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Practical Power Cable Ampacity Analysis

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Introduction

Cable network usually forms a backbone of the power system. Therefore, complete analysis of the power systems includes detailed analyses of the cable network, especially assessment of the cable ampacities. This assessment is necessary since cable current carrying capacity can depend on the number of factors that are predominantly determined by actual conditions of use. Cable current carrying capability 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 limit.”

Therefore, a cable current carrying capacity assessment is the calculation of the temperature increment of the conductors in an underground cable system under steady-state loading conditions.

The aim of this course is to acquaint the reader with basic numerical methods and methodology that is used in cable current sizing and calculations. Also use of computer software systems in the solution of cable ampacity problems with emphasis on underground installations is elaborated.

The ability of an underground cable conductor to conduct current depends on a number of factors. The most important factors of the utmost concern to the designers of electrical transmission and distribution systems are the following:

- Thermal details of the surrounding medium
- Ambient temperature
- Heat generated by adjacent conductors
- Heat generated by the conductor due to its own losses

Methodology for calculation of the cable ampacities is described in the National Electrical Code (NEC[®]) which uses Neher-McGrath method for the calculation of the conductor ampacities. Conductor ampacity is presented in the tables along with factors that are applicable for different laying formations. An alternative approach to the one

presented in the NEC[®] is the use of equations for determining cable current carrying rating. This approach is described in NFPA 70-1996.

Underground cable current capacity rating depends on various factors and they are quantified through coefficients presented in the factor tables. These factors are generated using Neher-McGrath method. Since the ampacity tables were developed for some specific site conditions, they cannot be uniformly applied for all possible cases, making problem of cable ampacity calculation even more challenging. In principle, factor tables can be used to initially size the cable and to provide close and approximate ampacities. However, the final cable ampacity may be different from the value obtained using coefficients from the factor tables. These preliminary cable sizes can be further used as a basis for more accurate assessment that will take into account very specific details such as soil temperature distribution, final cable arrangement, transposition, etc.

Assessment of the Heat Flow in the Underground Cable Systems

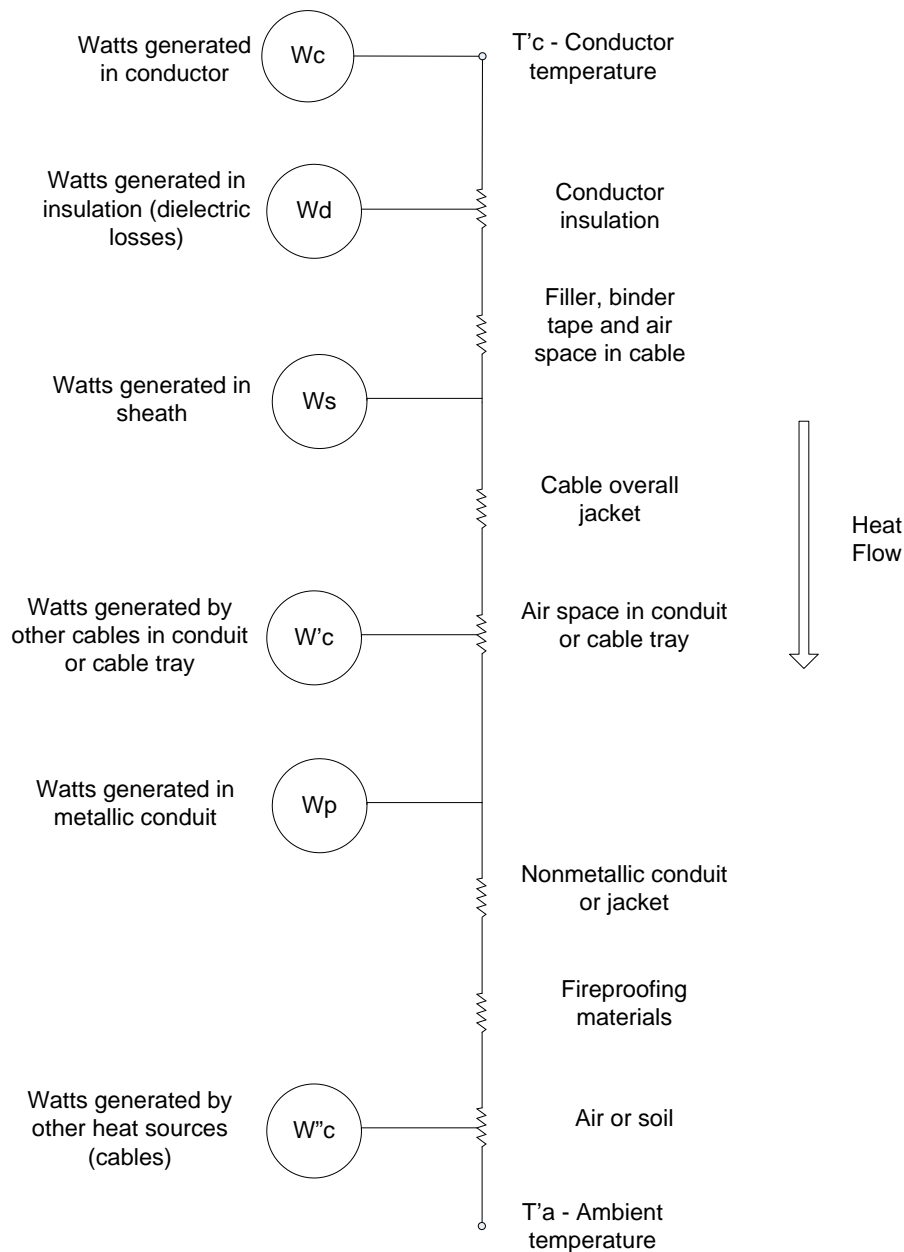
Underground cable sizing is one of the most important concerns when designing distribution and transmission systems. Once the load has been sized and confirmed, the cable system must be designed in a way to transfer the required power from the generation to the end user. The total number of underground cable circuits, their size, the method of laying, crossing with other utilities such as roads, telecommunication, gas, or water network are of crucial importance when determining design of the cable systems. In addition, underground cable circuits must be sized adequately to carry the required load without overheating.

Heat is released from the conductor as it transmits electrical current. Cable type, its construction details and installation method determine how many elements of heat generation exist. These elements can be Joule losses (I^2R losses), sheath losses, etc. Heat that is generated in these elements is transmitted through a series of thermal resistances to the surrounding environment.

Cable operating temperature is directly related to the amount of heat generated and the value of the thermal resistances through which it flows. Basic heat transfer principles are discussed in subsequent sections but a detailed discussion of all the

heat transfer particulars is well beyond the scope of this course.

Calculation of the temperature rise of the underground cable system consists of a series of thermal equivalents derived using Kirchoff's and Ohm's rules resulting in a relatively simple thermal circuit that is presented in the figure below.



Equivalent thermal circuit involves a number of parallel paths with heat entering at several different points. From the figure above, it can be noted that the final conductor temperature will be determined by the differential across the series of thermal resistances as the heat flows to the ambient temperature, T'_a .

The fundamental equation for determining ampacity of the cable systems in an underground duct follows the Neher-McGrath method and can be expressed as:

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

where,

T'_c is the allowable (maximum) conductor temperature (°C),

T'_a is ambient temperature of the soil (°C),

ΔT_d is the temperature rise of conductor caused by dielectric heating (°C),

ΔT_{int} is the temperature rise of conductor due to interference heating from cables in other ducts (°C), (Note: simulations calculation of ampacity equations are required since the temperature rise, due to another conductor depends on the current through it.)

R_{ac} is the AC current resistance of the conductor and includes skin, AC proximity and temperature effects ($\mu\Omega$ /ft), and

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

All effects that cause underground cable conductor temperature rise, except the conductor losses $I^2 R_{ac}$, are considered as adjustment to the basic thermal system.

In principle, the heat flow in watts is determined by the difference between two temperatures ($T'_c - T'_a$) which is divided by a separating thermal resistances. Analogy between this method and the basic equation for ampacity calculation can be made if both sides of the ampacity equation are squared and then multiplied by R_{ac} . The result is as follows:

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

Even though understanding of the heat transfer concepts is not a prerequisite for calculation of the underground cable ampacities using computer programs, this knowledge and understanding can be helpful for understanding how real physical

parameters affect cable current carrying capability. From the ampacity equation, it can be concluded how lower ampacities are constitutional with the following:

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

Factors that also reduce underground cable ampacity, but whose correlation to the cable ampacity equation is not apparent, are:

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

Use of Computer Programs for Calculation of Underground Cable Ampacity

Software programs usually use Neher-McGrath method for the calculation of the cable ampacity. They consider only temperature-limited, current-carrying capacity of cables. Calculation of the cable ampacity considers only power cables since control cables transmit very little current that has negligible effect to the overall temperature rise. Other important factors that need to be considered when selecting power cables are voltage drop, short circuit capability and future load growth.

Calculation of the underground cable ampacity is very complex process that requires analysis of multitude of different effects. In order to make calculations possible for a wide variety of cases, assumptions are made. Majority of these assumptions are developed by Neher and McGrath and they are widely accepted. There are also computer programs that base their assumptions on different methods but those are separately explained.

Basic steps that cable ampacity software tools use are discussed below. Described methodological procedure needs to be followed in order to obtain good and accurate results.

1. The very first step that needs to be taken when designing an underground cable system is to define which circuits need to be routed through the duct bank. Attention needs to be paid to existing circuits as well as future circuits that may be additionally installed. Only power cables need to be considered in this assessment but space needs to be allowed for spare ducts or for control and instrumentation cables.

2. The cable duct needs to be designed considering connected circuits, cable conductor axial separation, space available for the bank and factors that affect cable ampacity. For example, power cables that are installed in the vicinity of other power cables that are deeply buried, often have greatly reduced current carrying capacity. Also a decision regarding burying ducts or encasing them in the concrete need to be made. Also the size and type of ducts that need to be used should be decided. Lastly, a schematic drawing of the duct bank needs to be prepared indicating burial depths and axial spacing between cable conductors. Physical information of the duct installation need to be compiled including thermal resistivity of the soil and concrete as well as ambient temperature of the soil. It is important to note that soil thermal resistivity and temperature at specific areas (e.g., desert, frequently flooded areas) may be higher than the typical values that are normally used.

3. Overall installation information about power cables need to be collected and collated. Some basic information can be taken from the predefined tables but certain data needs to be obtained from manufacturer's specifications. Construction and operational parameters that include conductor size, operating voltage, conductor material, temperature rating, type of shield or sheath, jacket type and insulation type are need to be specified and considered.

4. Preliminary cable arrangement needs to be made based on predicted loads and load diversity factors. Circuits that are expected to transfer high current and those having high load factors should be positioned in outside ducts near the top of the bank to avoid use of larger conductors due to unnecessarily reduced ampacity. Normally, a

good compromise between the best use of duct space and greatest ampacity is achieved by installing each three-phase circuit in a separate duct. However, single-conductor cables without shield may have greater current carrying capacity if each phase conductor is installed in a separate non-metallic duct. In the case that the load factor is not known, a conservative value of 100% can be used, meaning that the circuit will always operate at peak load.

5. Presented steps can be used to initially size power cables based on the input factors such as soil thermal resistivity, cable grouping and ambient temperature. As soon as initial design is made, it can be further tuned and verified by entering the program data interactively into the computer software or preparing the batch program. Information that will be used for cable current carrying calculations need to consider the worst case scenario. If load currents are known, they can be used to find the temperatures of cables within each duct. Calculations of the temperature are particularly useful if certain circuits are lightly loaded, while the remaining circuits are heavily loaded and push ampacity limits. The load capacity of the greatly loaded cables would be decreased further if the lightly loaded cables were about to operate at a rated temperature, as the underground cable ampacity calculation normally assumes. Calculations of the temperature can be used as a rough indicator of the reserve capacity of each duct.

6. After running a program, results need to be carefully analyzed to check if design currents are less than ampacities or that calculated temperatures are less than rated temperatures. If obtained results indicate that initially considered design cannot be applied and used, various mitigation measures need to be considered. These measures include increasing conductor cross section, changing cable location and buying method or changing the physical design of the bank. Changing these parameters and observing their influence on the overall design can be done and repeated until an optimised design is achieved.

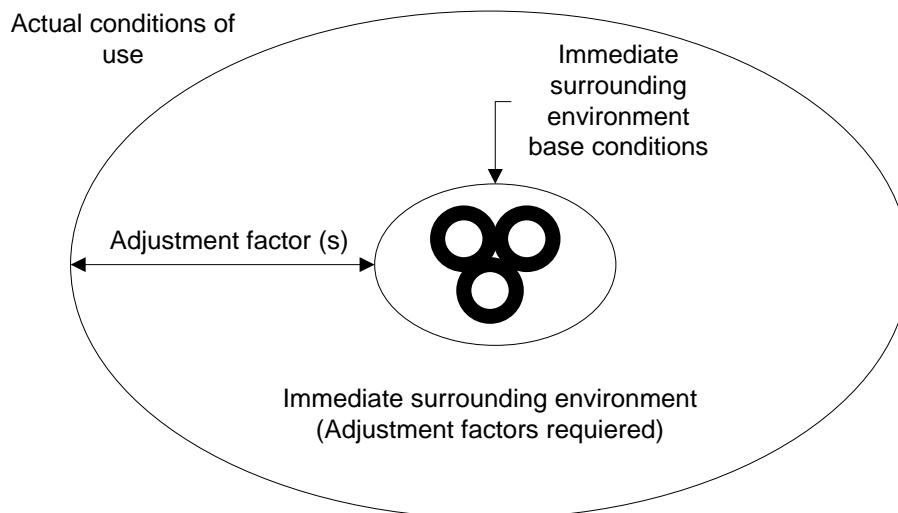
7. The conclusions of this assessment need to be filed and archived for use in controlling future modifications in duct bank usage (e.g., installation of cables in the remaining ducts).

Adjustment Factors for Cable Current Carrying Calculations

Underground cable ampacity values provided by cable manufacturers or relevant standards such as the NEC and IEEE Std 835-1994, are frequently based on specific laying conditions that were considered as important relative to the cable's immediate surrounding environment. Site specific conditions can include the following:

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

Usually, conditions in which the cable was installed do not match with those for which ampacities were calculated. This difference can be treated as a medium that is inserted between the base conditions (conditions that were used for calculation by the manufacturer or relevant institutions) and actual site conditions. This approach is presented in the figure below.



In principle, specified (base) ampacities need to be adjusted by using corrective factors to take into account the effect of the various conditions of use. A method for the calculation of cable ampacities illustrates the concept of cable derating and presents corrective factors that have effects on cable operating temperatures and hence cable conductor current capacities. In essence, this method uses derating corrective factors against base ampacity to provide ampacity relevant to site

conditions. This concept can be summarized as follows:

$$I' = F \cdot I$$

where,

I' is the current carrying capacity under the actual site conditions,

F is the total cable ampacity correction factor, and

I is the base current carrying capacity which is usually determined by the manufacturers or relevant industry standards.

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 total cable ampacity correction factor is made up of several components and can be expressed as:

$$F = F_t \cdot F_{th} \cdot F_g$$

where,

F_t is the correction factor that accounts for conductor temperature differences between the base case and actual site conditions,

F_{th} is the correction factor that accounts for the difference in the soil thermal resistivity, from the 90 °C–cm/W at which the base ampacities are specified to the actual soil thermal resistivity, and

F_g - is the correction factor that accounts for cable derating due to cable grouping.

Computer software based on Neher-McGrath method was developed to calculate correction factors F_{th} and F_g . It is used to calculate conductor temperatures for various installation conditions. This procedure considers each correction factor and together account for the overall derating effects.

The aforementioned correction factors are almost completely independent from each other. Even though specific software can simulate various configurations, the tables

presenting correction factors are based on the following simplified assumptions:

- Voltage ratings and cable sizes are used to combine cables for the tables presenting F_{th} factors. For specific applications in which RHO is considerably high and mixed group of cables are installed, correlation between correction factors cannot be neglected and error can be expected when calculating the overall conductor temperatures.
- Effect of the temperature rise due to the insulation dielectric losses is not considered for the temperature adjustment factor F_t . Temperature rise for polyethylene insulated cables rated below 15 kV is less than 2°C. If needed, this effect can be considered in F_t by adding the temperature rise due to the dielectric losses to the ambient temperatures T and T'_a .

In situations when high calculation accuracy is needed, previously listed assumptions cannot be neglected. However, cable current carrying capacity obtained using manual methods can be used as a starting approximation for complex computer solutions that can provide actual results based on the real design and cable laying conditions.

Ambient and Conductor Temperature Adjustment Factor (F_t)

Then ambient and conductor temperature adjustment factor is used to assess the underground cable ampacity in the case when the cable ambient operating temperature and the maximum permissible conductor temperature are different from the basic, starting temperature at which the cable base ampacity is defined. The equations for calculating changes in the conductor and ambient temperatures on the base cable ampacity are:

$$F_t = \left[\frac{T'_c - T'_a}{T_c - T_a} \times \frac{234.5 + T_c}{234.5 + T'_c} \right]^{1/2} \text{ - Copper}$$

$$F_t = \left[\frac{T'_c - T'_a}{T_c - T_a} \times \frac{228.1 + T_c}{228.1 + T'_c} \right]^{1/2} \text{ - Aluminium}$$

where,

T_c is the rated temperature of the conductor in °C at which the base cable rating is

specified,

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

T_a is the temperature of the ambient temperature in °C at which the base cable rating is defined, and

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

It is very difficult to estimate the maximum ambient temperature since it has to be determined based on historic data. For installation of underground cables, T'_a is the maximum soil temperature during summer at the depth at which the cable is buried. Generally, seasonal variations of the soil temperature follow sinusoidal pattern with the temperature of the soil reaching peak temperatures during summer months. The effect of seasonal soil temperature variation decreases with depth. Once a depth of 30 feet is reached, the soil temperature remains relatively constant.

Soil characteristics such as density, texture and moisture content as well as soil pavement (asphalt, cement) have considerable impact on the temperature of the soil. In order to achieve maximum accuracy, it is preferable to obtain T_a via field tests and measurements instead of using approximations that are based on the maximum atmospheric temperature.

For cable circuits that are installed in air, T_a is the maximum air temperature during summer peak. Due care needs to be taken for cable installations in shade or under direct sunlight.

Typical F_t adjustment factors for conductor temperatures ($T = 90^\circ\text{C}$ and 75°C) and temperatures of the ambient ($T = 20^\circ\text{C}$ for underground installation and 40°C for above-ground installation) are summarized in the tables below.

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 1. F_t factor for various copper conductors (ambient temp. $T_c = 75^\circ\text{C}$ and $T_a = 40^\circ\text{C}$)

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 2. Ft factor for various copper conductors, (ambient temp. $T_c = 90^\circ\text{C}$ and $T_a = 40^\circ\text{C}$)

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 3. Ft factor for various copper conductors, (ambient temp. $T_c = 75^\circ\text{C}$ and $T_a = 20^\circ\text{C}$)

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

Table 4. Ft factor for various copper conductors, (ambient temp. $T_c = 90^\circ\text{C}$ and $T_a = 20^\circ\text{C}$)

Thermal Resistivity Adjustment Factor (F_{th})

Soil thermal resistivity (RHO) presents the resistance to heat dissipation of the soil. It is expressed in $^\circ\text{C-cm/W}$. Thermal resistivity adjustment factors are presented in the table below for various underground cable laying configurations in cases in which RHO differs from 90°C-cm/W at which the base current carrying capacities are defined. The presented tables are based on assumptions that the soil has a uniform and constant thermal resistivity.

Cable Size	Number of CKT	RHO (° C-cm/W)							
		60	90	120	140	160	180	200	250
#12-#1	1	1.03	1	0.97	0.96	0.94	0.93	0.92	0.9
	3	1.06	1	0.95	0.92	0.89	0.87	0.85	0.82
	6	1.09	1	0.93	0.89	0.85	0.82	0.79	0.75
	9+	1.11	1	0.92	0.87	0.83	0.79	0.76	0.71
1/0-4/0	1	1.04	1	0.97	0.95	0.93	0.91	0.89	0.86
	3	1.07	1	0.94	0.9	0.87	0.85	0.83	0.8
	6	1.1	1	0.92	0.87	0.84	0.81	0.78	0.74
	9+	1.12	1	0.91	0.85	0.81	0.78	0.75	0.7
250-1000	1	1.05	1	0.96	0.94	0.92	0.9	0.88	0.85
	3	1.08	1	0.93	0.89	0.86	0.83	0.81	0.77
	6	1.11	1	0.91	0.86	0.83	0.8	0.77	0.72
	9+	1.13	1	0.9	0.84	0.8	0.77	0.74	0.69

Table 4. Fth: Adjustment factor for 0–1000 V cables in duct banks.
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	0.97	0.95	0.93	0.91	0.9	0.88
	3	1.07	1	0.94	0.90	0.87	0.84	0.81	0.77
	6	1.09	1	0.92	0.87	0.84	0.80	0.77	0.72
	9+	1.10	1	0.91	0.85	0.81	0.77	0.74	0.69
1/0-4/0	1	1.04	1	0.96	0.94	0.92	0.90	0.88	0.85
	3	1.08	1	0.93	0.89	0.86	0.83	0.80	0.75
	6	1.10	1	0.91	0.86	0.82	0.79	0.77	0.71
	9+	1.11	1	0.90	0.84	0.80	0.76	0.73	0.68
250-1000	1	1.05	1	0.95	0.92	0.90	0.88	0.86	0.84
	3	1.09	1	0.92	0.88	0.85	0.82	0.79	0.74
	6	1.11	1	0.91	0.85	0.81	0.78	0.75	0.70
	9+	1.12	1	0.90	0.84	0.79	0.75	0.72	0.67

Table 5. Fth: Adjustment factor for 1000–35000 V cables in duct banks.
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	0.91	0.86	0.82	0.79	0.77	0.74
	2	1.13	1	0.9	0.85	0.81	0.77	0.74	0.7
	3+	1.14	1	0.89	0.84	0.79	0.75	0.72	0.67
1/0-4/0	1	1.13	1	0.91	0.86	0.81	0.78	0.75	0.71
	2	1.14	1	0.9	0.85	0.8	0.76	0.73	0.69
	3+	1.15	1	0.89	0.84	0.78	0.74	0.71	0.67
250-1000	1	1.14	1	0.9	0.85	0.81	0.78	0.75	0.71
	2	1.15	1	0.89	0.84	0.8	0.76	0.73	0.69
	3+	1.15	1	0.88	0.83	0.78	0.74	0.71	0.67

Table 6. Fth: Adjustment factor for directly buried cables in duct banks.
Base ampacity given at an RHO of 90 °C–cm/W

Soil thermal resistivity depends on a number of different factors including moisture content, soil texture, density, and its structural arrangement. Generally, higher soil density or moisture content cause better dissipation of heat and lower thermal resistivity. Soil thermal resistivity can have a vast range being less than 40 to more than 300°C–cm/W. Therefore, a direct soil test is essential especially for critical applications. It is important to perform this test after dry peak summer when the moisture content in the soil is minimal. Field tests usually indicate wide ranges of soil thermal resistance for a specific depth. In order to properly calculate cable current carrying capacity, the maximum value of the thermal resistivities should be used.

Soil dryout effect that is caused by continuously loading underground cables can be considered by taking a higher thermal resistivity adjustment factor than the value that is obtained at site. Special backfill materials such as dense sand can be used to lower the effective overall thermal resistivity. These materials can also offset the soil dryout effect. Soil dryout curves of soil thermal resistivity versus moisture content can be used to select an appropriate value.

Grouping Adjustment Factor (F_g)

Cables that are installed in groups operate at higher temperatures than isolated cables. Operating temperature increases due to the presence of the other cables in the group which act as heating sources. Therefore, temperature increment caused by proximity of other cable circuits depends on circuit separation and surrounding media (soil, backfilling material, etc.). Generally, increasing the horizontal and vertical

separation between the cables would decrease the temperature interference between them and would consequently increase the value of F_g factor.

F_g correlation factors can vary widely depending on the laying conditions. They are usually found in cable manufacturer catalogues and technical specifications. These factors can serve as a starting point for initial approximation and can be later used as an input for a computer program.

Computer studies have shown that for duct bank installations, size and voltage rating of underground cables make a difference in the grouping adjustment factor. These factors are grouped as a function of cable size and voltage rating. In the case different cables are installed in the same duct bank, the value of the grouping adjustment factor is different for each cable size. In these situations, cable current carrying capacities can be determined by calculating cable ampacities starting from the worst (hottest) conduit location to the best (coolest) conduit location. This procedure will allow establishment of the most economical cable laying arrangement.

Other Important Cable Sizing Considerations

In order to achieve maximum utilization of the power cable, reduce operational costs, and minimize capital expanses, an important factor to consider is the proper selection of the conductor size. In addition, several other factors such as voltage drop, cost of losses, and the ability to carry short circuit currents should be considered. However, continuous current carrying capacity is of paramount importance.

Underground Cable Short Circuit Current Capability

When selecting the short circuit rating of a cable system, several factors are very important and need to be taken into account:

- *The maximum allowable temperature limit of the cable components (conductor, insulation, metallic sheath or screen, bedding armour, and oversheath).* For the majority of the cable systems, endurance of cable dielectric materials are a major concern and limitation. Energy that produces temperature rise is usually expressed by an equivalent I^2t value or the current that flows through the conductor in a specified time interval. Using this approach, the maximum

permitted duration for a given short circuit current value can be properly calculated.

- *The maximum allowable value of current that flows through conductor that will not cause mechanical breakdown due to increased mechanical forces.* Regardless of set temperature limitations, this determines a maximum current which must not be exceeded.
- *The thermal performance of cable joints and terminations at defined current limits for the associated cable.* Cable accessories also need to withstand mechanical, thermal and electromagnetic forces that are produced by the short-circuit current in the underground cable.
- *The impact of the installation mode on the above factors.*

The first factor is dealt with in more details and the results presented are based only on cable considerations. It is important to note that single short circuit current application will not cause any significant damage of the underground cable but repeated faults may cause cumulative damage which can eventually lead to cable failure.

It is not easy and feasible to determine complete limits for cable terminations and joints because their design and construction are not uniform and standardized, so their performance can vary. Therefore cable accessories should be designed and selected appropriately; however, it is not always financially justifiable and the short-circuit capability of an underground cable system may not be determined by the performance of its terminations and joints.

Calculation of Permissible Short-Circuit Currents

Short-circuit ratings can be determined following the adiabatic process methodology, which considers that all heat that is generated remains contained within the current transferring component, or non-adiabatic methodology, which considers the fact that the heat is absorbed by adjacent materials. The adiabatic methodology can be used when the ratio of the short-circuit duration to the conductor cross-sectional area is less than $0.1 \frac{s}{mm^2}$. For smaller conductors, such as screen wires, loss of heat from the

conductor becomes more important as the short-circuit duration increases. In those particular cases the non-adiabatic methodology can be used to give a considerable increase in allowable short-circuit currents.

Adiabatic method for short circuit current calculation

The adiabatic methodology, that neglects the loss of heat, is correct enough for the calculation of the maximum allowable short-circuit currents of the conductor and metallic sheath. It can be used in the majority of practical applications, and its results are on the safe side. However, the adiabatic methodology provides higher temperature rises for underground cable screens than they actually occur in reality and, therefore, should be applied with certain reserve.

The generalized form of the adiabatic temperature rise formula which is applicable to any initial temperature is:

$$I^2 t = K^2 S^2 \ln \left(\frac{\theta_f + \beta}{\theta_i + \beta} \right)$$

where,

I – Short circuit current (RMS over duration) (A)

t – Duration of short circuit(s). In the case of reclosures, t is the aggregate of the short-circuit duration up to a maximum of 5 s in total. Any cooling effects between reclosures are neglected.

K – Constant depending on the material of the current-carrying component:

$$K = \sqrt{\frac{Q_c(\beta + 20) \times 10^{-12}}{\rho_{20}}}$$

S – Cross-sectional area of the current-carrying component (mm²). For conductors and metallic sheaths it is sufficient to take the nominal cross-sectional area. In the case of screens, this quantity requires careful consideration.

θ_f – Final temperature (°C)

θ_i – Initial temperature (°C)

β – Reciprocal of the temperature coefficient of resistance of the current-carrying component at 0°C (K)

\ln – \log_e

Q_c – Volumetric specific heat of the current-carrying component at 20°C (J/Km³)

ρ_{20} – Electrical resistivity of the current-carrying component at 20°C (Ωm)

The constants used in the above formulae are given in the table below:

Material	K (As ² /mm ²)	β (K)	$Q_c \left(\frac{J}{Km^3} \right)$	$\rho_{20} (\Omega m)$
Copper	226	234.5	3.45×10^6	1.7241×10^{-8}
Aluminium	148	228	2.5×10^6	2.8264×10^{-8}
Lead	41	230	1.45×10^6	21.4×10^{-8}
Steel	78	202	3.8×10^6	13.8×10^{-8}

Table 7. Non-adiabatic method for short circuit current calculation

IEC 949 gives a non-adiabatic method of calculating the thermally permissible short-circuit current allowing for heat transfer from the current carrying component to adjacent materials. The non-adiabatic method is valid for all short-circuit durations and provides a significant increase in permissible short-circuit current for screens, metallic sheaths and some small conductors.

The adiabatic short-circuit current is multiplied by the modifying factor to obtain the permissible non-adiabatic short-circuit current. The equations used to calculate the non-adiabatic factor are given in IEC 949. For conductors and spaced screen wires fully surrounded by non-metallic materials, the equation for the non-adiabatic factor (e) is:

$$\varepsilon = \left[1 + X \left(\frac{T}{S} \right)^{1/2} + Y \left(\frac{T}{S} \right) \right]^{1/2}$$

Insulation	Constants for copper		Constants for aluminium	
	$X \left(\frac{\text{mm}^2}{\text{s}} \right)^{1/2}$	$Y \left(\frac{\text{mm}^2}{\text{s}} \right)$	$X \left(\frac{\text{mm}^2}{\text{s}} \right)^{1/2}$	$Y \left(\frac{\text{mm}^2}{\text{s}} \right)$
PVC - under 3 kV	0.29	0.06	0.4	0.08
PVC - above 3 kV	0.27	0.05	0.37	0.07
XLPE	0.41	0.12	0.57	0.16
EPR - under 3 kV	0.38	0.1	0.52	0.14
EPR - above 3 kV	0.32	0.07	0.44	0.1
Paper - fluid-filled	0.45	0.14	0.62	0.2
Paper – others	0.29	0.06	0.4	0.08

Table 7. Copper and Aluminium constants

For sheaths, screens and armour the equation for the non-adiabatic factor is:

$$\varepsilon = 1 + 0.61M\sqrt{T} - 0.069(M\sqrt{T})^2 + 0.0043(M\sqrt{T})^3$$

where,

$$M = \frac{\left(\sqrt{\frac{\sigma_2}{\rho_2}} + \sqrt{\frac{\sigma_3}{\rho_3}} \right)}{2\sigma_1\delta \times 10^{-3}} \cdot F$$

σ_1 – Volumetric specific heat of screen, sheath or armour $\left(\frac{J}{\text{Km}^3} \right)$

σ_2, σ_3 – Volumetric specific heat of materials each side of screen, sheath or armour $\left(\frac{J}{\text{Km}^3} \right)$

δ – Thickness of screen, sheath or armour (mm)

ρ_2, ρ_3 – Thermal resistivity of materials each side of screen, sheath or armour $\left(\frac{\text{Km}}{\text{W}} \right)$

F – Factor to allow for imperfect thermal contact with adjacent materials

The contact factor F is normally 0.7, however there are some exceptions. For example, for a current carrying component such as a metallic foil sheath, completely bonded on one side to the outer non-metallic sheath, a contact factor of 0.9 is used.

Influence of Method of Installation

When it is intended to make full use of the short-circuit limits of a cable, consideration should be given to the influence of the method of installation. An important factor concerns the extent and nature of the mechanical restraint imposed on the cable.

Longitudinal expansion of a cable during a short circuit can be significant, and when this expansion is restrained, the resultant forces are considerable.

For cables in air, it is advisable to install them so that expansion is absorbed uniformly along the length by snaking rather than permitting it to be relieved by excessive movement at a few points only. Fixings should be spaced sufficiently far apart to permit lateral movement of multi-core cables or groups of single core cables.

Where cables are installed directly in the ground, or must be restrained by frequent fixing, then provision should be made to accommodate the resulting longitudinal forces on terminations and joint boxes. Sharp bends should be avoided because the longitudinal forces are translated into radial pressures at bends in the cable such as insulation and sheaths. Attention is drawn to the minimum radius of installed bend recommended by the appropriate installation regulations. For cables in air, it is also desirable to avoid fixings at a bend which may cause local pressure on the cable.

Voltage Drop

When current flows in a cable conductor there is a voltage drop between the ends of the conductor, which is the product of the current and the impedance. If the voltage drop was excessive, it could result in the voltage supplied to the equipment being too low for proper operation. The voltage drop is of more consequence at the low end of the voltage range of supply voltages than it is at higher voltages, and generally it is not significant as a percentage of the supply voltage for cables rated above 1000V, unless very long route lengths are involved.

Voltage drops for individual cables are given in the units millivolts per ampere per metre length of cable. They are derived from the following formulae:

- For single-phase circuits, $\text{mV/A/m} = 2Z$
- For 3-phase circuits, $\text{mV/A/m} = \sqrt{3}Z$

where,

mV/A/m = voltage drop in millivolts per ampere per metre length of cable route

Z = impedance per conductor per kilometer of cable at maximum normal operating

temperature (Ω/km)

In a single-phase circuit, two conductors (the phase and neutral conductors) contribute to the circuit impedance, and this accounts for the number 2 in the equation. If the voltage drop is to be expressed as a percentage of the supply voltage, for a single-phase circuit it has to be related to the phase-to-neutral voltage U_0 , i.e., 240 V when supply is from a 240/415V system.

In a 3-phase circuit, the voltage drop in the cable is $x/3$ times the value for one conductor. Expressed as a percentage of the supply voltage, it has to be related to the phase-to-phase voltage U , i.e., 415 V for a 240/415 V system.

Regulations used to require that the drop in voltage from the origin of the installation to any point in the installation should not exceed 2.5% of the nominal voltage when the conductors are carrying the full load current, disregarding starting conditions. The 2.5% limit has since been modified to a value appropriate to the safe functioning of the equipment in normal service, it being left to the designer to quantify this. However, for final circuits protected by an overcurrent protective device having a nominal current not exceeding 100A, the requirement is deemed to be satisfied if the voltage drop does not exceed the old limit of 2.5%. It is therefore likely that for such circuits the limit of 2.5% will still apply more often than not in practice.

The reference to starting conditions relates especially to motors, which take a significantly higher current in starting than when running at operating speeds. It may be necessary to determine the size of the cable on the basis of restricting the voltage drop at the starting current to a value which allows satisfactory starting, although this may be larger than required to give an acceptable voltage drop at running speeds. To satisfy the 2.5% limit, if the cable is providing a single-phase 240V supply, the voltage drop should not exceed 6V and, if providing a 3-phase 415V supply, the voltage drop should not exceed 10.4V. Mostly, in selecting the size of cable for a particular duty, the current rating will be considered first. After choosing a cable size to take into account the current to be carried as well as the rating and type of the overload protective device, the voltage drop then has to be checked. To satisfy the 2.5% limit for a 240 V single-phase or 415 V 3-phase supply, the following condition should be met:

- For the single-phase condition, $mV/A/m < 6000/(IL)$
- For the 3-phase condition, $mV/A/m < 10400/(IL)$

where,

I – Full load current to be carried (A)

L – Cable length (m)

The smallest size of cable for which the value of $mV/A/m$ satisfies this relationship is then the minimum size required on the basis of 2.5% maximum voltage drop. For other limiting percentage voltage drops and/or for voltages other than 240/415 V, the values of 6V (6000mV) and 10.4V (10400 mV) are adjusted proportionately. Calculations on these simple lines are usually adequate. Strictly, however, the reduction in voltage at the terminals of the equipment being supplied will be less than the voltage drop in the cable calculated this way, unless the ratio of inductive reactance to resistance of the cable is the same as for the load, which will not normally apply. If the power factor of the cable in this sense (not to be confused with dielectric power factor) differs substantially from the power factor of the load, and if voltage drop is critical in determining the required size of cable, a more precise calculation may be desirable.

Another factor which can be taken into account when the voltage drop is critical is the effect of temperature on the conductor resistance. The tabulated values of voltage drop are based on impedance values in which the resistive component is such that when the conductor is at the maximum permitted sustained temperature for the type of cable on which the current ratings are based. If the cable size is dictated by voltage drop instead of the thermal rating, the conductor temperature during operation will be less than the full rated value, and the conductor resistance will be lower than allowed in the tabulated voltage drop. On the basis that the temperature rise of the conductor is approximately proportional to the square of the current, it is possible to estimate the reduced temperature rise at a current below the full rated current. This can be used to estimate the reduced conductor temperature and, in turn, from the temperature coefficient of resistance of the conductor material, it can be used to estimate the reduced conductor resistance. Substitution of this value for the resistance at full rated temperature in the formula for impedance enables the reduced impedance and voltage

drop to be calculated. Standards give a generalized formula for taking into account that the load is less than the full current rating. A factor C_t can be derived from the following:

$$C_t = \frac{230 + t_p - (C_a^2 C_g^2 - \frac{I_b^2}{I_t^2})(t_p - 30)}{230 + t_p}$$

where,

t_p = maximum permitted normal operating temperature (°C)

C_a = the rating factor for ambient temperature

C_g = the rating factor for grouping of cables

I_b = the current actually to be carried (A)

I_t = the tabulated current rating for the cable (A)

For convenience, the formula is based on a temperature coefficient of resistance of 0.004 per degree Celsius at 20°C for both copper and aluminium. This factor is for application to the resistive component of voltage drop only. For cables with conductor sizes up to 16 mm² this is effectively the total mV/A/m value.

Cable manufacturers will often be able to provide information on corrected voltage drop values when the current is less than the full current rating of the cable, with the necessary calculations having been made on the lines indicated. If the size of cable required to limit the voltage drop is only one size above the size required on the basis of thermal rating, then the exercise is unlikely to yield a benefit. If, however, two or more steps in conductor size are involved, it may prove worthwhile to check whether the lower temperature affects the size of the cable required. The effect is likely to be greater at the lower end of the range of sizes, where the impedance is predominantly resistive, than towards the upper end of the range where the reactance becomes a more significant component of the impedance.

The effect of temperature on voltage drop is of particular significance in comparing XLPE insulated cables with PVC insulated cables. From the tabulated values of

voltage drop, it appears that XLPE cables are at a disadvantage in giving greater voltage drops than PVC cables, but this is because the tabulated values are based on the assumption that full advantage is taken of the higher current ratings of the XLPE cables, with associated higher permissible operating temperature. For the same current as that for the same size of PVC cable, the voltage drop for the XLPE cable is virtually the same.

If a 4-core armoured 70 mm² (copper) 600/1000 V XLPE insulated cable, with a current rating of 251 A in free air with no ambient temperature or grouping factors applicable, was used instead of the corresponding PVC insulated cable to carry 207A, which is the current rating of the PVC cable under the same conditions, the calculation would yield:

$$C_t = \frac{230 + 90 - (1 - 0.68) \cdot 60}{230 + 90} = 0.94$$

If the (mV/A/m) r value for the XLPE cable (0.59) is multiplied by 0.94, it gives (to two significant digits) 0.55, which is the same as for the PVC cable. The (mV/A/m) x value for the XLPE cable is in fact a little lower than that for the PVC cable, 0.13, compared with 0.14, but this has little effect on the (mV/A/m) z value which, to two significant digits, is 0.57 for both cables.

Practical Example – 33kv cable required current rating

The objective of this exercise is to size 33 kV underground cable in order to connect it to the secondary side of the 220/34.5 kV, 105/140 MVA Transformer ONAN/ONAF. The following input data is used:

Parameter description	Value
Maximum steady state conductor temperature	90°C
Maximum transient state conductor temperature	250°C
ONAN Rating of Transformer (S)	105 MVA
ONAF Rating of Transformer (P)	140 MVA
Rated voltage (V)	33 kV

The initial calculations are performed as follows:

Full Load Current (I)	$= \frac{S}{\sqrt{3}V}$
Full Load Current (I)	$= \frac{140 \times 10^6}{\sqrt{3} \times 33 \times 10^3}$
Full Load Current (I)	= 450 A
Proposed Cross section of the Cable Size	= 1C x 630 mm ²

33 kV Cable Installation Method

Proposed Cross section of the Cable Size	= 1C x 630 mm ²
Soil Thermal Resistivity Native Soil – Option 1	= 3.0 K.m/W.
Soil Thermal Resistivity Special Backfill – Option 2	= 1.2 K.m/W
Soil Ambient Temperature	= 40°C
Mode of Laying	= Trefoil Formation

Two scenarios with different soil thermal resistivity were investigated. Thermal soil resistivity of 3.0 K.m/W was used in Option 1 whereas thermal soil resistivity of 1.2 K.m/W was used in Option 2. Cables are laid directly into ground without any additional measures in Option 1. Cable trenches are filled with special backfill that reduces thermal soil resistivity to 1.2 K.m/W in Option 2. Special backfill is used along the whole 33 kV cable route.

Direct Buried in Ground – Option 1

The following installation conditions are considered for the Cable Continuous Current rating calculation:

Depth of burial	= 1 m
Axial distance between cables	= 0.4 m

The selected 33 kV, 1C, 630 mm² cable can transfer 755 A (laid directly, ground temperature 20°C, q = 1.5 Km/W, depth of laying 0.8 m, laid in trefoil touching). This

information is obtained from the cable manufacturer catalogue.

Calculation of the cable current carrying capacity for the given site conditions is performed as follows:

Variation in ground temperature coefficient = 0.86

Rating factor for depth of laying = 0.97

Rating factor for variation in thermal resistivity of soil and grouping (as per cable manufacturer catalogue) = 0.55

Cable current carrying capacity (I) = $755 \times 0.86 \times 0.97 \times 0.55 = 346$ A

Number of runs per phase = $2450 / 346 = 7.08$

Required number of runs per phase = 7

The calculation above indicated that 7 runs per phase of 33 kV, 1C, 630 mm² cable will be needed to transfer 140 MVA on 33 kV voltage level.

Rating factors for variation in ground temperature and variation of installation depth are obtained from the cable manufacturer catalogues. Alternatively they can be found in IEC 60502 standard.

Voltage Drop Calculation

Voltage drop is calculated as follows:

$$V_d = I(A) \cdot L(\text{km}) \cdot \text{mV}(V/A/\text{km})$$

where,

I(A) = operating current

L(km) = cable length

mV (V/A/km) = nominal voltage drop

Nominal voltage drop is taken from the cable manufacturer catalogues.

$$mV (V/A/km) = 0.0665$$

Voltage drop is:

$$V_d = I(A) \cdot L(km) \cdot mV = 276 A \cdot 1.5 km \cdot 0.0665 V/A/km = 27.53 V \Rightarrow 0.08\%$$

(maximum possible cable length is considered)

It can be concluded that the voltage drop is within permissible limits.

Direct Buried in Ground – Option 2

Cable special backfill was considered in the option 2. That was done to assess how reduced thermal soil resistivity will affect cable ampacity. The following installation conditions are considered for the Cable Continuous Current rating calculation.

Depth of burial = 1 m

Axial distance between cables = 0.4 m

The selected 33 kV, 1C, 630 mm² cable can transfer 755 A (laid directly, ground temperature 20°C, $q = 1.5 \text{ }^\circ\text{Cm/W}$, depth of laying 0.8 m, laid in trefoil touching) as provided by the cable manufacturer specifications.

The calculation of the cable current carrying capacity for the given site conditions is done as follows:

Variation in ground temperature coefficient = 0.85

Rating factor for depth of laying = 0.97

Rating factor for variation in thermal resistivity of soil and grouping (as per cable manufacturer catalogue) = 1

Rating factor for variation in cable grouping = 0.75

Cable current carrying capacity (I) = $755 \cdot 0.85 \cdot 0.97 \cdot 0.75 = 466 \text{ A}$

Number of runs per phase = $2450/466 = 5.25$

Required number of runs per phase = 6

The calculation above indicated that 6 runs per phase of 33 kV, 1C, 630 mm² cable will be needed to transfer 140 MVA on 33 kV voltage level.

Rating factors for variation in ground temperature and variation of installation depth are obtained from the cable manufacturer catalogues. Alternatively they can be found in IEC 60502 standard.

Voltage Drop Calculation

Voltage drop is calculated as follows:

$$V_d = I(A) \cdot L(\text{km}) \cdot \text{mV}(V/A/\text{km})$$

where,

I(A) = operating current

L(km) = cable length

mV (V/A/km) = nominal voltage drop

Nominal voltage drop is taken from the cable manufacturer catalogues.

$$\text{mV (V/A/km)} = 0.06712$$

Voltage drop is:

$$V_d = I(A) \cdot L(\text{km}) \cdot \text{mV} = 459 \text{ A} \cdot 1.5 \text{ km} \cdot 0.06712 \text{ V/A/km} = 46.21 \text{ V} \Rightarrow 0.139\%$$

(maximum possible cable length is considered)

It can be concluded that the voltage drop is within permissible limits.

It is recommended that the backfill used shall be red dune sand tested for the thermal resistivity value of 1.2°C K.m/W or below. The calculations in Option 2 indicate that only 6 cable runs per phase would be needed if such laying conditions are achieved. As per the information available, the length of the cable route is about 700 m. Using

imported red dune sand, approximately 6.3 km of cables can be saved per transformer and still achieve the same power transfer capacity. Bentonite shall be used to fill in road crossing cable ducts

Practical Example – 15 kV cables in duct banks

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 have a diameter of 5 in (trade size) of PVC, and are separated by 7.5 in (center-to-center spacing), as shown in the Figure 1 below. 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. To achieve this, the base ampacities of the cables are found first. These ampacities are then derated using the adjustment factors.

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.

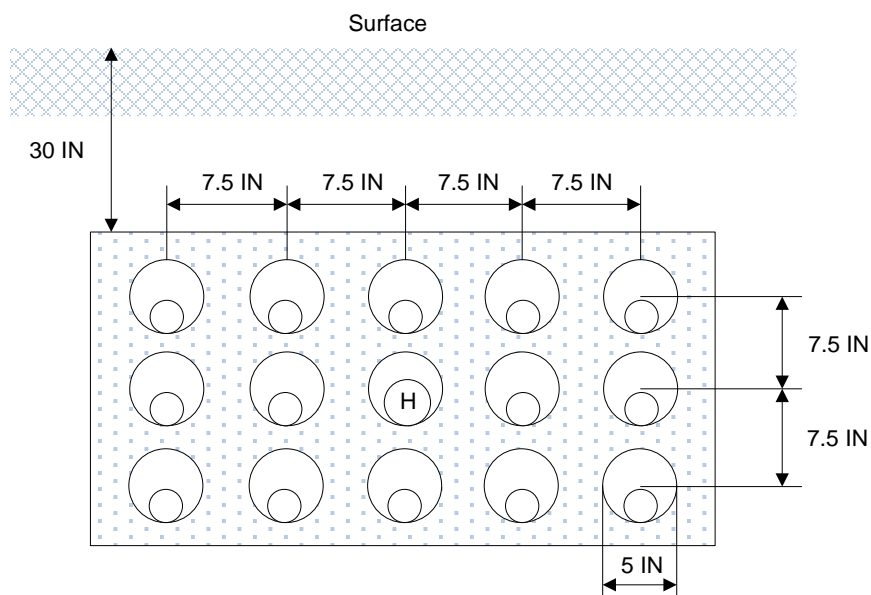


Figure 1. 3 × 5 duct bank arrangement

Base Ampacities

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

$$I = 375 \text{ A (350 kcmil)}$$

$$I = 450 \text{ A (500 kcmil)}$$

Manual Method

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

$$F_t = 0.82 \text{ for adjustment in the ambient temperature from } 20\text{--}30^\circ\text{C} \text{ and conductor temperature from } 90\text{--}75^\circ\text{C}$$

$$= 0.90 \text{ for adjustment in the thermal resistivity from a RHO of } 90\text{--}120^\circ\text{C-cm/W}$$

$$F_g = 0.479 \text{ for grouping adjustment of 15 kV, 3/C 350 kcmil cables installed in a } 3 \times 5 \text{ duct bank}$$

$$F_g = 0.478 \text{ for grouping adjustment of 15 kV, 3/C 500 kcmil cables installed in a } 3 \times 5 \text{ duct bank}$$

The overall cable adjustment factors are:

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

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

The maximum allowable ampacity of each cable size is the multiplication 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.

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

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

Conclusion

Analytical derating of cable ampacity is a complex and tedious process. A manual method was developed 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.