as is illustrated in Figure 13-1. This circuit includes a number of parallel paths with heat entering at several points. Under conditions of equilibrium, the conductor temperature will be determined by the temperature differential created across a series of thermal resistances as the heat flows to the ambient temperature $T'_c = T'_a + \Delta T$).

To understand the basic calculation procedure used in cable ampacity programs, consider the fundamental equation for the ampacity of a cable in an underground duct.

$$I = \left[\frac{T'_c - (T'_a + \Delta T_d + \Delta T_{int})}{(R_{ac})(R'_{ca})}\right]^{1/2} \text{kA} \tag{13-1}$$

This equation follows the Neher-McGrath method where

T'_c	is the allowable conductor temperature (°C),
T'_a	is the soil ambient temperature (°C),
ΔT_d	is the temperature rise of conductor due to dielectric heating (°C),
ΔT_{int}	is the temperature rise of conductor due to interference heating from cables in other ducts (°C). (Note that since the temperature rise, due to another conductor,

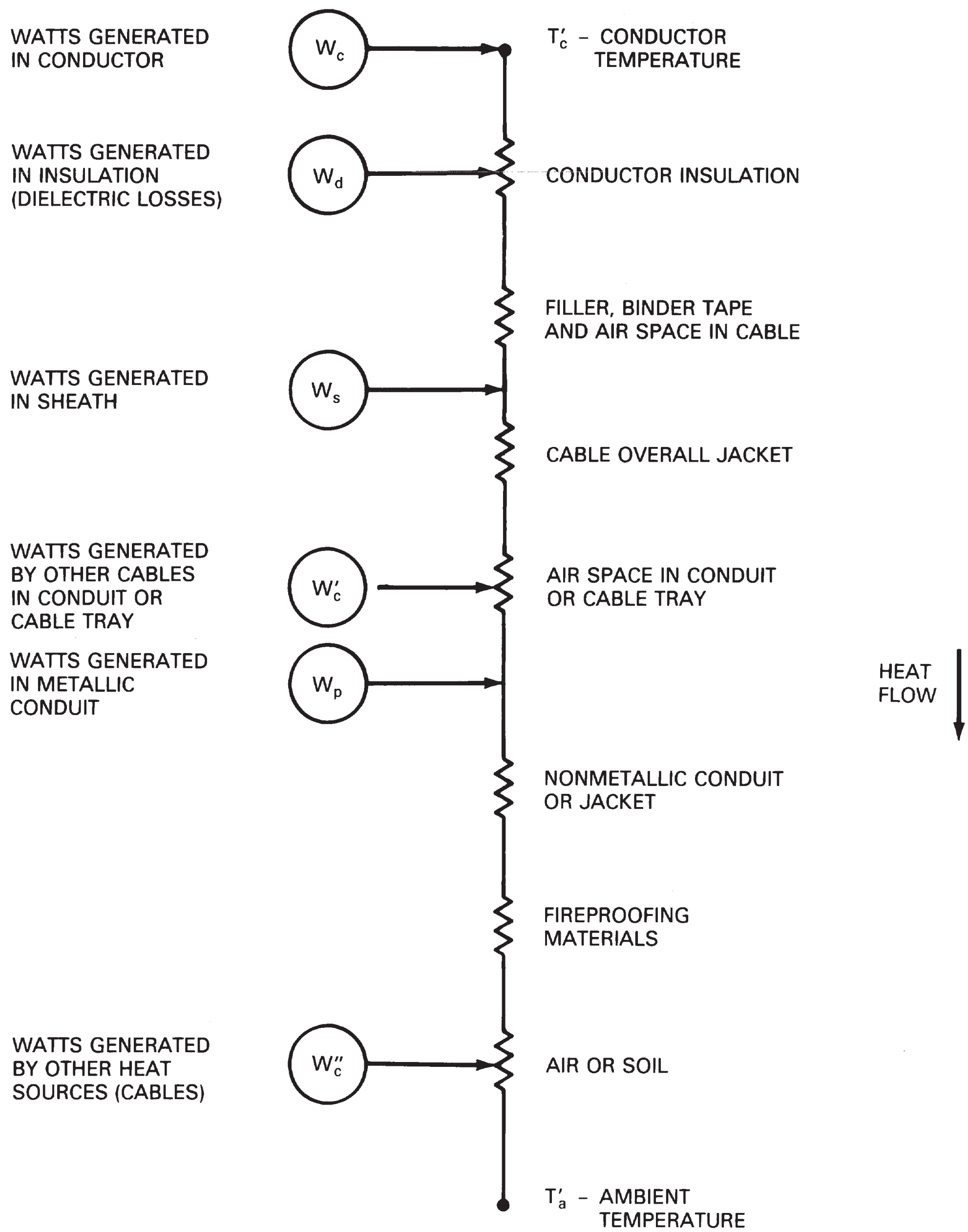

Figure 13-1—A generalized model for heat flow from heat sources in a cable system to ambient temperature through a series of thermal resistances

depends on the current through it, simultaneous solutions of ampacity equations are required.)

R_{ac} is the electrical alternating current resistance of conductor including skin, proximity, and temperature effects (μΩ/ft),

R'_{ca} is the effective total thermal resistance from conductor to ambient soil adjusted to include effects of load factor, shield/sheath losses, metallic conduit losses, and the effect of multiple conductors in the same duct (thermal-Ω/ft, °C-ft/W).

Note that all effects that produce a conductor temperature rise except the conductor loss (I^2R_{ac}) have been treated as adjustments to the basic thermal system. Fundamentally, the difference between two temperatures (e.g., $T'_c - T'_a$) divided by a separating thermal resistance equals the heat flow in watts (or W/ft of conductor). The similarity of the procedure used in the cable ampacity program to that used with the traditional approach is apparent if both sides of the ampacity equation are squared and then multiplied by R_{ac}. The result is as follows:

$$I^2R_{ac} = \frac{T'_c - (T'_a + \Delta T_d + \Delta T_{int})}{(R'_{ca})} \text{ W/ft} \qquad (13\text{-}2)$$

Although it is not necessary to understand these heat transfer concepts in order to use cable ampacity programs, such knowledge may be helpful for understanding how physical parameters affect ampacity. Observation of the ampacity equation shows how lower ampacities are inherent with the following:

— Lower conductor operating temperatures
— Higher soil ambient temperatures
— Smaller conductors (higher R_{ac})
— Higher thermal resistivities of earth, concrete, insulation, duct, etc. (higher R'_{ca})
— Deeper burial depths (higher R'_{ca})
— Closer cable spacing (higher ΔT_{int})
— Cables located in inner, rather than outer, ducts (higher ΔT_{int})

Other factors that decrease ampacity and whose relationship to the ampacity equation is not readily apparent include the following:

— Higher load factor (higher R'_{ca})
— Higher voltage (higher ΔT_d)
— Higher insulation SIC and power factor (higher ΔT_d)
— Lower shield/sheath electrical resistance (higher R'_{ca})

13.3 Application of computer program

The calculations used in cable ampacity programs are normally based on the Neher-McGrath method. In computing cable ampacities in duct banks, only power cables need to be considered, since control cables, carrying very little current, contribute very little to the overall temperature rise. Cable ampacity programs deal only with the temperature-limited, current-carrying capacity of cables. Voltage drop, future load growth, and short-circuit capability are also important factors that should be considered when selecting cables.

The calculation of cable ampacity in underground installations is a very complicated procedure requiring the evaluation of a multitude of subtle effects. In order to make the calculations possible for a wide variety of cases, certain assumptions are made. Most of the assumptions are developed by Neher and McGrath in [B10] and are widely accepted. Some programs may make other assumptions that should be understood.

The basic steps in applying cable ampacity programs follow. It is important to follow methodical procedures in order to obtain good results with minimum effort.

a) The first step in designing an underground cable installation is to establish which circuits are to be routed through the duct bank. Consideration should be given to present circuits as well as to circuits that may be added in the future. Only power cables need to be included as current-carrying conductors in analysis; but space allowances must be made for spare ducts or for control and instrumentation circuits.
b) The duct bank should be designed with consideration given to the circuits contained, the space available for the bank, cable separation criteria, and factors that affect ampacity. For example, cables buried deeply or surrounded by other power cables often have greatly reduced ampacity. It should be decided if ducts will be directly buried or encased in concrete. The size(s) and type(s) of duct to be used should be determined. Finally, a sketch of the duct bank should be prepared with burial depth and spacing of ducts clearly shown. Physical data on the duct installation should be compiled, including thermal resistivity of the soil, ambient temperature of the soil, and thermal resistivity of the concrete. Note that soil thermal resistivity and temperature at some locations (e.g., desert) may be much greater than the typical values often used.
c) Complete data on all power cables used in the installation must be assembled. Some data may be taken from standard tables; but certain data should be based on manufacturer's specifications. Conductor size, conductor material, operating voltage, type of shield or sheath, temperature rating, insulation type, and jacket type are especially important.
d) An initial cable placement layout should be designed, based on anticipated loads and load factors. Circuits with high currents and load factors (ratio of average to peak load over a given load cycle) should be placed in outside ducts near the top of the bank to eliminate the need for larger conductors due to unnecessarily reduced ampacity. Frequently, a good compromise between best use of duct space and highest ampacity is achieved by installing each three-phase circuit in a separate duct. However, nonshielded single- conductor cables may have a higher ampacity with each phase conductor in a separate nonmetallic duct. If the load factor cannot be evaluated readily, a conservative value of 1.0 may be entered, which implies that the circuit always operates at peak load.
e) The manual method presented in this chapter can be used to initially size the cables based on the ambient temperature, soil thermal resistivity, and grouping of the cables.
f) Once the initial design is established and all necessary data have been collected, the user should enter the program data interactively or prepare an input data file for a

batch program. Normally, the data should be prepared for standard ampacity calculation, using the worst-case conditions. If actual load currents are known, these may be entered to find the temperatures of cables within each duct. Temperature calculations are especially useful if some circuits are lightly loaded, while others carry heavy loads that push ampacity limits. If the lightly loaded circuits were to operate at rated temperature, as the ampacity calculation assumes, the load capability of the heavily loaded circuits would be reduced. Temperature calculations may also be used as a rough indicator of the reserve capacity of each duct.

g) After a program is run, the user should carefully analyze the results to verify that design currents are less than ampacities (if an ampacity calculation is performed), or that actual temperatures are less than rated temperatures (if a temperature calculation is performed). If the initial design is shown to be inadequate, various corrective measures should be considered. These include increasing conductor sizes, modifying cable locations, and changing the physical design of the bank. The effects of various parameters may be analyzed by repeating these steps until a satisfactory overall design is achieved.

h) The results of such an analysis should be documented and permanently archived for use in properly controlling and/or analyzing future changes in duct bank usage (i.e., installation of cables in spare ducts).

13.4 Ampacity adjustment factors

The ampacity values stated (specified) by the cable manufacturer and/or other authoritative sources, such as the NEC and IEEE Std 835-1994, are usually based on some very specific conditions relative to the cable's immediate surrounding environment. The following are examples of some specific conditions:

- Installation under an isolated condition
- Installation of groups of three or six circuits
- Soil thermal resistivity (RHO) of 90 °C–cm/W
- Ambient temperature of 20 °C or 40 °C

In practice, the surrounding medium or environment in which cables are to be installed rarely matches those conditions under which the stated ampacities apply. The differences can be thought of as an intermediate medium (requiring adjustment factors for conditions of use) inserted between the base conditions (an environment at which the base ampacity is specified by the manufacturer or other authoritative sources) and the actual conditions of use. This process is presented pictorially in Figure 13-2. It illustrates that the nature of the practical problem is to adjust the specified (base) ampacities of the cables by an adjustment factor to account for the effects of the various intermediate elements or conditions of use.

A simple manual method of determining cable ampacities is presented here to illustrate the concept of cable derating and to present the different factors that have a direct effect on the operating temperatures of the conductors.

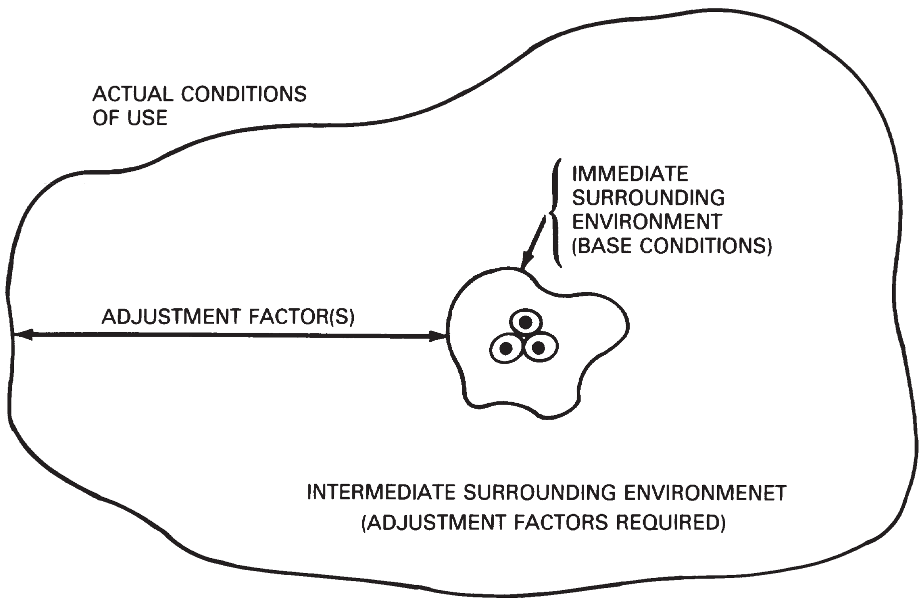

Figure 13-2—Simplified illustration of the heat transfer model used to determine the cable ampacity (3–1/C cables shown)

This method is based on the concept of an adjustment (derating) factor applied against a base ampacity to provide the allowable cable ampacity.

$$I' = FI \tag{13-3}$$

where

- I' is the allowable ampacity under the actual installation conditions,
- F is the overall cable ampacity adjustment factor,
- I is the base ampacity, i.e., the ampacity specified by the manufacturers or other authoritative sources, such as the ICEA. For example, the ampacity of a cable that is installed in an underground conduit under isolated conditions with an ambient temperature of 20 °C and soil thermal resistivity RHO of 90 °C-cm/W.

The overall cable adjustment factor is a correction factor that takes into account the differences in the cable's actual installation and operating conditions from the base conditions. This factor establishes the maximum load capability that results in an actual cable life equal to or greater than that expected when operated at the base ampacity under the specified conditions.

The overall ampacity adjustment factor is composed of several components as indicated in Equation (13-4).

$$F = F_t F_{th} F_g \tag{13-4}$$

where

- F_t is the adjustment factor to account for the differences in the ambient and conductor temperatures from the base case,
- F_{th} is the adjustment factor to account for the difference in the soil thermal resistivity, from the RHO of 90 °C–cm/W at which the base ampacities are specified,
- F_g is the adjustment factor to account for cable grouping.

To obtain the values of the adjustment factors F_{th} and F_g, an elaborate computer program was developed based on the Neher-McGrath method and was used to calculate the conductor temperatures for various arrangements. The program takes into account each adjustment factor in Equation (13-4) which together account for the more significant effects indicated in Figure 13-1 for underground installations. Thousands of computer runs were made to determine the adjustment factor tables. These tables were then verified by utilizing the NEC, IEEE Std 835-1994, and the *Underground Systems Reference Book* [B18]. Knutson and Miles [B1], Shokooh and Knutson 1988 [B14], and Shokooh and Knutson 1983 [B15] report the results of similar efforts for ampacity adjustment factors based on the Neher-McGrath method.

The various adjustment factors in Equation (13-4) are largely, but not completely, independent from each other. Although the computer program can simulate any complex configuration, for the sake of clarity, the ampacity adjustment tables reported here are based on the following simplifying assumptions:

a) Cables for some voltage ratings and sizes are combined for the F_{th} tables. For some applications where RHO is considerably high (more than 180 °C–cm/W) and a mixed group of cables are installed, the interdependencies of the adjustment factors for different cable sizes may not be negligible and up to a 4% error in the overall conductor temperatures may be expected.

b) The effect of the temperature rise due to the insulation dielectric losses is neglected for the temperature adjustment factor, F_t. This temperature rise for rubber and polyethylene insulated cables rated 15 kV and below (sizes 1000 kcmil and below) is less than 2 °C. However, this effect can be included in F_t by adding the temperature rise due to the dielectric losses to the ambient temperatures T_a and T'_a.

c) The often negligible effects of any applicable sheath, shield, and metallic conduit losses depicted in Figure 13-1 are ignored.

In the final design case where accuracy and precision are required, the previously mentioned assumptions cannot be disregarded, and the ampacities obtained from the manual method can be used as an initial approximation for computer simulation of the actual design conditions.

13.4.1 F_t (ambient and conductor temperature adjustment factor)

This adjustment factor is used to determine the cable ampacity when the operating ambient temperature and/or the maximum allowable conductor temperature differ from the original temperatures at which the cable base ampacity is specified. The expression for calculating the effect of changes in the conductor and ambient temperatures on the base ampacity is given by F_t in Equations (13-5) and (13-6) for copper and aluminum conductors, respectively.

$$F_t = \left[\frac{T'_c - T'_a}{T_c - T_a} \times \frac{234.5 + T_c}{234.5 + T'_c} \right]^{1/2} \text{(copper)} \qquad (13\text{-}5)$$

$$F_t = \left[\frac{T'_c - T'_a}{T_c - T_a} \times \frac{228.1 + T_c}{228.1 + T'_c} \right]^{1/2} \text{(aluminum)} \qquad (13\text{-}6)$$

where

T_c is the conductor rated temperature in °C at which the base ampacity is specified,

T'_c is the maximum allowable conductor operating temperature in °C,

T_a is the ambient temperature in °C at which the base ampacity is specified,

T'_a is the actual (maximum) soil ambient temperature in °C.

The maximum operating ambient temperature is usually difficult to obtain and has to be estimated based on historical meteorological data. For application in underground cables, T'_a is the maximum soil temperature at the depth of installation at peak summertime. In general, seasonal temperature variations of the soil follow a roughly sinusoidal cycle with soil temperature peaking during the summer months. The effect of seasonal variation in soil temperature decreases with depth until the depths of 20–30 ft are reached, at which the soil temperature remains fairly constant.

Certain characteristics of the soil (texture, density, and moisture content) and soil pavement (asphalt, cement, etc.) have a noticeable effect on the soil temperature profile. For maximum accuracy, it is important to obtain T_a via a field test rather than using an approximate value based on the maximum atmospheric temperature. For cable installation in air, T_a is the maximum air temperature at peak summertime. Special attention should be given for cable applications in the shade or under direct sunlight.

Adjustment factors for typical copper conductor temperatures (T_c = 90 °C and 75 °C) and ambient temperatures (T_a = 20 °C for underground installation and 40 °C for above-ground installation) at which the base ampacities are specified, are calculated from Equation (13-5) and tabulated in Tables 13-1 through 13-4.

Table 13-1—F_t: Adjustment factor for various copper conductors and ambient temperatures when T_c = 75 °C and T_a = 40 °C

T'_c in °C	T'_a in °C					
	30	35	40	45	50	55
60	0.95	0.87	0.77	0.67	0.55	0.39
75	1.13	1.07	1.00	0.93	0.85	0.76
90	1.28	1.22	1.17	1.11	1.04	0.98
110	1.43	1.34	1.34	1.29	1.24	1.19

Table 13-2—F_t: Adjustment factor for various copper conductors and ambient temperatures when T_c = 90 °C and T_a = 40 °C

T'_c in °C	T'_a in °C					
	30	35	40	45	50	55
75	0.97	0.92	0.86	0.79	0.72	0.65
85	1.06	1.01	0.96	0.90	0.84	0.78
90	1.10	1.05	1.00	0.95	0.89	0.84
110	1.23	1.19	1.15	1.11	1.06	1.02
130	1.33	1.30	1.27	1.23	1.19	1.16

Table 13-3—F_t: Adjustment factor for various copper conductors and ambient temperatures when T_c = 75 °C and T_a = 20 °C

T'_c in °C	T'_a in °C					
	10	15	20	25	30	35
60	0.98	0.93	0.87	0.82	0.76	0.69
75	1.09	1.04	1.00	0.95	0.90	0.85
90	1.18	1.14	1.10	1.06	1.02	0.98
110	1.29	1.25	1.21	1.18	1.14	1.11

Table 13-4—F_t: Adjustment factor for various copper conductors and ambient temperatures when T_c = 90 °C and T_a = 20 °C

T'_c in °C	T'_a in °C					
	10	15	20	25	30	35
75	0.99	0.95	0.91	0.87	0.82	0.77
85	1.04	1.02	0.97	0.93	0.89	0.85
90	1.07	1.04	1.00	0.96	0.93	0.89
110	1.16	1.13	1.10	1.06	1.02	0.98
130	1.24	1.21	1.18	1.16	1.13	1.10

13.4.2 F_{th} (thermal resistivity adjustment factor)

Soil thermal resistivity (RHO) indicates the resistance to heat dissipation of the soil in °C–cm/W. Tables 13-5 through 13-7 indicate the adjustment factors required when the actual soil thermal resistivity is different from the RHO of 90 °C–cm/W at which the base ampacities are specified. These tables are calculated based on an assumption that the soil has a uniform and constant thermal resistivity.

Table 13-5—F_{th}: Thermal resistivity adjustment factor for 0–1000 V cables in duct banks with base ampacity given at an RHO of 90 °C-cm/W

Cable Size	Number of CKT	RHO (°C-cm/W)							
		60	90	120	140	160	180	200	250
#12–#1	1	1.03	1.0	0.97	0.96	0.94	0.93	0.92	0.90
	3	1.06	1.0	0.95	0.92	0.89	0.87	0.85	0.82
	6	1.09	1.0	0.93	0.89	0.85	0.82	0.79	0.75
	9+	1.11	1.0	0.92	0.87	0.83	0.79	0.76	0.71
1/0–4/0	1	1.04	1.0	0.97	0.95	0.93	0.91	0.89	0.86
	3	1.07	1.0	0.94	0.90	0.87	0.85	0.83	0.80
	6	1.10	1.0	0.92	0.87	0.84	0.81	0.78	0.74
	9+	1.12	1.0	0.91	0.85	0.81	0.78	0.75	0.70
250–1000	1	1.05	1.0	0.96	0.94	0.92	0.90	0.88	0.85
	3	1.08	1.0	0.93	0.89	0.86	0.83	0.81	0.77
	6	1.11	1.0	0.91	0.86	0.83	0.80	0.77	0.72
	9+	1.13	1.0	0.90	0.84	0.80	0.77	0.74	0.69

Table 13-6—F_{th}: Thermal resistivity adjustment factor for 1001–35 000 V cables in duct banks with base ampacity given at an RHO of 90 °C-cm/W

Cable Size	Number of CKT	RHO (°C-cm/W)							
		60	90	120	140	160	180	200	250
#12–#1	1	1.03	1.0	0.97	0.95	0.93	0.91	0.90	0.88
	3	1.07	1.0	0.94	0.90	0.87	0.84	0.81	0.77
	6	1.09	1.0	0.92	0.87	0.84	0.80	0.77	0.72
	9+	1.10	1.0	0.91	0.85	0.81	0.77	0.74	0.69
1/0–4/0	1	1.04	1.0	0.96	0.94	0.92	0.90	0.88	0.85
	3	1.08	1.0	0.93	0.89	0.86	0.83	0.80	0.75
	6	1.10	1.0	0.91	0.86	0.82	0.79	0.77	0.71
	9+	1.11	1.0	0.90	0.84	0.80	0.76	0.73	0.68
250–1000	1	1.05	1.0	0.95	0.92	0.90	0.88	0.86	0.84
	3	1.09	1.0	0.92	0.88	0.85	0.82	0.79	0.74
	6	1.11	1.0	0.91	0.85	0.81	0.78	0.75	0.70
	9+	1.12	1.0	0.90	0.84	0.79	0.75	0.72	0.67

Table 13-7—F_{th}: Thermal resistivity adjustment factor for cables directly buried with base ampacity given at an RHO of 90 °C-cm/W

Cable Size	Number of CKT	RHO (°C-cm/W)							
		60	90	120	140	160	180	200	250
#12–#1	1	1.10	1.0	0.91	0.86	0.82	0.79	0.77	0.74
	2	1.13	1.0	0.90	0.85	0.81	0.77	0.74	0.70
	3+	1.14	1.0	0.89	0.84	0.79	0.75	0.72	0.67
1/0–4/0	1	1.13	1.0	0.91	0.86	0.81	0.78	0.75	0.71
	2	1.14	1.0	0.90	0.85	0.80	0.76	0.73	0.69
	3+	1.15	1.0	0.89	0.84	0.78	0.74	0.71	0.67
250–1000	1	1.14	1.0	0.90	0.85	0.81	0.78	0.75	0.71
	2	1.15	1.0	0.89	0.84	0.80	0.76	0.73	0.69
	3+	1.16	1.0	0.88	0.83	0.78	0.74	0.71	0.67

Typical values of thermal resistivity for various materials are as follows (see the NEC).

Material type	(°C-cm/W)
Solid paper insulation	700
Varnished cambric	600
Polyvinyl chloride (PVC)	650
Paper	550
Neoprene	519
Rubber, jute, textiles	500
Fiber duct	480
Polyethylene (PE)	450
Transite duct	200
Somastic	100
Concrete	55–85
Average soil	90
Very dry soil (rocky or sandy)	120
Damp soil (coastal areas, high water table)	60
EPR	400
Crosslinked polyethylene	370

The thermal resistivity of the soil depends on a number of factors, such as soil texture, moisture content, density, and structural arrangement of the soil grains. In general, higher density or moisture content of the soil results in a better heat dissipating ability and lower thermal resistivity. There is a tremendous variation in the soil thermal resistivities ranging from a RHO of less than 40 to more than 300 °C–cm/W. Based on these facts, it is apparent that direct testing of the soil is essential. Furthermore, it is important that this test be conducted after a prolonged dry spell at a peak summer temperature when the soil moisture content is minimal. The result of such a field test usually indicates a wide range of soil thermal resistance for a given depth over a test site. For the purpose of cable ampacity deratings, the maximum value of the thermal resistivities for a given cable route should be used.

The effect of soil dryout, which is caused by the continuous loading of the cables, can be taken into account by considering a RHO higher than the actual value obtained from the soil test. Use of dense sandy soil as backfill can lower the effective overall thermal resistivity and can offset the soil dryout effect. Dryout curves of RHO versus moisture content can be obtained to help select an appropriate value.

In cases where the soil thermal resistivity is very high and corrective backfill with low thermal resistivity is used, Tables 13-5 through 13-7 are inaccurate and may not produce cable ampacity values that are acceptable even on an approximate basis.

13.4.3 F_g (grouping adjustment factor)

Grouped cables will operate at a higher temperature than isolated cables. The increase in the operating temperature is due to the presence of the other cables in the group, which act as heat sources. Therefore, the amount of interference temperature rise from other cables in the group depends on the separation of the cables and the surrounding media.

In this subclause, adjustment factors for cables installed with maintained separation in underground duct banks and for directly buried cables are given in Tables 13-8 through 13-11. For cable separations other than those considered in these tables, one can use one's own judgment for estimating the value of F_g or use a computer program directly without an initial approximation for the grouping effect. In general, increasing the horizontal and vertical spacing between the cables would decrease the temperature interference between them and, therefore, increase the value of F_g.

Table 13-8—F_g: Grouping adjustment factor for 0–5000 V 3/C, or triplexed cables in duct banks (no spare ducts, nonmetallic conduits of 5 in with center-to-center spacing of 7.5 in)

Cable size	No. of rows	Number of columns														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
#8	1	1.00	.942	.885	.835	.795	.768	.745	.727	.710	.698	.688	.679	.671	.664	.658
	2	.930	.840	.772	.723	.687	.660	.638	.620	.604	.592	.582	.572	.564	.557	.550
	3	.870	.772	.694	.632	.596	.569	.548	.532	.519	.508	.498	.490	.482	.476	.470
	4	.820	.710	.629	.571	.536	.509	.490	.472	.458	.446	.436	.428	.420	.412	.405
#6	1	1.00	.930	.874	.826	.790	.760	.737	.718	.702	.690	.680	.671	.663	.656	.650
	2	.920	.813	.747	.700	.665	.638	.615	.598	.583	.572	.561	.552	.544	.537	.530
	3	.860	.747	.679	.625	,588	.560	.540	.525	.510	.498	.490	.481	.473	.467	.460
	4	.810	.700	.620	.565	.531	.503	.484	.467	.452	.440	.431	.422	.415	.408	.400
#4	1	1.00	.925	.871	.817	.781	.750	.726	.707	.691	.678	.668	.659	.651	.646	.640
	2	.920	.809	.742	.693	.659	.632	.610	.593	.579	.567	.555	.547	.539	.530	.525
	3	.850	.742	.668	.615	.578	.551	.531	.514	.500	.489	.480	.471	.464	.458	.450
	4	.805	.690	.610	.560	.524	.497	.477	.460	.447	.435	.425	.418	.410	.401	.395
#2	1	1.00	.918	.858	.808	.770	.741	.720	.701	.688	.677	.667	.658	.650	.641	.635
	2	.920	.800	.723	.680	.648	.623	.602	.586	.572	.560	.549	.540	.530	.522	.514
	3	.840	.723	.657	.608	.568	.540	.520	.504	.490	.479	.470	.461	.454	.447	.440
	4	.800	.685	.608	.553	.518	.490	.471	.453	.440	.429	.420	.411	.402	.395	.390
#1	1	1.00	.918	.849	.799	.753	.721	.699	.682	.669	.659	.650	.643	.639	.632	.630
	2	.920	.795	.702	.650	.613	.583	.563	.546	.530	.520	.510	.502	.494	.488	.482
	3	.830	.702	.618	.562	.525	.500	.480	.464	.450	.440	.430	.421	.413	.406	.400
	4	.740	.634	.551	.497	.465	.440	.421	.405	.392	.383	.374	.366	.359	.352	.348
1/0	1	1.00	.910	.842	.791	.745	.716	.694	.678	.665	.655	.646	.639	.635	.628	.626
	2	.915	.790	.700	.642	.604	.575	.555	.537	.523	.511	.503	.494	.486	.480	.475
	3	.817	.700	.610	.554	.520	.494	.474	.457	.444	.432	.424	.415	.408	.400	.394
	4	.735	.629	.546	.492	.460	.435	.417	.402	.391	.381	.371	.363	.355	.349	.343
2/0	1	1.00	.910	.842.	.791	.745	.716	.694	.678	.665	.655	.646	.639	,635	.628	.626
	2	.915	.790	700	.642	.604	.575	.555	.537	.523	.511	.503	.494	.486	.480	.475
	3	.817	.700	.610	.554	.520	.494	.474	.457	.444	.432	.424	.415	.408	.400	.394
	4	.735	.629	.546	.492	.460	.435	.417	.402	.391	.381	.371	.363	.355	.349	.343
3/0	1	1.00	.910	.842	.791	.745	.716	.694	.678	.665	.655	.646	.639	.635	.628	.626
	2	.915	.790	.700	.642	.604	.575	.555	.537	.523	.511	.503	.494	.486	.480	.475
	3	.817	.700	.610	.554	.520	.494	.474	.457	.444	.432	.424	.415	.408	.400	.394
	4	.735	.629	.546	.492	.460	.435	.417	.402	.391	.381	.371	.363	.355	.349	.343
4/0	1	1.00	.908	.830	.780	.737	.709	.690	.673	.660	.650	.642	.635	.628	.623	.619
	2	.910	.770	.684	.635	.599	.570	.550	.532	.518	.506	.498	.489	.481	.475	.470
	3	.810	.684	.602	.548	.515	.489	.469	.452	.440	.429	.420	.411	.403	.397	.391
	4	.730	.624	.541	.487	.456	.431	.414	.399	.388	.378	.368	.360	.352	.346	.341
250	1	1.00	.905	.830	.777	.725	.692	.668	.646	.628	.615	.603	.597	.590	.583	.580
	2	.890	.770	.675	.609	.570	.542	.519	.500	.485	.474	.466	.458	.450	.445	.440
	3	.780	.675	.579	.518	.480	.454	.434	.420	.408	.398	.390	.383	.378	.373	.370
	4	.694	.588	.512	.460	.422	.397	.379	.364	.352	.345	.338	.331	.327	.323	.320

Table 13-8—F_g: Grouping adjustment factor for 0–5000 V 3/C, or triplexed cables in duct banks (no spare ducts, nonmetallic conduits of 5 in with center-to-center spacing of 7.5 in) (*Continued*)

Cable size	No. of rows	Number of columns														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
350	1	1.00	.905	.830	.770	.720	.688	.661	.640	.622	.608	.597	.590	.583	.578	.573
	2	.887	.749	.664	.609	.570	.540	.518	.499	.484	.474	.465	.458	.450	.445	.440
	3	.775	.664	.575	.515	.479	.453	.433	.419	.406	.397	.389	.382	.377	.372	.369
	4	.690	.587	.511	.457	.421	.395	.377	.362	.351	.343	.336	.330	.325	.321	.318
500	1	1.00	.897	.815	.762	.708	.678	.652	.630	.613	.599	.588	.581	.575	.570	.565
	2	.882	.745	.656	.608	.569	.539	.516	.498	.483	.473	.463	.457	.450	.444	.439
	3	.770	.656	.570	.514	.478	.452	.432	.417	.404	.395	.388	.381	375	.370	.367
	4	.685	.585	510	.454	.420	.393	.374	.360	.349	.340	.333	.328	.323	.319	.315
750	1	1.00	.890	.802	.747	.700	.670	.640	.622	.605	.590	.580	.572	.566	.560	.555
	2	.870	.725	.641	.591	.552	.522	.500	.484	.469	.457	.448	.440	.434	.430	.425
	3	.760	.641	.560	.507	.470	.445	.425	.410	.398	.389	.380	.374	.369	.363	.360
	4	.680	.579	.501	.448	.413	.389	.371	.357	.346	.337	.330	.323	.318	.314	.310
1000	1	1.00	.885	.795	.740	.695	.665	.639	.618	.600	.585	.574	.567	.561	.555	.551
	2	.858	.716	.632	.582	.544	.513	.493	.474	.460	.448	.439	.431	.425	.420	.415
	3	.748	.632	.551	.499	.464	.439	.419	.403	.392	.383	.375	.369	.363	.358	.355
	4	.676	.574	.497	.444	.409	.385	.367	.353	.342	.333	.326	.319	.315	.311	.308

Table 13-9—F_g: Grouping adjustment factor for 5001–35 000 V 3/C, or triplexed cables in duct banks (no spare ducts, nonmetallic conduits of 5 in with center-to-center spacing of 7.5 in)

Cable size	No. of rows	Number of columns														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
#6	1	1.00	.920	.854	.803	.758	.726	.699	.678	.660	.646	.635	.628	.620	.615	.610
	2	.920	.800	.714	.660	.620	.590	.570	.552	.540	.530	.521	.515	.509	.503	.500
	3	.840	.714	.625	.569	.530	.501	.484	.470	.459	.450	.442	.436	.429	.423	.420
	4	.770	.642	560	.506	.469	.441	.422	.406	.394	.385	.378	.371	.367	.362	.358
#4	1	1.00	.920	.852	.800	.755	.722	.695	.673	.655	.642	.630	.623	.615	.610	.605
	2	.920	.795	.714	.660	.620	.590	.570	.552	.540	.530	.521	.515	.434	.430	.425
	3	.835	.709	.615	.561	.521	.493	.474	.459	.488	.439	.430	.424	.420	.416	.412
	4	.760	.630	.548	.498	.460	.430	.410	.395	.382	.374	.367	.361	.356	.352	.350
#2	1	1.00	.910	.836	.784	.748	.714	.688	.665	.649	.635	.625	.616	.609	.602	.598
	2	.920	.782	.689	.639	.599	.570	.548	.531	.518	.508	.500	.494	.489	.484	.480
	3	.820	.689	.600	.544	.505	.479	.460	.445	.433	.424	.417	.410	.405	.400	.395
	4	.746	.622	.539	.484	.445	.415	.396	.382	.370	361	.353	.348	.342	.338	.334
#1	1	1.00	.905	.827	.777	.731	.697	.670	.645	.626	.610	.598	.588	.579	.571	.565
	2	.920	.771	.681	.629	.590	.560	.538	.519	.502	.491	.480	.471	.462	.455	.450
	3	.816	.681	.588	.532	.497	.469	.448	.432	.418	.407	.397	.389	.382	.376	.370
	4	.785	.605	.524	.471	.435	.410	.390	.376	.364	.353	.347	.340	.333	.328	.323
1/0	1	1.00	.904	.825	.775	.729	.695	.668	.643	.624	.609	.597	.587	.578	.570	.564
	2	.912	.765	.671	.619	.580	.549	.527	.509	.494	.481	.471	.462	.453	.446	.440
	3	.811	.671	.581	.525	.488	.460	.440	.423	.409	.398	.387	.379	.372	.365	.359
	4	.730	.604	.518	.464	.431	.406	.385	.372	.359	.349	.341	.335	.329	.324	.320

Table 13-9—F_g: Grouping adjustment factor for 5001–35 000 V 3/C, or triplexed cables in duct banks (no spare ducts, nonmetallic conduits of 5 in with center-to-center spacing of 7.5 in) (*Continued*)

Cable size	No. of rows	Number of columns														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2/0	1	1.00	.904	.823	.773	.728	.694	.668	.643	.624	.609	.580	.597	.587	.578	.570
	2	.903	.761	.667	.612	.573	.542	.520	.500	.488	.475	.463	.455	.448	.441	.434
	3	.800	.667	.578.	.520	.482	.454.	.433	.418	.402	.391	.382	.374	.367	.360	.353
	4	.722	.597	511	.460	.425	400	.380	.365	.353	.343	.335	.329	.322	.317	.312
3/0	1	1.00	.898	.814	.765	.722	.690	.661	.637	.618	.602	.590	.580	.571	.563	.556
	2	.898	.752	.664	.609	.570	.539	.451	.498	.483	.471	.461	.451	.443	.437	.429
	3	.802	.664	.572	.514	.479	.451	.430	.414	.399	.388	.379	.371	.364	.357	.350
	4	.720	.593	.508	.456	.421	.396	.377	.362	.350	.340	.332	.327	.320	.314	.310
4/0	1	1.00	.894	.811	.762	.717	.682	.653	.631	.612	.597	.585	.574	.566	.558	.550
	2	.896	.743	.656	.603	.565	.536	.513	.496	.480	.468	.459	.449	.441	.434	.427
	3	.795	.656	.564	.513	.474	.447	.427	.411	.397	.386	.377	.369	.362	.355	.349
	4	.711	.584	.502	.450	.417	.392	.374	.359	.348	.338	.329	.324	.317	.311	.307
250	1	1.00	.892	.811	.762	.715	.679	.645	.620	.600	.583	.572	.564	.557	.552	.550
	2	.885	.741	.654	.594	.552	.523	.500	.482	.469	.457	.447	.438	.430	.422	.416
	3	.785	.654	.559	.498	.459	.429	.408	.388	.373	.361	.351	.342	.335	.328	.321
	4	.701	.580	.500	.448	.414	.385	.365	.348	.332	.321	.311	.302	.295	.288	.281
350	1	1.00	.890	.807	.754	.700	.661	.634	.609	.589	.572	.561	.552	.548	.542	.540
	2	.872	.733	.641	.580	.538	.510	.488	.470	.455	.443	.432	.423	.415	.408	.400
	3	.772	.641	.550	.492	.451	.420	.396	.377	.362	.350	.340	.331	.323	.316	.310
	4	.681	.572	.491	.440	.402	.375	.354	.337	.322	.311	.300	.292	.285	.278	.271
500	1	1.00	.885	.801	.745	.692	.650	.620	.593	.573	.559	.548	.539	.533	.529	.526
	2	.862	.728	.634	.572	.531	.502	.480	.462	.447	.435	.425	.415	.407	.400	.391
	3	.765	.634	.542	.483	.446	.415	.391	.373	.358	.346	.335	.327	.319	.311	.305
	4	.676	.574	.497	.444	.409	.385	.367	.353	.342	.333	.326	.319	.315	.311	.308
750	1	1.00	.879	.790	.780	.682	.647	.615	.589	.570	.556	.545	.536	.530	.524	.520
	2	.850	.710	.622	.560	.520	.490	.469	.450	.436	.424	.412	.402	.394	.388	.381
	3	.755	.622	.530	.479	.441	.410	.387	.368	.352	.341	.331	.322	.314	.307	.300
	4	.671	.560	.480	.430	.392	.366	.345	.328	.314	.302	.292	.284	.277	.270	.263
1000	1	1.00	.873	.786	.730	.680	.642	.609	.582	.562	.548	.537	.528	.521	.516	.512
	2	.844	.705	.614	.554	.514	.485	.463	.445	.430	.418	.406	.397	.390	.383	.376
	3	.745	.614	.523	.472	.434	.403	.381	.363	.348	.337	.327	.318	.309	.301	.294
	4	.663	.552	.473	.422	.385	.359	.338	.321	.307	.295	.285	.278	.270	.263	.256

Table 13-10—F_g: Grouping adjustment factor for directly buried 3/C, or triplexed cables (7.5 in horizontal and 10 in center-to-center vertical spacing)

Number of layers	Number of horizontal cables						
	1	2	3	4	6	9	12
1	1.0	0.82	0.70	0.63	0.56	0.51	0.49
2	0.81	0.62	0.53	0.48	0.41	—	—

Table 13-11—F_g: Grouping adjustment factor for directly buried 1/C, or triplexed cables (7.5 in horizontal and 10 in center-to-center vertical spacing)

Number of layers	Number of horizontal cables			
	3	6	9	12
1	1.0	0.79	0.71	0.68
2	0.73	0.58	—	—

Based on the computer studies for duct bank installations, it was found that the size and voltage rating of the cables make a noticeable difference in the value of F_g. Therefore, the adjustment factors for cable groupings are tabulated as functions of cable sizes and voltage ratings. For applications where a mixed group of cables are installed in a duct bank, the value of F_g will be different for each cable size. In this case, it is recommended that cable ampacities be determined as the location of the cables is progressively changed from the worst (hottest) conduit locations and the best (coolest) conduit locations to establish the most economical arrangement.

Note that no grouping adjustment factor is given for cables installed in air or in conduits in air. Refer to the NEC and IEEE Std 835-1994 for the allowable ampacities of cable installed in conduits in air.

13.5 Example

To illustrate the use of the method described in this chapter, a 3 × 5 duct bank system (3 rows, 5 columns) is considered. The duct bank contains 350 kcmil and 500 kcmil (15 kV, 3/C) copper cables. Ducts are a diameter of 5 in (trade size) of PVC, and are separated by 7.5 in (center-to-center spacing), as shown in Figure 13-3. The soil thermal resistivity (RHO) is 120 °C-cm/W, and the maximum soil ambient temperature is 30 °C.

The objective of this example is to determine the maximum ampacities of the cables under the specified conditions of use, i.e., to limit the conductor temperature of the hottest location to 75 °C (an NEC requirement for wet locations). To achieve this, the base ampacities of the cables are found first. These ampacities are then derated using the adjustment factors. The computer program is then used to verify the derated ampacities by calculating the actual conductor temperatures.

The depth of the duct bank is set at 30 in for this example. For average values of soil thermal resistivity, the depth can be varied by approximately ±10% without drastically affecting the resulting ampacities. However, larger variations in the bank depth, or larger soil thermal resistivities, may significantly affect ampacities.

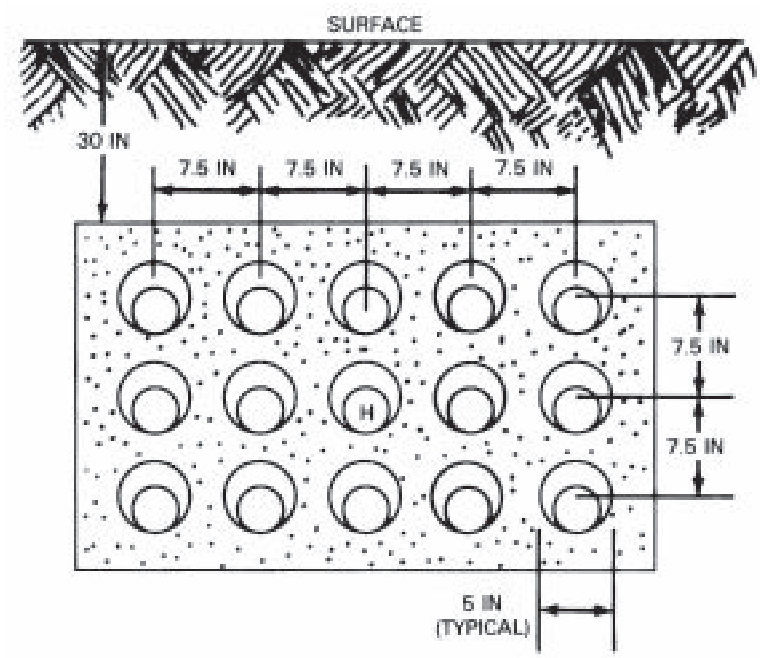

Figure 13-3—3 × 5 duct bank arrangement

13.5.1 Base ampacities

From the NEC ampacity tables, the base ampacities of 15 kV three-conductor cables under an isolated condition and based on a conductor temperature of 90 °C, ambient soil temperature of 20 °C, and thermal resistivity (RHO) of 90 °C-cm/W are as follows:

I = 375 A (350 kcmil)

I = 450 A (500 kcmil)

13.5.2 Manual method

The required ampacity adjustment factors for the ambient and conductor temperatures, thermal resistivity, and grouping are as follows:

F_t = 0.82 for adjustment in the ambient temperature from 20–30 °C and conductor temperature from 90–75 °C (see Table 13-4).

F_{th} = 0.90 for adjustment in the thermal resistivity from a RHO of 90–120 °C–cm/W (see Table 13-6).

F_g = 0.479 for grouping adjustment of 15 kV, 3/C 350 kcmil cables installed in a 3 × 5 duct bank (see Table 13-8).

F_g = 0.478 for grouping adjustment of 15 kV, 3/C 500 kcmil cables installed in a 3 × 5 duct bank (see Table 13-8).

The overall cable adjustment factors are:

$F = 0.82 \times 0.90 \times 0.479 = 0.354$ (350 kcmil cables)

$F = 0.82 \times 0.90 \times 0.478 = 0.353$ (500 kcmil cables)

The maximum allowable ampacity of each cable size is the multiplication product of the cable base ampacity by the overall adjustment factor. This ampacity adjustment would limit the temperature of the hottest conductor to 75 °C when all of the cables in the duct bank are loaded at 100% of their derated ampacities.

$I' = 375 \times 0.354 = 133$ A (350 kcmil cables)

$I' = 450 \times 0.353 = 159$ A (500 kcmil cables)

13.5.3 Computer method

As the last step, a computer program is run to simulate the actual conductor temperature using the ampacities determined by the manual method. The computer program used here is the same program that was used to generate the ampacity adjustment factors. The output report of the program is shown in Figure 13-4, where (a) indicates all input parameters and (b) indicates conduit locations and conductor temperatures.

The objective for this design was to find the cable ampacities that would limit the conductor temperature to 75 °C. The results of the computer study indicate that the hottest conductor is located in the middle row (2) and middle column (3) with a temperature of 74.3 °C. The ampacities obtained from the manual method for this simplified example case exactly agree with the ampacities obtained by the computer calculations. In more general cases, however, where the assumptions listed in 13.4 do not apply, computer calculation would be necessary to establish final ampacities

Project:	**Example**	**Page:**	**1**
Location:	**Irvine, California**	**Date:**	**09-01-1989**
Contract:	**1234567**	**Study:**	**SC-100**
Engineer:	**F. S.**		

Cable ampacity derating example—3 × 5 duct bank application

Cable size	No. of cond.	Volt (kV)	Type	DC resistance (μΩ/ft)	O.D. (in)	Insul. thermal R (Ω/ft)	Dielec-tric losses (W/ft)	Y_c	Y_s
500	3	15	CU	21.60	2.590	1.430	0.056	0.018	0.000
350	3	15	CU	30.80	2.290	1.564	0.048	0.009	0.000

Instal-lation	Conduit type	No. of rows	No. of cols.	Ref . depth (in)	Height (in)	Width (in)	RHO		Ambient temp. °C
							Soil	Fill	
Duct bank	PVC	3	5	30.0	27.0	42.0	120.0	90.0	30.0

Row	Col.	Horiz. dist. (in)	Vert. dist. (in)	Load current (A)	Cable					Conduit (in)	
					No.	C/C	Size	kV	Type	Size	Thick-ness
1	1	6.00	6.00	159.0	1	3	500	15	CU	5.040	0.260
2	1	6.00	13.50	159.0	1	3	500	15	CU	5.040	0.260
3	1	6.00	21.00	159.0	1	3	500	15	CU	5.040	0.260
1	2	13.50	6.00	159.0	1	3	500	15	CU	5.040	0.260
2	2	13.50	13.50	159.0	1	3	500	15	CU	5.040	0.260
3	2	13.50	21.00	159.0	1	3	500	15	CU	5.040	0.260
1	3	21.00	6.00	133.0	1	3	350	15	CU	5.040	0.260
2	3	21.00	13.50	133.0	1	3	350	15	CU	5.040	0.260
3	3	21.00	21.00	133.0	1	3	350	15	CU	5.040	0.260
1	4	28.50	6.0	133.0	1	3	350	15	CU	5.040	0.260
2	4	28.50	13.50	133.0	1	3	350	15	CU	5.040	0.260
3	4	28.50	21.00	133.0	1	3	350	15	CU	5.040	0.260
1	5	37.00	6.00	133.0	1	3	350	15	CU	5.040	0.260
2	5	37.00	13.50	133.0	1	3	350	15	CU	5.040	0.260
3	5	37.00	21.00	133.0	1	3	350	15	CU	5.040	0.260

(a) Input parameters

Figure 13-4—Computer program output report for cable ampacity derating

Project:	**Example**				**Page:**	**2**
Location:	**Irvine, California**				**Date:**	**09-01-1989**
Contract:	**1234567**				**Study:**	**SC-100**
Engineer:	**F. S.**					
	Cable ampacity derating example—3 × 5 duct bank application					
	Columns	**1**	**2**	**3**	**4**	**5**
Row 1	Cable:	500	500	350	350	350
	Amp:	159.0	159.0	133.0	133.0	133.0
	Temp:	66.8	69.7	70.9	69.9	66.6
Row 2	Cable:	500	500	350	350	350
	Amp:	159.0	159.0	133.0	133.0	133.0
	Temp:	69.7	73.0	74.3	73.1	69.3
Row 3	Cable:	500	500	350	350	350
	Amp:	159.0	159.0	133.0	133.0	133.0
	Temp:	69.3	72.3	73.5	72.4	69.0

(b) Conduit locations and conductor temperatures

Figure 13-4—Computer program output report for cable ampacity derating (*Continued*)

13.6 Conclusion

Analytical derating of cable ampacity is a complex and tedious process. A manual method was developed in this chapter that uses adjustment factors to simplify cable derating for some very specific conditions of use and produce close approximations to actual ampacities. The results from the manual method can then be entered as the initial ampacities for input into a cable ampacity computer program. The speed of the computer allows the program to use a more complex model, which considers factors specific to a particular installation and can iteratively adjust the conductor resistances as a function of temperature. The following is a list of factors that are specific for the cable system:

- — Conduit type
- — Conduit wall thickness
- — Conduit inside diameter
- — Asymmetrical spacing of cables or conduits
- — Conductor load currents and load cycles
- — Height, width, and depth of duct bank
- — Thermal resistivity of backfill and/or duct bank
- — Thermal resistance of cable insulation
- — Dielectric losses of cable insulation
- — AC/DC ratio of conductor resistance

The results from the computer program should be compared with the initial ampacities found by the manual process to determine whether corrective measures, i.e., changes in cable sizes, duct rearrangement, etc., are required. Many computer programs alternatively calculate cable temperatures for a given ampere loading or cable ampacities at a given temperature. Some recently developed computer programs perform the entire process to size the cables automatically. To find an optimal design, the cable ampacity computer program simulates many different cable arrangements and loading conditions, including future load expansion requirements. This optimization is important in the initial stages of cable system design since changes to cable systems are costly, especially for underground installations. Additionally, the downtime required to correct a faulty cable design may be very long.

13.7 References

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NFPA 70-1996, National Electrical Code® (NEC®).[4]

13.8 Bibliography

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[B2] *National Electrical Code Committee Repor*t, 1980 Annual Meeting.

[B3] *National Electrical Code Committee Report*, 1986 Annual Meeting.

[B4] *National Electrical Code Committee Report*, 1989 Annual Meeting.

[B5] *National Electrical Code Technical Committee Documentation*, 1980 Annual Meeting.

[B6] *National Electrical Code Technical Committee Documentation*, 1983 Annual Meeting.

[B7] *National Electrical Code Technical Committee Documentation*, 1986 Annual Meeting.

[B8] *National Electrical Code Technical Committee Documentation*, 1989 Annual Meeting.

[B9] *National Electrical Code Technical Committee Report*, 1983 Annual Meeting.

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[3]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[4]The NEC is available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA. It is also available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[B11] NEMA Subcommittee Final Report, *Determination of Maximum Permissible Current Carrying Capacity of Code Insulated Wires and Cable for Building Purposes, Part IV*.[5]

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[B16] Simmons, D. M., "Calculation of the Electrical Problems of Underground Cables," *The Electric Journal*, East Pittsburgh, PA, May–Nov. 1932.

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[5]NEMA publications are available from the National Electrical Manufacturers Association, 1300 N. 17th St., Ste. 1847, Rosslyn, VA 22209, USA.