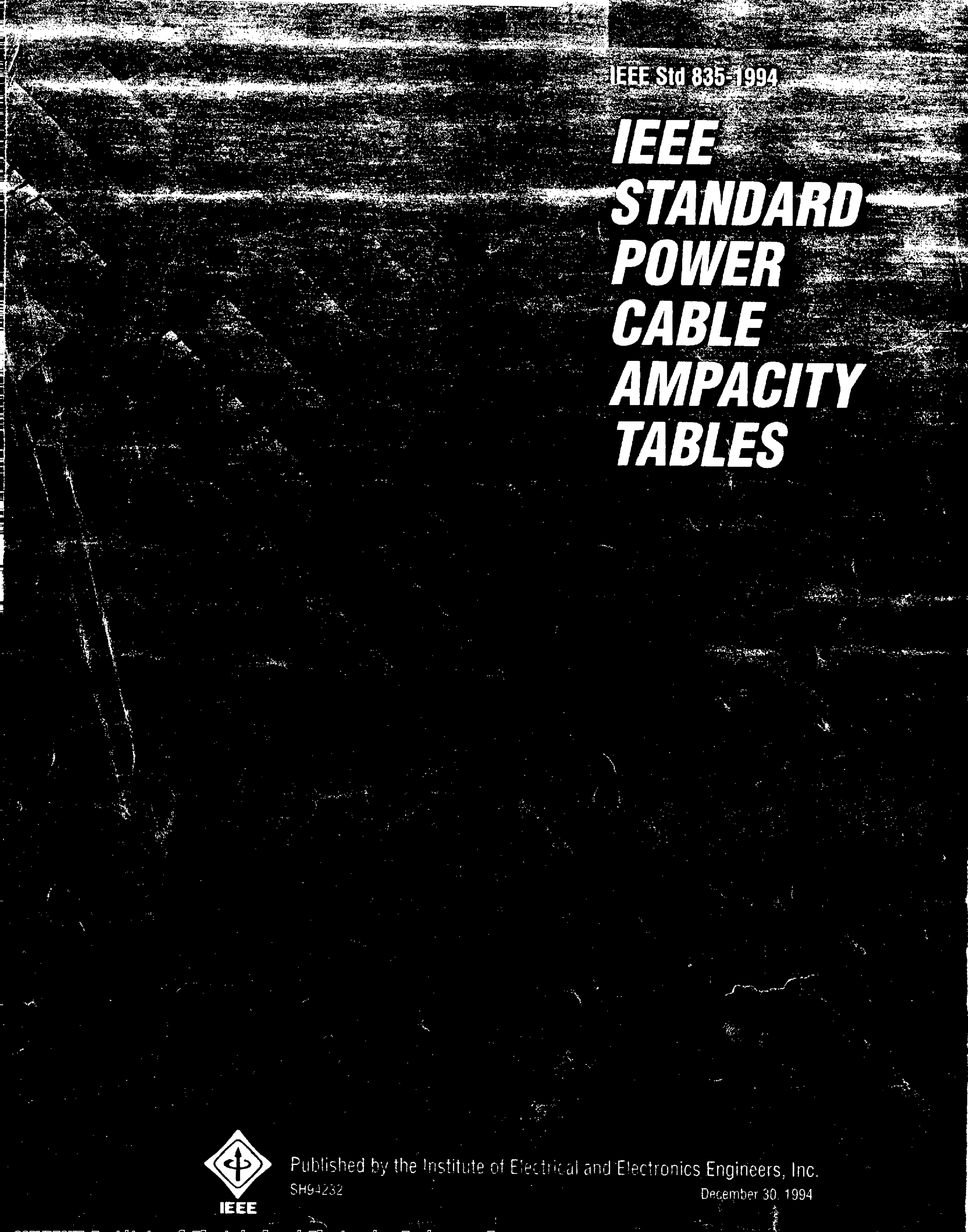

IEEE Std 835-1994

IEEE STANDARD POWER CABLE AMPACITY TABLES

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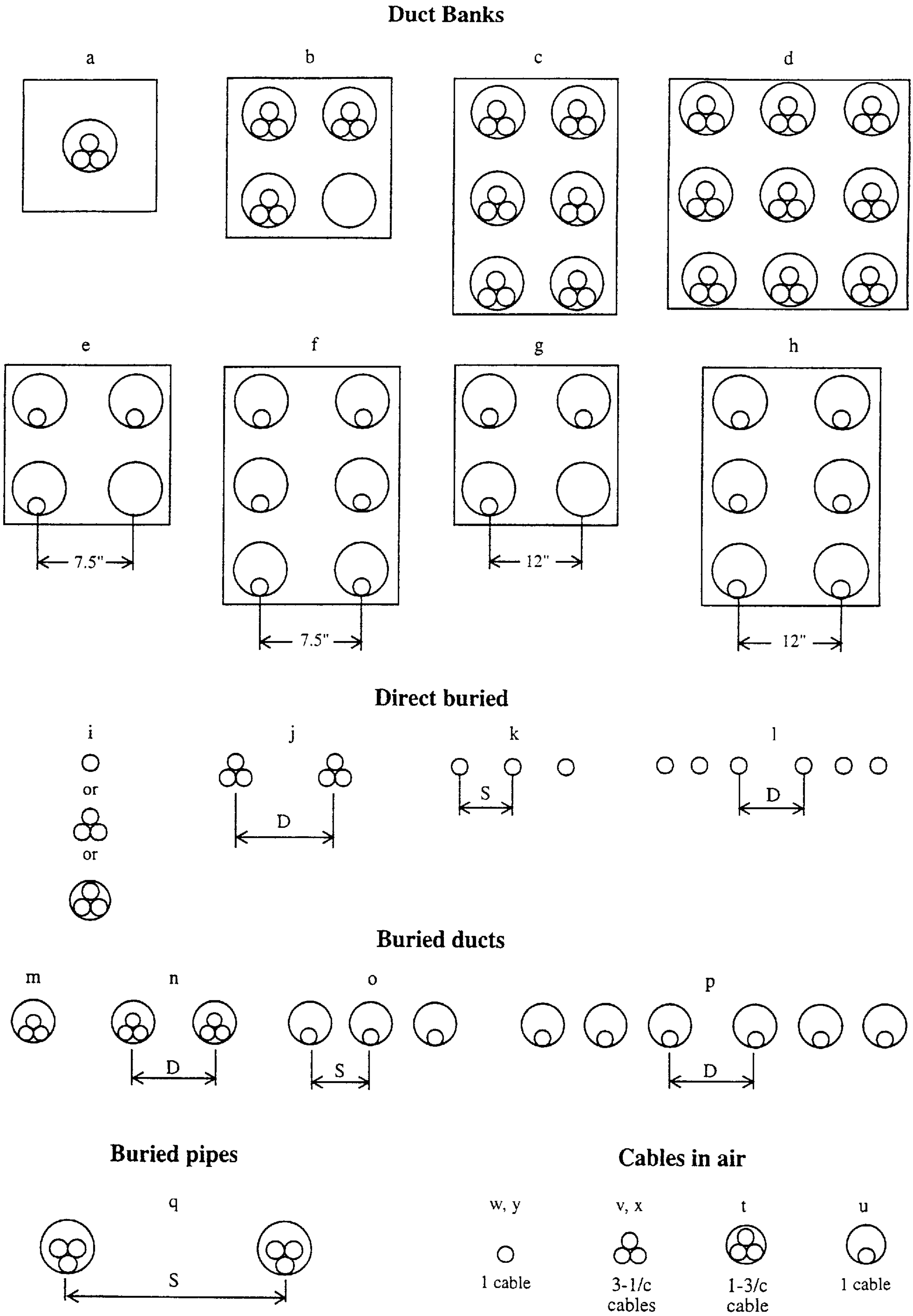

Figure 1—Cable geometry

IEEE Std 835-1994

IEEE Standard Power Cable Ampacity Tables

Sponsor

Insulated Conductors Committee
of the
IEEE Power Engineering Society

Approved September 22, 1994

IEEE Standards Board

Abstract: Over 3000 ampacity tables for extruded dielectric power cables rated through 138 kV and laminar dielectric power cables rated through 500 kV are provided.

Keywords: ampacity, cable, dielectric, extruded, laminar, power

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Foreword

(This foreword is not a part of IEEE Std 835-1994, IEEE Standard Power Cable Ampacity Tables.)

The original edition of the "Current Carrying Capacity" tables was published by the Insulated Power Cable Engineers Association (IPCEA) in 1943. With the advent of new types of cables and better knowledge of thermal circuits, IPCEA decided, in 1954, that a new edition should be published. Since the AIEE Insulated Conductors Committee was interested in the subject, a joint AIEE-IPCEA working group was formed to handle the technical aspects. The members of this working group were J. H. Neher, Chair, F. H. Buller, R. W. Burrell, W. A. Del Mar, M. H. McGrath, E. J. Merrell, H. A. Schumacher and R. J. Wiseman. The financing of the computer programming and calculations was underwritten by IPCEA, now ICEA, while the AIEE (now the IEEE) assumed the publishing role for the 1962 version of the AIEE-IPCEA Ampacity Tables Standard. This standard, identified as AIEE S-135-1 and S-135-2 and IPCEA Publication P-46-426, served the industry well for the last 30 years.

From 1970 onward, the design and application of medium and high voltage cables underwent many changes. The use of medium voltage extruded dielectric cables grew tremendously in the United States and throughout many other industrialized countries. New insulating materials and improvements in the design and installation of underground cables were developed, creating a need for updating and expanding the original ampacity tables. Advances in computer technology could also be utilized to facilitate the work on new tables.

Because of continuing demand for upgraded tables, the IEEE Insulated Conductors Committee (ICC) was asked to undertake a project to meet this need. In the late 1970's, ICC formed a working group within the Cable Characteristics Subcommittee, Project 3-1, to prepare a document outlining the scope of work necessary to establish parameters, and to update the cable constructions and design changes that had taken place since the original publication. This would then lead to a revision and expansion of the ampacity tables. This document, P835, was prepared and subsequently approved by the ICC and the IEEE Standards Board in 1984. However, the large amount of computer time and work by experts in the field to compile the actual tables placed this project beyond the reach of the normal volunteer approach to creating IEEE standards. Thus, due to lack of funds, the project languished for several years.

In 1990, following a special meeting of the ICC officers and colleagues during the Winter Power Meeting in Atlanta, a new effort to resurrect this project was developed. This new effort included a drive to raise the necessary funds through contributions from companies and individuals who would benefit from the new tables. This was the first attempt ever to raise funds from IEEE members and companies to support a standard. Following IEEE approval, this drive was launched and was successful in meeting the project's financial needs. A letter ballot was circulated to ICC voting members in 1990 to reaffirm the scope of the project. After minor changes were made to resolve negative votes, the IEEE contracted for the needed services. Following completion of the initial tables, a team of volunteers was appointed to verify preliminary results through manual computations.

In addition to the Chair, Past Chair, and members of the Working Group (listed on the next page), other ICC members are deserving of special recognition in bringing this project to fruition. Roland Watkins, while ICC Chair in 1990 and 1991, was instrumental in reviving the project and instigating the successful fund raising effort. Past ICC Chairs E. Duffy, I. Berkhan, J. B. Gardner, B. Smith, and T. Balaska worked diligently during their terms, along with the past chairs of the Working Group, to solve the problems that were delaying the project. A special thanks is given to M. A. Martin, Jr., who fostered this project from its early beginnings in the late 1970's to its publication in 1994. Over this time period, he spent many volunteer hours educating the IEEE on the need for this project.

While it is the policy of the IEEE to not publicly recognize IEEE employees and paid professionals involved in the development of IEEE standards, it goes without saying that this document could not have been created without their dedicated effort. We must also document the use of commercial computer programs identified as USAMP and TRAMP in the compilation of these tables, although IEEE owns the copyright and assumes full responsibility for this publication.

The initial ground work by the original AIEE-IPCEA Working Group laid the foundation for ampacity tables in this IEEE standard. The IEEE sincerely appreciates the working relationship it has maintained with ICEA and the effort by ICEA members in the development of new tables.

Past and present members of the Working Group are as follows:

D. A. Voltz, *Chair* **P. A. Nobile**, *Vice Chair*
M. A. Martin, Jr., *Past Chair* **D. A. Silver**, *Past Chair*

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A. Ernst
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P. A. Nobile, *Chair*

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K. W. Brown
R. L. Harp

IEEE also wishes to give a special thanks to the following individuals and organizations for their financial contribution to this venture. It was their dedication and effort that allowed this project to go forward.

Alcatel Canada Wire Inc.
Allegheny Power Services Corporation
Anixter Inc.
Atlantic Electric
BICC Cables Corporation on behalf of the
Corporation and two of its business units:
  CABLEC Continental Cables Company
  CABLEC Utility Cable Company
Canada Wire
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Cristino Associates, Inc.
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Florida Power Corporation
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Lynches River Electric Cooperative, Inc.
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The scope of this standard was approved by the IEEE Standards Board on June 27, 1991. The IEEE Standards Board approved this standard on September 22, 1994, with the following membership:

Also included are the following nonvoting IEEE Standards Board liaisons:

Stephen J. Huffman
IEEE Standards Project Editor

Contents

Index to tables

Type 1
600 V–5 kV unshielded extruded

Cable geometry (see figure 1)	Number of conduits	Number of circuits	Number of conductors per position	Copper	Aluminum
In Duct Bank					
a	1	1	3	1	37
b	3	3	3	3	39
c	6	6	3	5	41
d	9	9	3	7	43
Direct Buried					
i	-	1	3x1/c or 1CN or 1x3/c	9	45
j	-	2	3x1/c or 2CN or 3/c	19	55
Horizontal Conduit in Air					
t	1	1	3	29	65
In Free Air					
v	-	1	3	31	67
w	-	1	1	33	69
In Unventilated Riser					
x	1	1	3	35	71

The first page of each series of tables is indicated.

Type 2
5–15 kV, two conductor, concentric neutral, extruded

Cable geometry (see figure 1)	Number of conduits	Number of circuits	Number of conductors per position	5 kV		15 kV	
				Copper	Aluminum	Copper	Aluminum
Direct Buried							
i	-	1	3x1/c or 1CN or 1x3/c	73	139	205	271
j	-	2	3x1/c or 2CN or 2x3/c	83	149	215	281
k	-	1	3x1/c or 3CN	93	159	225	291
Direct Buried Conduits							
m	1	1	3	103	169	235	301
n	2	2	3	113	179	245	311
o	3	1	1	123	189	255	321
Horizontal Conduit in Air							
u	1	1	1	133	199	265	331
In Free Air							
w	-	1	1	135	201	267	333
In Unventilated Riser							
y	1	1	1	137	203	269	335

The first page of each series of tables is indicated.

Type 3
5–46 kV, single conductor, shielded, extruded

Cable geometry (see figure 1)	Number of conduits	Number of circuits	Number of conductors per position	5–15 kV		25–46 kV	
				Copper	Aluminum	Copper	Aluminum
In Duct Bank							
a	1	1	3	337	509	681	853
b	3	3	3	341	513	685	857
c	6	6	3	345	517	689	861
d	9	9	3	349	521	693	865
e	3	1	1	353	525	697	869
f	6	2	1	355	527	699	871
Direct Buried							
i	-	1	3x1/c or 1CN or 1x3/c	357	529	701	873
j	-	2	3x1/c or 2CN or 2x3/c	377	549	721	893
k	-	1	3x1/c or 3CN	397	569	741	913
l	-	2	1	417	589	761	933
Direct Buried Conduits							
m	1	1	3	437	609	781	953
n	2	2	3	457	629	801	973
o	3	1	1	477	649	821	993
p	6	2	1	487	659	831	1003
Horizontal Conduit in Air							
t	1	1	3	497	669	841	1013
In Free Air							
v	1	1	3	501	673	845	1017
In Unventilated Riser							
x	1	1	3	505	677	849	1021

The first page of each series of tables is indicated.

Type 4
69–138 kV, single conductor, shielded, unfilled XLPE

Cable geometry (see figure 1)	Number of conduits	Number of circuits	Number of conductors per position	69 kV		115–138 kV	
				Copper	Aluminum	Copper	Aluminum
In Duct Bank							
g	3	1	1	1025	1098	1171	1244
h	6	2	1	1028	1101	1174	1247
Direct Buried							
i	-	1	3	1031	1104	1177	1250
j	-	2	3	1047	1120	1193	1266
k	-	1	1	1063	1136	1209	1282
l	-	2	1	1079	1152	1225	1298
In Unventilated Riser							
x	1	1	3	1095	1168	1241	1314

The first page of each series of tables is indicated.

NOTE—Ampacities for type 4 cables are followed by pages for watts loss and constants.

Type 5
69–138 kV, single conductor, shielded, filled, XLPE/EPR

Cable geometry (see figure 1)	Number of conduits	Number of circuits	Number of conductors per position	69 kV		115–138 kV	
				Copper	Aluminum	Copper	Aluminum
In Duct Bank							
g	3	1	1	1317	1390	1463	1536
h	6	2	1	1320	1393	1466	1539
Direct Buried							
i	-	1	3	1323	1396	1469	1542
j	-	2	3	1339	1412	1485	1558
k	-	1	1	1355	1428	1501	1574
l	-	2	1	1371	1444	1517	1590
In Unventilated Riser							
x	1	1	3	1387	1460	1533	1606

The first page of each series of tables is indicated.

NOTE—Ampacities for type 5 cables are followed by pages for watts loss and constants.

Type 6
5 kV and 15 kV, three conductor, shielded, extruded

Cable geometry (see figure 1)	Number of conduits	Number of circuits	Number of conductors per position	5 kV		15 kV	
				Copper	Aluminum	Copper	Aluminum
In Duct Bank							
a	1	1	3	1609	1643	1677	1711
b	3	3	3	1611	1645	1679	1713
c	6	6	3	1613	1647	1681	1715
d	9	9	3	1615	1649	1683	1717
Direct Buried							
i	-	1	3	1617	1651	1685	1719
j	-	2	3	1627	1661	1695	1729
Horizontal Conduit in Air							
u	1	1	1	1637	1671	1705	1739
In Free Air							
w	-	1	3	1639	1673	1707	1741
In Unventilated Riser							
y	1	1	1	1641	1675	1709	1743

The first page of each series of tables is indicated.

Type 7
5–35 kV, single conductor, paper with lead sheath

Cable geometry (see figure 1)	Number of conduits	Number of circuits	Number of conductors per position	5 kV		15 kV		35 kV	
				Copper	Aluminum	Copper	Aluminum	Copper	Aluminum
In Duct Bank									
a	1	1	3	1745	1786	1827	1868	1909	1950
b	3	3	3	1746	1787	1828	1869	1910	1951
c	6	6	3	1747	1788	1829	1870	1911	1952
d	9	9	3	1748	1789	1830	1871	1912	1953
e	3	1	1	1749	1790	1831	1872	1913	1954
f	6	2	1	1750	1791	1832	1873	1914	1955
Direct Buried									
i	-	1	3	1751	1792	1833	1874	1915	1956
j	-	2	3	1759	1800	1841	1882	1923	1964
k	-	1	1	1767	1808	1849	1890	1931	1972
l	-	2	1	1775	1816	1857	1898	1939	1980
Horizontal Conduit in Air									
t	1	1	3	1783	1824	1865	1906	1947	1988
In Free Air									
v	-	1	3	1784	1825	1866	1907	1948	1989
In Unventilated Riser									
x	1	1	3	1785	1826	1867	1908	1949	1990

The first page of each series of tables is indicated.

Type 8
5–35 kV, three conductor, paper with lead sheath

Cable geometry (see figure 1)	Number of conduits	Number of circuits	Number of conductors per position	5 kV		15 kV		35 kV	
				Copper	Aluminum	Copper	Aluminum	Copper	Aluminum
In Duct Bank									
a	1	1	3	1991	2014	2037	2060	2083	2106
b	3	3	3	1992	2015	2038	2061	2084	2107
c	6	6	3	1993	2016	2039	2062	2085	2108
d	9	9	3	1994	2017	2040	2063	2086	2109
Direct Buried									
i	-	1	3	1995	2018	2041	2064	2087	2110
j	-	2	3	2003	2026	2049	2072	2095	2118
Horizontal Conduit in Air									
u	1	1	1	2011	2034	2057	2080	2103	2126
In Free Air									
w	-	1	3	2012	2035	2058	2081	2104	2127
In Unventilated Riser									
y	1	1	1	2013	2036	2059	2082	2105	2128

The first page of each series of tables is indicated.

Type 9
69–500 kV, single conductor, self-contained, liquid filled, paper

Cable geometry (see figure 1)	Number of conduits	Number of circuits	Number of conductors per position	69 kV		115 kV		138 kV			
								Copper		Aluminum	
				Copper Lead	Aluminum Lead	Copper Lead	Aluminum Lead	Lead	Alum	Lead	Alum
In Duct Bank											
g	3	1	1	2129	2176	2223	2270	2317	2364	2411	2458
h	6	2	1	2132	2179	2226	2273	2320	2367	2414	2461
Direct Buried											
k	-	1	1	2135	2182	2229	2276	2323	2370	2417	2458
l	-	2	1	2151	2198	2245	2292	2339	2386	2433	2461
Horizontal (Non-Metallic) Conduit in Air											
u	1	1	1	2167	2214	2261	2308	2355	2402	2449	2496
In Free Air											
w	-	1	1	2170	2217	2264	2311	2358	2405	2452	2499
Unventilated (Non-Metallic) Riser											
y	1	1	1	2173	2220	2267	2314	2361	2408	2455	2502

Cable geometry (see figure 1)	Number of conduits	Number of circuits	Number of conductors per position	230 kV				345 kV				500 kV	
				Copper		Aluminum		Copper		Aluminum		Copper	Alum
				Lead	Alum	Lead	Alum	Lead	Alum	Lead	Alum	Alum	Alum
In Duct Bank													
g	3	1	1	2505	2528	2551	2574	2597	2620	2643	2666	2689	2712
h	6	2	1	2508	2531	2554	2577	2600	2623	2646	2669	2692	2715
Direct Buried													
k	-	1	1	2511	2534	2557	2580	2603	2626	2649	2672	2695	2718
l	-	2	1	2514	2538	2561	2584	2607	2630	2653	2676	2699	2722
Horizontal (Non-Metallic) Conduit in Air													
u	1	1	1	2519	2542	2565	2588	2611	2634	2657	2680	2703	2726
In Free Air													
w	-	1	1	2522	2545	2568	2591	2614	2637	2660	2683	2706	2729
Unventilated (Non-Metallic) Riser													
y	1	1	1	2525	2548	2571	2594	2617	2640	2663	2686	2709	2732

The first page of each series of tables is indicated.

Type 10
69 kV, three conductor, self-contained, liquid filled paper

Cable geometry (see figure 1)	Number of conduits	Number of circuits	Number of conductors per position	Copper Lead	Aluminum Lead
In Duct Bank					
a	1	1	3	2735	2785
b	3	3	3	2738	2788
c	6	6	3	2741	2791
d	9	9	3	2744	2794
Direct Buried					
i	1	1	3	2747	2797
j	2	2	3	2763	2813
In Free Air					
w	-	1	3	2779	2829
Unventilated (Non-Metallic) Riser					
y	1	1	3	2782	2832

The first page of each series of tables is indicated.

Type 11
69–500 kV, paper-insulated, high-pressure liquid-filled, pipe type

Number of pipes	Spacing	69 kV		115 kV		138 kV	
		Copper	Aluminum	Copper	Aluminum	Copper	Aluminum
In Buried Pipe							
1	-	2835	2844	2853	2862	2871	2880
2	24 in	2838	2847	2856	2865	2874	2883
2	36 in	2841	2850	2859	2868	2877	2886

Number of pipes	Spacing	230 kV		345 kV		500 kV	
		Copper	Aluminum	Copper	Aluminum	Copper	Aluminum
In Buried Pipe							
1	-	2889	2898	2907	2916	2925	2934
2	24 in	2892	2901	2910	2919	2928	2937
2	36 in	2895	2904	2913	2922	2931	2940

The first page of each series of tables is indicated.

Type 12
115–500 kV, LPP insulated, high-pressure liquid-filled, pipe type

Number of pipes	Spacing	115 kV		138 kV		230 kV	
		Copper	Aluminum	Copper	Aluminum	Copper	Aluminum
In Buried Pipe							
1	-	2943	2952	2961	2970	2979	2988
2	24 in	2946	2955	2964	2973	2982	2991
2	36 in	2949	2958	2967	2976	2985	2994

Number of pipes	Spacing	345 kV		500 kV	
		Copper	Aluminum	Copper	Aluminum
In Buried Pipe					
1	-	2997	3006	3015	3024
2	24 in	3000	3009	3018	3027
2	36 in	3003	3012	3021	3030

The first page of each series of tables is indicated.

Type 13
69–138 kV, paper insulated, high-pressure gas-filled, pipe type

Number of pipes	Spacing	69 kV		115 kV		138 kV	
		Copper	Aluminum	Copper	Aluminum	Copper	Aluminum
In Buried Pipe							
1	-	3033	3042	3051	3060	3069	3078
2	24 in	3036	3045	3054	3063	3072	3081
2	36 in	3039	3048	3057	3066	3075	3084

The first page of each series of tables is indicated.

Introduction to the Power Cable Ampacity Tables

1. Overview

1.1 Scope

This standard provides calculated ratings for the following cables:

Type 1:	600 V–5 kV unshielded extruded dielectric
Type 2:	5–15 kV two conductor shielded URD single phase extruded dielectric
Type 3:	5–46 kV single conductor extruded dielectric
Type 4:	69–138 kV single conductor, unfilled, crosslinked polyethylene
Type 5:	69–138 kV single conductor, filled crosslinked polyethylene and ethylene propylene rubber
Type 6:	5 kV and 15 kV three conductor extruded dielectric
Type 7:	5–35 kV single conductor paper insulated, lead sheathed
Type 8:	5–35 kV, three conductor, paper insulated, lead sheathed, shielded
Type 9:	69–500 kV, single conductor, self contained, paper insulated, liquid filled
Type 10:	69 kV, three conductor, self-contained, paper insulated, liquid filled
Type 11:	69–500 kV high pressure, paper insulated, liquid filled, pipe type
Type 12:	115–500 kV high pressure, laminated paper, polypropylene insulated, liquid filled, pipe type
Type 13:	69–138 kV high-pressure gas-filled, pipe type

Installation conditions include duct banks (as shown in figure 1), direct buried cables, cables buried in ducts, buried pipes, horizontal cable in ducts, in air and vertical non-vented riser cables. The various operating conditions for each of the cable designs and installation conditions are described in the technical features of the tables (clause 3).

1.2 Purpose

Over the past 30 years the AIEE S-135-1 and S-135-2 (IPCEA P-46-426) Power Cable Ampacities publications have often been referred to as the "black books" and have been used by engineers, planners, and system designers throughout the world. During this time period, these publications were the only complete document on power cable ampacities in the United States. In 1976, the Insulated Conductors Committee, in cooperation with the Insulated Cables Engineering Association (ICEA) and the National Electrical Manufacturers Association (NEMA), published supplemental ampacity tables to provide ampacity ratings for single conductor cables with shield losses due to circulating currents. That publication was needed due to the tremendous increase in the use of single conductor extruded dielectric cables with multiple point bonding and grounding.

As time passed, new cable designs were developed with synthetic insulation, different shielding designs and higher operating voltages and temperatures. Moreover, new technology and equipment was developed for measuring the thermal properties of soil. These developments with heat transfer in soils provided a different understanding and approach for rating cables based on maximum cable/earth interface temperature. In addition, new forced convection heat transfer analytical methods were employed for cables in air, which provided for less conservative ampacity ratings.

The tables in this standard reflect these changes in methodology and provide the user with a vast array of cable ampacity ratings for 600 V utilization cables, medium voltage distribution cable and high voltage transmission cables.

2. References

This standard shall be used in conjunction with the following references. Other related documents are listed as bibliographical items in clause 4.

AEIC CS4-93, Specifications for Impregnated-Paper-Insulated Low and Medium Pressure Self-Contained Liquid-Filled Cable.[1]

AEIC G1-68, Guide for Application of AEIC Maximum Insulation Temperatures at the Conductor for Impregnated-Paper-Insulated Cables.

ICEA P-45-482 (1979), Short Circuit Performance of Metallic Shielding and Sheaths.[2]

IEC 287 (1982), Calculation of the Continuous Current Rating of Cables (100% load factor).[3]

IEEE Std 738-1993, IEEE Standard for Calculating the Current Temperature of Bare Overhead Conductors (ANSI).[4]

NEMA WC50-1988/ICEA P-53-426, Ampacities, 15–69 kV 1/c Power Cable Including Effect of Shield Losses (Solid Dielectrics).[5]

3. Technical features of the tables

3.1 Parameters

The calculated ampacities in this standard are based on the parameters and assumptions discussed in the following subclauses.

3.1.1 Voltage

600 V–5 kV, 5 kV, 15 kV, 25 kV, 46 kV, 69 kV, 115 kV, 138 kV, 230 kV, 345 kV and 500 kV as indicated for each cable type.

3.1.2 Load and loss factors

Load factors of 75 and 100 percent (%) and corresponding loss factors 62.5 and 100 percent (%) for buried cables.

3.1.3 Dielectric loss

The dielectric loss was computed based on the values of dissipation factor and dielectric constants listed below. The dielectric loss may have a significant effect on cable ampacity for multiple 15–35 kV cables in a duct bank or for some cables rated above 35 kV. However, in general, the dielectric loss is negligible for single circuit extruded dielectric cables rated up to 35 kV, unless the dissipation factor increases significantly with elevated operating temperatures.

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[1] AEIC publications are available from the Association of Edison Illuminating Companies, 600 N. 18th Street, P. O. Box 2641, Birmingham, AL 35291-0992, USA.

[2] ICEA publications are available from ICEA, P.O. Box 411, South Yarmouth, MA 02664, USA

[3] IEC publications are available from IEC Sales Department, Case Postale 131, 3 rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse. IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

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

[5] NEMA publications are available from the National Electrical Manufacturers Association, 2101 L Street NW, Washington, DC 20037, USA.

For paper cables made prior to 1967, AEIC G1-68[6] recommends higher values of dissipation factor in many cases. See 3.4.2 for method of adjustment for ampacity due to higher dielectric loss.

The dissipation factors (tan δ) and specific inductive capacitance (SIC) for the cable designs in this standard are shown in table 1.

Table 1—Dissipation factors and specific inductive capacitance for cable designs in this standard

Cable type	Description	Tan δ	SIC
4	Extruded dielectric unfilled (69–138kV)	.1%	2.3
5	Extruded dielectric-filled (69–138 kV)	1.5%	3.0
7	Paper/lead 5 kV	2.2%	3.7
7	Paper/lead 15 kV	1.6%	3.7
7	Paper/lead 35 kV	1.1%	3.7
8	3/C paper-lead-cable 5 kV	1.6%	3.7
8	3/C paper-lead-/gas filled 15 kV	1.6%	3.7
8	3/C paper-lead-/gas filled 35 kV	1.1%	3.7
9	Self contained liquid filled 69–138 kV	.33%	3.5
9	Self contained liquid filled 230 kV	.27%	3.5
9	Self contained liquid filled 345–500 kV	.24%	3.5
10	3/C-self contained liquid filled 69 kV	.33%	3.5
11	High pressure-liquid filled, paper/pipe type 69–138 kV	.30%	3.5
11	High pressure-liquid filled, paper/pipe type 230–500 kV	.25%	3.5
12	High pressure-liquid filled, paper/pipe type 115–500 kV	.10%	2.8
13	High pressure-paper insulated gas-filled pipe type 69–138 kV	.30%	3.5

3.1.4 Thermal resistivity

3.1.4.1 Earth thermal resistivity

Thermal resistivities of 60 °C, 90 °C, and 120 °C centimeters per watt (°C cm/W) are shown as 60 RHO, 90 RHO, and 120 RHO in the tables. In the past, when the thermal resistivity of the earth was not known a rho of 90 was recommended for rating the cable. However, the ratings for buried cables are significantly affected by the earth's portion of the thermal circuit and therefore correct knowledge of the effective soil thermal resistivity and soil thermal stability is paramount in establishing the correct rating for a buried cable system.

3.1.4.2 Duct banks

— Fiber duct: 480 °C cm/W
— Concrete: 60 °C cm/W

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[6] Information on references can be found in clause 2.

3.1.4.3 Jackets

- Cable types 3–6: 600 °C cm/W
- Cable types 7–10: 500 °C cm/W

3.1.4.4 Cable insulation

- Extruded insulations: 350 °C cm/W
- Paper (solid) and low pressure gas filled: 600 °C cm/W
- Paper (self contained) liquid filled: 550 °C cm/W
- Paper or LPP (pipe type): 600 °C cm/W

3.1.4.5 Pipe coating

- 400 °C cm/W

3.1.5 Temperatures

Ambient temperatures were selected at 25 °C earth ambient for buried cables and 40 °C for air. Conductor temperatures are as shown in table 2.

3.2 Cable constructions

3.2.1 Conductors

Copper and aluminum conductors are considered in this standard. Conductor sizes span the range covered by applicable industry standards, however all sizes are not shown. The variety of conductor sizes used for each cable type are shown in table 3. Strand types are as follows:

C	concentric
CR	compact round
CCR	concentric round
SG	compact segmental (4 segments)
SECT	120° sector
HC	hollow core concentric
HS	6 segment hollow core

3.2.2 Insulation

Cable insulation thicknesses for each cable type are shown in table 3.

3.2.3 Metallic shields

Metallic shield losses were included for all cable types except type 1. The operating conditions for the metallic shield were as follows:

- Cables in trefoil geometry: short-circuited
- Spaced cables:
  - Short-circuited shields up to and including 500 kcmil copper and 750 kcmil aluminum
  - Short- and open-circuited shields for 750–2350 kcmil copper and 1000–1750 kcmil aluminum
  - Open-circuited shields only for 1500 kcmil copper and 2000 kcmil aluminum and larger
- Pipe cables: short-circuited shields

Table 2—Conductor temperatures (°C)

Cable type	Installation conditions				
	Duct bank	**Direct buried**	**Buried duct**	**Buried pipe**	**Air**
1	75°/90°	50–90°[a]	X	X	75°/90°
2	X	50–90°[a]	50–90°[a]	X	75°/90°
3	75°/90°	50–90°[a]	50–90°[a]	X	75°/90°
4	90°	50–90°[b]	X	X	90°
5	90°	50–90°[b]	X	X	90°
6	75°/90°	50–90°[a]	X	X	75°/90°
7 (5 kV)	95°	50–95°[c]	X	X	95°
7 (15 kV)	90°	50–90°[b]	X	X	90°
7 (35 kV)	80°	50–80°[d]	X	X	80°
8 (5–15 kV)	90°	50–90°[b]	X	X	90°
8 (35 kV)	80°	50–80°[d]	X	X	80°
9 (69–138 kV)	85°	50–85°[e]	X	X	85°
9 (230–500 kV)	85°	85°	X	X	85°
10	85°	50–85°[e]	X	X	85°
11	X	X	X	85°	X
12	X	X	X	85°	X
13	X	X			X

[a] includes 50°, 65°, 75°, 80°, 90° temperatures
[b] includes 50°, 65°, 80°, 90° temperatures
[c] includes 50°, 65°, 85°, 95° temperatures
[d] includes 50°, 65°, 70°, 80° temperatures
[e] includes 50°, 65°, 75°, 85° temperatures

Metallic shield sizes for extruded dielectric cables rated through 46 kV ranged from full conductance of the core conductor to an equivalent 1/36 conductance as shown in the tables. Extruded dielectric cables rated 69–138 kV have metallic shields sized for carrying fault current in accordance with ICEA P-45-482 for thermoplastic jackets. Shield sizes and fault current duty are as shown below:

Fault current magnitude	Shield resistance (µΩ/ft @ 25 °C)
10 kA for 8 cycles (0.133 sec)	207
15 kA for 8 cycles	138
20 kA for 8 cycles	103
30 kA for 8 cycles	69

Three conductor shielded extruded dielectric cables 5 kV and 15 kV (type 6) have a 5 mil copper tape shield on each single conductor within the cable.

Table 3—Cable conductor sizes and insulation thicknesses

Cable type	Voltage	Conductor sizes	Insulation thickness (mils)
1	600 to 5 kV	#12AWG–#10AWG	45
1	600 to 5 kV	#8AWG–#2AWG	60
1	600 to 5 kV	#1AWG–#4/0 AWG	80
1	600 to 5 kV	250–500 kcmil	95
1	600 to 5 kV	600–1000 kcmil	110
2	5 kV	#4–4/0 AWG	90
2	15 kV	#4–4/0 AWG	175
3	5–15 kV	#2AWG–1000 kcmil	175
3	5–15 kV	1000–2000 kcmil	220
3	25–46 kV	#1AWG–2000 kcmil	345
4–5	69 kV	500–2500 kcmil	650
4–5	115–138 kV	750–2500 kcmil	800
6	5 kV	#8AWG–1000 kcmil	90
6	15 kV	#2AWG–1000 kcmil	175
7	5 kV	#4/0AWG–1000 kcmil	100
7	5 kV	1250–3000 kcmil	105
7	15 kV	#4/0AWG–3000 kcmil	165
7	35 kV	#4/0AWG–3000 kcmil	330
8	5 kV	#6AWG–1000 kcmil	85 × 45
8	15 kV	#4AWG–#2AWG	180
8	15 kV	#1/0AWG–1000	165
8	35 kV	#2/0AWG–1000	330
9	69 kV	#4/0AWG–3000	270
9	115 kV	350–750 kcmil	420
9	115 kV	1000–3000 kcmil	375
9	138 kV	750 kcmil	490
9	138 kV	1000–3000 kcmil	440

Table 3—Cable conductor sizes and insulation thicknesses (*Continued*)

Cable type	Voltage	Conductor sizes	Insulation thickness (mils)
9	230 kV	1000–2000 kcmil	745
9	230 kV	2250–3000 kcmil	605
9	345 kV	1000–1250 kcmil	1020
9	345 kV	1500–3000 kcmil	905
9	500 kV	2000–2250 kcmil	1325
9	500 kV	2500–4000 kcmil	1235
10	69 kV	1/0 AWG–1000 kcmil	270
11	69 kV	3/0 AWG–4000 kcmil	270
11	115 kV	350 kcmil–750 kcmil	420
11	115 kV	1000–4000 kcmil	375
11	138 kV	500–750 kcmil	490
11	138 kV	1000–4000 kcmil	440
11	230 kV	1000–2000 kcmil	745
11	230 kV	2250–4000 kcmil	605
11	345 kV	1000–1250 kcmil	1020
11	345 kV	1500–4000 kcmil	905
11	500 kV	2000–4000 kcmil	1100
12	115 kV	350–4000 kcmil	250
12	138 kV	500–750 kcmil	300
12	138 kV	1000–4000 kcmil	270
12	230 kV	1000–2000 kcmil	475
12	230 kV	2250–4000 kcmil	490
12	345 kV	1500–4000 kcmil	600
12	500 kV	2000–4000 kcmil	745
13	69 kV	3/0 AWG–4000 kcmil	300
13	115 kV	500–4000 kcmil	485
13	138 kV	500–4000 kcmil	585

Paper lead (type 7) cables and three conductor paper lead/low pressure gas (type 8) cables have lead sheaths with 7.84% IACS conductivity lead in accordance with AEIC G1-68 specifications. Each conductor shield with 3 mil copper tape and intercalated paper tape. Paper lead self-contained cables (types 9 and 10) have lead sheaths (7.84% IACS lead) for 3 conductor cables and single conductor cables through 345 kV. Ratings for corrugated aluminum shields are also included for 138–500 kV single conductor cables. Shield size is in accordance with AEIC CS4-93 pipe type cables.

3.2.4 Jackets and pipe coatings

Jackets were included on cable types 3, 4, 5, 6 (7 and 8 for cables direct buried only), 9 and 10. Jacket thickness for all cable types except 9 and 10 were as follows:

Calculated diameter under jacket (in)	Jacket thickness (mils)
up to 1.500	80
1.501 to 2.500	110
2.501 and larger	140

Cable types 9 and 10 have jacket thicknesses in accordance with table III in AEIC CS4-93.

Pipe coatings for pipe type cables (types 11, 12 and 13) were as follows:

Pipe size (in)	Coating thickness
4 1/2 × 0.237	0.070
5 9/16 × 0.258	0.070
6 5/8 × 0.250	0.070
8 5/8 × 0.250	0.070
10 3/4 × 0.250	0.110
12 3/4 × 0.250	0.110

3.3 Installation conditions

3.3.1 Duct banks (30 inches cover over top of duct bank)

Duct bank geometry is shown in installations a–h of figure 1. Duct spacing (S) is 7.5 inches for installations b, c, d, e, and f and 12 inches for installations g and h.

3.3.2 Direct buried

Cables directly buried in the earth 36 inches deep for installations i through l as indicated in the tables and shown in figure 1. Cable spacing (S) is 7.5 inches, except for cable types 4, 5, and 9, where spacing is 12 inches. Circuit spacing (D) is 24 inches for installations j and l. Where cables are touching, the spacing between cables is equal to the diameter of the cable.

3.3.3 Buried ducts

Cables buried in ducts, 36 inches deep for installations m–p as indicated in the tables and shown in figure 1. Cable spacing (S) is 7.5 inches and circuit spacing (D) is 24 inches. Where conduits are touching for type 2 cables the spacing between cables is equal to the diameter of the cable.

3.3.4 Buried pipes

Pipe type cables buried 36 in deep for installation q as indicated in the tables and shown in figure 1. Circuit spacing (S) is 24 and 36 in.

3.3.5 Cables in air

Cables in still air are rated at 40 °C ambient temperature, no solar heat and no wind. Cables in moving air are rated with ambient air at 40° C, solar effect at 95 W/ft^2 (horizontal) and 65 W/ft^2 (vertical) and wind speed of 2 ft/sec. Installation conditions include cables and conduits in horizontal position and non-ventilated vertical risers.

Coefficient of emissivity (ε) and absorptivity (α) are as follows:

Surface	No sun	Sun	
	ε	α	ε
Lead sheaths	0.30	0.30	0.30
Black jackets	0.92	0.95	0.92
Steel pipe	0.50	0.50	0.50

3.3.6 Conduit and duct diameters

Conduit and duct diameter are selected to provide a minimum of 0.75 in of clearances between O.D. of cable or circumscribed diameter of three triplexed cables and I.D. of conduit or duct. Minimum duct size is 5.047 I.D. with 0.250 in wall.

Conduit or duct sizes for steel or PVC are as follows:

Nominal diameter (in)	O.D. (in)	Wall (in)	I.D. (in)
2	2.375	0.154	2.067
3	3.500	0.216	3.068
4	4.500	0.237	4.026
5	5.563	0.258	5.047
6	6.625	0.280	6.065
8	8.625	0.322	7.981
10	10.75	0.365	10.02

3.4 Adjustments for change in parameter

3.4.1 Adjust for changes in ambient temperature

The ampacities in the tables of this standard are based on an ambient temperature of 25 °C for buried cables and 40 °C for cables in air. Ampacities may be corrected for different ambient temperatures using the following equation:

$$I' = \sqrt{\frac{T_c - T_a'}{T_c - T_a}} \times I$$

where

T_c is maximum conductor temperature used in the tables
T_a is ambient temperature used in the tables
I is ampacity shown in tables for T_c and T_a
T_a' is new ambient temperature
I' is adjusted ampacity for ambient temperature T_a'

Ampacities for cables in air are calculated with the heat transfer parameters that are a function of temperature. The ampacities shown in the table were calculated iteratively to produce correct temperature gradients for each condition. Therefore, adjustments to the ambient air temperature will result in errors for the $\bar{R}_{sd}$ and $\bar{R}_e$ terms. Therefore, it is recommended that ampacities for aerial cables be re-calculated as needed.

3.4.2 Adjustment for change in maximum conductor temperature or temperature due to dielectric loss

The ampacities in the tables are based on various maximum conductor temperatures as shown in table 2. Also, the temperature rise due to dielectric loss (ΔT_d) is proportional to the dissipation factor and specific inductive capacitance (SIC). Therefore, if either the temperature of temperature rise is different than that used in the ampacity tables, the ampacity may be corrected using the following equation:

$$I' = \sqrt{\frac{T_c' - T_a - \Delta T_d'}{T_c - T_a - \Delta T_d} \times \frac{\tau_c + T_c}{\tau_c + T_c'}} \times I$$

where

T_c is maximum conductor temperature used in the tables.
T_a is ambient temperature used in the tables
ΔT_d is temperature rise due to dielectric loss
I is ampacity shown in tables for T_c, T_a, and ΔT_d
T_c' is new maximum conductor temperature
$\Delta T_d'$ is new temperature rise due to dielectric loss
τ_c is inferred temperature of zero electrical resistance (234.5 for copper conductors, 228.1 for aluminum conductors)

When $T_{c'} > T_c$ the above formula will give conservative values since it is based on the ratio of direct current losses at the two temperatures while the ratio of the alternating-current conductor and shield losses (if any) to direct-current conductor losses decreases with increasing conductor temperature. Deviations from true ampacities will depend on the conductor size, shield size and installation configuration. However, this correction is more precise for smaller and higher resistance shields.

3.5 Method of calculation

Calculations for buried cable systems are based on the procedures shown in [B4]. Calculations for cables or conduits in air are based on procedures shown in IEEE Std 738-1993, [B1], and [B2].

Due to the variety of operating conditions and many cable designs considered in this standard, the procedures shown in [B4] and IEEE Std 738-1993 have been modified or supplemented to improve the accuracy or to simplify the calculation procedure in some cases. The following gives an outline of the additions or modifications for the method of calculation.

3.5.1 Single phase cables

Current in the concentric neutral was assumed to be equal to half of the conductor current. Resistance of concentric neutral was equal to both full and one-half conductance of phase conductor. Q_s modified as follows:

$$Q_s = 1 + R_s / 4R_{dc}$$

3.5.2 Dielectric loss

Dielectric losses were computed at rated voltage up to 138 kV and at 230 kV + 5%, 345 kV + 5%, and 500 kV + 5%.

3.5.3 Three conductor cables—thermal resistance of insulation

The thermal resistance of the insulation and shielding tapes for three conductor cables was calculated with methods shown in sections C3, C4, and C5 of IEC 287 (1982).

3.5.4 Conductor losses

NOTE—The source for equations 1, 2, 3, and 4 is NEMA WC50-1988/ICEA P-53-426.

3.5.4.1 Skin effect

Equation 21 of [B4] was replaced with the following equations:

$$Ycs = Fsp(x)$$

where

$$x = \frac{R_{dc}}{k_s} \tag{1}$$

and

$$Fsp(x) = \frac{11.0}{\left(x + \frac{4}{x} - \frac{2.56}{x^2}\right)^2} \tag{2}$$

except where x has a value < 7.2, then:

$$Fsp(x) = \frac{11.0(1 - 0.1102/x)}{\left(4 + \frac{4}{x} - \frac{2.56}{x^2}\right)^2} \tag{3}$$

3.5.4.2 Proximity effect

Equation 24 of [B4] was supplemental where $F(x_p)$ was calculated as follows:

$$F(x_p) = Fsp(x)\text{, where } x = \frac{R_{dc}}{k_p} \tag{4}$$

and $Fsp(x)$ is identical to equations 2 and 3.

3.5.5 Shield loss

NOTE—The source for equation 5 is NEMA WC50-1988/ICEA P-53-426.

Circulating current losses (Y_{sc}) were calculated for cables as described in 3.2.3 for cable geometries shown in figure 1 (except geometry l and p) using equations from table XIII in chapter 10 of [B5]. For items l and p of figure 1, general equations (number 17, 18, 19, 20, and 21) of [B3] were used to solve for shield currents $\bar{I}_1$, $\bar{I}_2$, and $\bar{I}_3$.[7] For all double circuits, shield currents are equal for cables A_1 and A_2, B_1 and B_2, and C_1 and C_2 (items f, h, l, and p of figure 1). Equation 27 of [B4] has been replaced by:

$$Y_{sc^{(n)}} = \left[\frac{\bar{I}_n}{\bar{I}_b}\right]^2 \frac{R_s}{R_{dc}} \tag{5}$$

where $Y_{sc}{}^{(n)}$ is the ratio of the shield loss in cable n to the conductor direct current loss. The reference conductor current is $\bar{I}_B = 1 + j0$. $\bar{I}_1$ through $\bar{I}_6$ are the shield currents of cables A_1, B_1, C_1, A_2, B_2, and C_2. The phase sequence for vertical geometries (items f and h of figure 1) is

$$\begin{bmatrix} A & C \\ B & B \\ C & A \end{bmatrix}$$

and for horizontal geometries (items l and p of figure 1) is *ABC–CBA*.

The phase sequences assume a rotation where *A* indicates the leading phase and *C* indicates the lagging phase. However, for the single circuit arrangements shown in items k and o of figure 1, the maximum value of shield loss occurs on one of the outside cables for all possible phase sequences (*A–B–C*, *C–B–A* or *A–C–B*) and the ampacity is not affected.

These solutions assume that the conductor currents of all phases are equal in magnitude, which may be an important consideration where two parallel circuits are tied to the same load buss. For the double circuit arrangements of items l and p of figure 1, alternate phase sequence arrangements A_1–B_1–C_1–A_2–B_2–C_2 or A_1–A_2–B_1–B_2–C_1–C_2 would result in a significant imbalance between conductor currents if the two circuits were operated in parallel from a common buss.

Eddy current losses (Y_{sc}) were calculated for all-metallic shields following the assumption that a path is present in the shields for the eddy currents to flow. Large cables with close spacing and open wire shields will therefore be conservatively rated for eddy current losses, as the losses cannot occur in open wire shields.

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[7] Miller's equations assume that currents exist in the shield but not in the earth (shields bonded at more than one point but grounded at only one point). However, in cases where earth currents exist due to multiple ground, they are small because of the relatively high impedance of the earth. These small earth currents will not significantly affect the values of Y_{sc}.

3.5.6 Horizontal cables in air

NOTE— The source for equations 6, 7, 8, and 9 is IEEE Std 738-1993.

The external thermal resistance $(\bar{R}_{sd'})$ for horizontal cables or conduit in air is calculated using the following equations:

$$\bar{R}_e' = \frac{n'\Delta T}{W_c + W_r} TOF \tag{6}$$

where

n'	is number of conductors within stated diameter
ΔT	is $T_s - T_a$ temperature difference between cable or conduit surface and ambient (°C)
W_c	is W loss from free or forced convection (W/ft)
W_r	is W loss from radiation/W/ft

Free convection (V = wind velocity = 0)

$$W_c = 0.072 d^{0.75} \Delta T^{1.25} \tag{7}$$

where

d is D_s' (in) per Neher-McGrath [B4]

$\Delta T = T_s - T_a$

Forced convection ($V > 0$)

W_c = larger of W_{c1} and W_{c2}

$$W_{c1} = [1.01 + 0.371 (d\ \rho f\ V/\mu)^{0.52}]\, k_f \Delta T \tag{8}$$

$$W_{c2} = 0.1695 (d\ \rho f\ V/\mu)^{0.6} k_f \Delta T \tag{9}$$

where

d	is D_s' (in) per Neher-McGrath
ρf	is air density (lb/ft^3) @ t_f
t_f	is air film temperature $(t_s - t_a)/2$ (°C)
V	is velocity of air (ft/h)
μ	is absolute viscosity of air (lb/h, ft)
k_f	is thermal conductivity of air (w/ft–°C)

$$W_r = 0.10256 D_s' \varepsilon \Delta T (1 + 0.0167 Tm) \text{ W/ft} \text{ (equation 55A of Neher-McGrath)}$$

where

ε is emissivity of cable or conduit surface

3.5.7 Vertical cables in air-cable riser

NOTES
1— The source for equations 10, 11, 12, 13, and 14 is [B1] and [B2].
2— An * (asterisk) is used to note that *Nu* (Nusselt number), *Gr* (Grashof number) and *Pr* (Prandtl number) are non-dimensionalized and may be calculated with U.S. standard or metric units.

The internal thermal resistance $(\bar{R}_{sd'})$ between cable surface and riser conduit surface is calculated using the following equations:

$$\bar{R}_{sd} = \frac{n'\Delta T}{W_{cv} + W_r} TOF \qquad (10)$$

where

n = number of conductors within a stated diameter

$\Delta T = T_j - T_{ik}$ = temperature difference between cable surface and inside surface of riser

$$W_{cv} = \frac{hA\Delta T}{x}$$

where

$$h = \frac{N_u k_f}{x}$$

therefore

$$W_{cv} = \frac{0.083\ \mathrm{k}_f N_u \pi d \Delta T}{x} \mathrm{W/ft} \qquad (11)$$

where

k_f	is thermal conductivity or air (W/ft °C)
N_u	is Nusselt number
d	is D_s', circumscribed diameter of cables (in) (Neher-McGrath)
x	is height of riser (ft)

$$*N_u = C(GrPr)^m$$

$$*Gr = \frac{\mathrm{g}\beta\Delta \mathrm{T} \mathrm{x}^3}{\mu k^2}$$

$$*Pr = \frac{C_p \mu_k}{k_f} (\approx 0.7)$$

where

x is height of riser
β is expansion coefficient of air
g is acceleration of gravity
μ_k is kinematic viscosity of air
C_p is specific heat or air
k_f is thermal conductivity of air

for $10^4 \geqq GrPr \leqq 10^9$, $C = 0.59$, $m = 0.25$

for $10^9 > GrPr \eqslantless 10^{19}$, $C = 0.21$, $m = 0.4$

W_r (equation 55A Neher-McGrath) except convert ε (surface emissivity) to an effective emissivity ($\varepsilon_{\mathrm{eff}}$)

$$\varepsilon_{eff} = \frac{1}{\left[\frac{1}{\varepsilon_c} + \frac{d}{D}\left(\frac{1}{\varepsilon_r} - 1\right)\right]} \tag{12}$$

where

ε_c is cable surface emissivity
ε_r riser surface emissivity
d is D_s,
D is I.D. of riser

The external thermal resistance $(\bar{R}_e)$ between riser surface and ambient air is calculated using the following equations:

$$\bar{R}_e = \frac{n'\Delta T}{W_{cv} + W_r} TOF \tag{13}$$

where

n' is number of conductors within a stated diameter

$\Delta T = T_k - T_a$, temperature difference between outside surface of riser and ambient air.

$$W_{cv} = \frac{hA\Delta T}{x}$$

$$h = \frac{Nu_x k_f}{x}$$

$$W_{cv} = \frac{0.083\ k_f Nu_x \pi D \Delta T}{x} \mathrm{W/ft} \tag{14}$$

where

k_f	is thermal conductivity of air (W/ft–°C)
Nu_x	is Nusselt number
D	is outside diameter of riser (in)
x	is height of riser (ft)

$$*Nu_x = C(Gr_xPr)^m$$

$$*Gr_x = \frac{g\beta q_w x^4}{k_f \mu_k^2}$$

$$*\mathrm{Pr} = \frac{C_p \mu_k}{k_f} (\approx 0.7)$$

where

x	is expansion coefficient of air
g	is acceleration of gravity
μ_k	is kinematic viscosity of air
C_p	is specific heat
k_f	is thermal conductivity of air
q_w	is heat flux on riser surface in W per unit area
q_w	is $(W_{cv} + W_r)/\pi D$

for $10^5 \geq Gr_x \leq 10^{11}$, $C = 0.6$, $m = 0.4$

for $10^{11} > Gr_x \leq 10^{16}$, $C = 0.17$, $m = 0.25$

W_r (equation 55A Neher-McGrath) except ε = riser emissivity and $Tm = 0.5(T_a + T_k)$

where

T_k	is temperature of riser surface (°C)
T_a	is ambient temperature (°C)

3.6 Definition of constants

Various constants are tabulated for cables rated 69 kV and above. These constants may be used to verify methods of calculation or for comparison between cable ratings.

$\overline{R}_i$	is thermal resistance of insulation wall (TOF)
$\overline{R}_j$	is thermal resistance of jacket (TOF)
$\overline{R}_{sd}$	is thermal resistance from cable surface to inside surface of duct, conduit or vertical riser (TOF)
$\overline{R}_d$	is thermal resistance of non-metallic conduit or duct wall (TOF)
$\overline{R}_e$	is thermal resistance from cable or conduit surface to ambient earth including mutual heating from all other cables (buried cables). Thermal resistance from cable conduit or riser surface to ambient air (aerial cables) (TOF).
Q_s	is average effective ratio of conductor pulse shield loss to conductor loss.

For the case of *N* 1/c spaced cables, the losses in each cable are different. The average effective loss is defined as follows:

$$Q_s = \frac{\sum_{m=1}^{N} [Q_s(m) R(n, m)]}{\sum_{m=1}^{N} [R(n, m)]}$$

where

N	is number of spaced cables
n	is hottest cable
m	is index of each cable

For $m \neq n$: $R(n, m)$ = mutual thermal resistance between cables m and n.

For $m=n$: $R(n, m) = \bar{R}_j + \bar{R}_{sd} + \bar{R}_d + \bar{R}_e(n)$

Q_e	is ratio of "conductor + shield + conduit or pipe loss" to "conductor loss"
R_{ac}	is ac resistance at the conductor (μΩ/ft)
W_d	is dielectric loss (W/ft)

Total W/ft is tabulated corresponding to each ampacity. The losses are included for all cables in the circuit.

Total W/ft^2 is tabulated for single conductor and three conductor cables (types 1–10) that are direct buried. The effective outside diameters for the cable geometries are as follows:

Cable	Diameter
3-1/c cables direct buried	1.587 × O.D. of one cable
3-1/c cable in conduit	O.D. of conduit
1-1/c cable direct buried	O.D. of cable
1-1/c cable in conduit	O.D. of conduit
1-3/c cable direct buried	O.D. of 3/c cable

Shield resistance is shown in μΩ/ft at 20 °C.

Neutral size is shown as a conductance ratio of metallic shield size to phase conductor size.

4. Bibliography

[B1] Hartlein, R. A., "Heat Transfer from Electric Power Cables Enclosed in Vertical Protective Shield." Thesis, Georgia Institute of Technology, 1982.

[B2] Holman, J. P., *Heat Transfer*, 4th ed. New York: McGraw-Hill, 1976.

[B3] Miller, K. W., "Sheath Currents, Sheath Losses, Induced Sheath Voltages and Apparent Conductor Impedances of Metal Sheathed Carrying Alternating Current." Thesis, University of Illinois Graduate School, Chicago, 1929.

[B4] Neher, J. H. and McGrath, M. H., "The Calculation of the Temperature Rise and Load Capability of Cable Systems," *A.I.E.E. Transactions*, vol. 76, pt. III, pp. 752–772, Oct. 1957.

[B5] *Underground Systems Reference Book*, EEI Publication 55-16, Edison Electric Institute, New York, 1957.

Annex A
Electrical/thermal circuit

(normative)

A.1 Electrical/thermal analog circuit

Steady-state temperature rise calculations for insulated cable systems are made using the Neher-McGrath method for all buried cables and the House & Tuttle (IEEE Std 738-1993) method for cables in air. These analytical methods are employed through the application of thermal equivalents of Ohm's and Kirchoff's Laws to a simple thermal circuit which is described in figure A1.

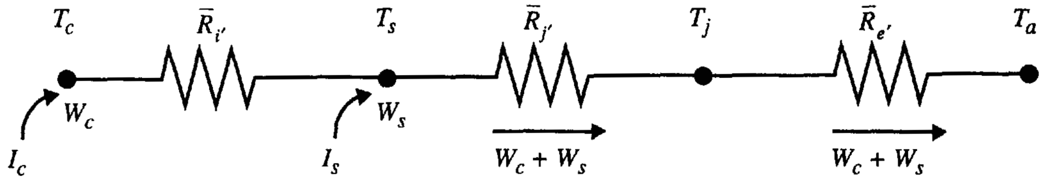

Figure A1—Application of thermal equivalents of Ohm's and Kirchoff's Laws to a simple thermal circuit

where

I_c	is current in the conductor (A)
W_c	is W generated in the conductor (heat) (W/ft)
I_s	is current in the metallic shield (A)
W_s	is W generated in the shield
$W_c + W_s$	is W generated in the conductor and shield (W/ft)
T_c	is temperature of the conductor (°C)
T_s	is temperature of the shield (°C)
T_j	is temperature of jacket (°C)
T_a	is ambient temperature (°C)
$\bar{R}_{i'}$	is thermal resistance of insulation [Thermal Ohm Feet (TOF)]
$\bar{R}_{j'}$	is thermal resistance of jacket (can also include conduits) (TOF)
$\bar{R}_{e'}$	is thermal resistance of the earth or external thermal circuit (air, duct bank, etc.) (TOF)

Define circuit equivalents and collect terms:

$$T_c = W_c\bar{R}_i' + (W_c + W_s)\bar{R}_j' + (W_c + W_s)\bar{R}_e' + T_a$$

$$T_c - T_a = W_c\bar{R}_i' + (W_c + W_s)\bar{R}_j' + (W_c + W_s)\bar{R}_e'$$

Divide by W_c

$$\frac{T_c - T_a}{W_c} = \bar{R}_i' + \left(\frac{W_c + W_s}{W_c}\right)\bar{R}_j' + \left(\frac{W_c + W_s}{W_c}\right)\bar{R}_e'$$

Let $Q_s = \frac{W_c + W_s}{W_c}$ (Ratio of losses in the conductor and shield to the conductor)

then

$$\frac{T_c - T_a}{W_c} = \bar{R}_i' + Q_s\bar{R}_j' + Q_s\bar{R}_e'$$

NOTE—The right side of the above equation is designated $\bar{R}_{ca}'$ as in equation 8 of Neher-McGrath [B4] where $\bar{R}_{ca}'$ is the total thermal resistance between the conductor and ambient.

then

$$T_c - T_a = W_c\bar{R}_{ca}'$$

where

W_c $= I^2 Rdc\,(1 + Y_c)$
I = current in conductor
Rdc = dc resistance of conductor
$(1 + Y_c)$ = skin and proximity effects

therefore

$$T_c - T_a = I^2 Rdc\,(1 + Y_c) \times \bar{R}_{ca}'$$

Solve for I:

$$I = \sqrt{\frac{T_c - T_a}{Rdc\,(1 + Y_c) \times \bar{R}_{ca}'}} \times 10^3 \text{A (equation 9 in Neher-McGrath)}$$

When dielectric losses are present in the cable system the additional losses are present and result in temperature rise expressed as:

$$\Delta T_d = W_d\bar{R}_{da}' \ {}^\circ\text{C (equation 6 in Neher-McGrath)}$$

From equation 9 in Neher-McGrath, it follows that the temperature rise due to dielectric loss is calculated as follows:

$$I = \sqrt{\frac{T_c - (T_a + \Delta T_d)}{Rdc\,(1 + Yc) \times \bar{R}_{ca}'}} \times 10^3 \text{A}$$

A.2 Calculation examples

Equations are numbered identical to those shown in [B4]. The remaining equations are identified from IEEE Std 738-1993 or NEMA WC50-1988/ICEA P-53-426, and are noted separately.

A.2.1 Example 1: 3-1/c 350 kcmil aluminum, 600 V cables installed in a 3 inch PVC conduit in the earth

Calculation example for:

3-1/c 350 kcmil aluminum conductor cables, 600 V, XHHW insulated (0.095 in wall) installed in 3 inch PVC conduit, buried 36 inches in earth.

Earth thermal resistivity: 120 °C cm/W (ρ_e)
Ambient earth temperature: 25 °C
Load factor: 75%
Operating temperature: 90 °C

Cable Dimensions

O.D. over conductor: 0.681 in
O.D. over insulation: 0.871 in
* Circumscribed diameter = 2.15 × 0.871 = 1.873 in

Conductor resistance

Rdc of 350 kcmil aluminum cable = 50.5 µΩ/ft @ 25 °C (value from tables)

Temperature correction

$$Rdc = \frac{228.1 + 90}{228.1 + 25} \times 50.5 = 63.47 \text{ microhms/ft @ } 90\ ^\circ\text{C}$$

Skin effect

$$Y_{cs} = F_{sp}(x)$$

where

$$k_s = 1 \text{ and } F_{sp}(x) = \frac{11.0}{\left(x + \frac{4}{x} - \frac{2.56}{x^2}\right)^2}$$ (equation F2 of NEMA WC50-1988/ICEA P-53-426)

$$x = \frac{Rdc}{k_s}$$

$$x = \frac{63.47}{1} = 63.47$$

$$F_{sp}(x) = \frac{11.0}{\left(63.47 + \frac{4}{63.47} - \frac{2.56}{(63.47)^2}\right)^2}$$

$$F_{sp}(x) = 0.0027$$

Proximity effect

where

$$F(xp) = F_{sp}(x)$$

$$x = \frac{Rdc}{k_p}$$

$$Ycp = Fxp\left(\frac{Dc^2}{s}\right) \times \left[\frac{1.18}{F(xp) + 0.27} + 0.312\left(\frac{Dc}{S}\right)^2\right] \text{ (equation 24)}$$

$$Ycp = 0.0027\left(\frac{0.681}{0.871}\right)^2 \times \left[\frac{1.18}{0.0027 + 0.27} + 0.312\left(\frac{0.681}{0.871}\right)^2\right]$$

$$Y_{cp} = 0.0075$$

AC resistance

$$R_{ac} = Rdc\,(1 + Ycs + Ycp) \text{ (equation 20)}$$

$$R_{ac} = 63.47\,(1 + 0.0027 + 0.0075)$$

$$R_{ac} = 64.12 \text{ microhm/ft @ 90 °C}$$

Thermal resistances

Insulation

$$\bar{R}_i' = 0.012\bar{\rho}i\log\frac{Di}{Dc} \text{ TOF (equation 38)}$$

$$\bar{R}_i' = 0.012\,(350)\,\log\frac{0.871}{0.681}$$

$$\bar{R}_i' = 0.449 \text{ TOF}$$

Cable to conduit

$$R_{sd}' = \frac{n'A}{1 + (B + CTm)\,D_s'} \text{ TOF (Equation 41)}$$

$$R_{sd}' = \frac{3\,(17)}{1 + [2.3 + 0.024\,(70)]\;(2.15 \times 0.871)}$$

$$R_{sd}' = 6.033 \text{ TOF}$$

Conduit wall

Dimensions

O.D: 3.50 in

I.D.: 3.068 in

Wall: 0.216 in

$$\bar{R}_c' = 0.0104\rho_c n'\left(\frac{t}{D - t}\right) \text{ TOF (Equation 40)}$$

$$\bar{R}_c' = 0.0104 \times 600 \times 3\left(\frac{0.216}{3.50 - 0.216}\right)$$

$$\bar{R}_c' = 1.232 \text{ TOF}$$

Thermal diffusivity (Dx calculation)

$$D_x = 1.02\sqrt{\alpha \times 24 \text{ hrs.}} \text{ (equation 45)}$$

where

$$\alpha = \frac{104}{\rho_e^{0.8}}$$

$$\alpha = \frac{104}{120^{0.8}} = 2.26 \text{ in}^2/\text{h}$$

$$D_x = 1.02\sqrt{2.26 \times 24}$$

$$D_x = 7.51 \text{ in}$$

Earth to ambient

$$R_e{}' = 0.012\rho_e{}'n'\left[\log\frac{Dx}{De} + LF\log\left(\frac{4L}{D_x}\right)\right]\ \text{TOF (equation 44)}$$

where

$Dx = 7.51$ in

$L = 36$ in

$F = 1$

$De = 3.5$ in

$LF = 0.3lf + 0.7\,(lf)^2$ (equation 3)

$$R_e{}' = (0.012)\,(120)\,(3)\left[\log\frac{7.51}{3.5} + 0.62\log\left(\frac{4\times 36}{7.51}\right)1\right]$$

$R_e{}' = 4.868$ TOF

Total effective thermal resistance

$\bar{R}_{ca}{}' = \bar{R}_i{}' + \bar{R}_{sd}{}' + \bar{R}_c{}' + \bar{R}_e{}'$ (equation 8) NOTE—Q_s term drops out with unshielded cables

$= 0.449 + 6.033 + 1.232 + 4.868$
$= 12.58$ TOF

Ampacity

$$I = \sqrt{\frac{T_c - T_a}{Rdc\,(1+Y_c)\,\bar{R}_{ca}{}'}}\ \text{kA (equation 9)}$$

$$I = \sqrt{\frac{90-25}{(64.12)\,(12.58)}} = 0.284\times 10^3\text{A}$$

$I = 284$ A for cables in 3 inch buried conduit

Revise calculation for same cables directly buried in the earth.

Thermal resistance to earth to ambient

**New effective diameter $-1.594 \times 0.871 = 1.39$ in

$$\bar{R}_e{}' = (0.012)\,(120)\,(3)\left[\log\frac{7.51}{1.39} + 0.62\log\left(\frac{4\times 36}{7.51}\right)1\right]$$

$\bar{R}_e{}' = 6.60$ TOF

Total effective thermal resistance

$$\bar{R}_{ca}' = \bar{R}_i' + \bar{R}_e'$$

$$\bar{R}_{ca} = 0.449 + 6.60$$

$$\bar{R}_{ca} = 7.049 \text{ TOF}$$

Ampacity

$$I = \sqrt{\frac{90 - 25}{(64.12)\ (7.049)}} = 0.379 \times 10^3$$

$I = 379$ A (directly buried)

*Diameter for convective heat transfer

**Effective diameter to account for superposition and mutual heating for conduction

A.2.2 Example 2: 3-1/c 250 kcmil aluminum, 35 kV, wire shielded, XLPE cables installed in separate 3 inch PVC conduits, buried flat

Calculation example for:

3-1/c kcmil aluminum conductor cables, 35 kV, cross-linked polyethylene insulated (0.345 inch wall), 12#14 AWG copper concentric wire shield, with 0.080 inch PVC jacket over each cable.

Circuit installed in three 3 inch PVC conduits, spaced flat, buried 36 inches in the earth

Earth thermal resistivity: 60 °C-cm/W
Ambient temperature: 25 °C
Load factor: 100%
Operating temperature: 90 °C
Cable shields are multi-point bonded and grounded.

Cable dimensions

O.D. over conductor: 0.558 in
O.D. over conductor shield: 0.558 in
O.D. over insulation: 1.278 in
O.D. over insulation shield: 1.358 in
O.D. over metallic shield: 1.486 in
O.D. over jacket: 1.646 in

Conductor resistance

R_{dc} for 250 kcmil aluminum conductor = 70.8 μΩ/ft @ 25 °C (value from tables)

Temperature Correction

$$R_{dc} = \frac{228.1 + 90}{228.1 + 25} \times 70.8 = 88.98 \text{ microhms/ft @ } 90\ ^\circ\text{C}$$

Skin effect

$$Ycs = F_{sp}(x) = \frac{11.0}{\left(x + \frac{4}{x} - \frac{2.56}{x^2}\right)^2} \quad \text{(equation F2 of NEMA WC50-1988/ICEA P-53-426)}$$

where

$$k_s = 1$$

$$x = \frac{R_{dc}}{k_s} \text{ and } x = \frac{88.98}{1}$$

where

$$x = F_{sp}(x) = \frac{11.0}{\left(88.98 + \frac{4}{88.98} - \frac{2.56}{(88.98)^2}\right)}$$

$$F_{sp}(x) = 0.001$$

Proximity effect

where

$$F(xp) = Fsp(x)$$

$$x = \frac{R_{dc}}{k_p}$$

$$k_p = 1$$

$$Ycp = F(xp)\left(\frac{D_c}{S}\right)^2 \times \left[\frac{1.18}{F(xp) + 0.27} + 0.312\left(\frac{Dc}{S}\right)^2\right] \text{ (equation 24)}$$

$$Ycp = 0.001\left(\frac{0.558}{7.5}\right)^2 \times \left[\frac{1.18}{0.001 + 0.27} + 0.312\left(\frac{0.558}{7.5}\right)^2\right]$$

$Ycp = 0.00024$ (negligible)

AC resistance

$$R_{ac} = R_{dc}(1 + Ycs + Ycp) \text{ (equation 20)}$$

$$R_{ac} = 88.98(1 + 0.001)$$

= 89.07 microhms/ft @ 90 °C

Shield resistance

$$Rs = \frac{\rho_s Lf}{nd^2}$$ microhms/ft @ 25 °C (equation E-1 of NEMA WC50-1988/ICEA P-53-426)

where

ρs = resistivity of copper shield: 10.575 Ω cm ft @ 25 °C
Lf = lay factor 1.05 (increase in length due to helical application)
n = number of wires = 12
d = diameter of each wire (#14AWG) = 0.0641 in

$$Rs = \frac{(10.575)(1.05)}{12(0.0641)^2} = 225.21 \times 10^{-6} \text{ ohms/ft}$$

$$Rs = 225.21 \text{ microhms/ft @ 25 °C (1/3 neutral)}$$

$$Rs \text{ @ 80 °C} = \frac{234.5+80}{234.5+25} \times 225.21$$

$$Rs_{80} = 272.93 \text{ microhms/ft @ 80 °C}$$

Mutual reactance (conductor to shield)

$$X_M = 0.882 f \log \frac{2S}{Dsm} \text{ microhms/ft (equation 28)}$$

$$X_M = 0.882\,(60) \log \frac{2 \times 7.5}{1.422} Dsm = 1.358 + 0.641 = 1.422$$

$$X_M = 54.15 \text{ microhms/ft}$$

Y_{se} (eddy current) = 0 (no path in shield for eddy currents)

Ratio of losses

$$Q_s = \frac{W_c + W_s}{W_c} = 1 + \frac{W_s}{W_c} \text{ (equation 18)}$$

$$\frac{W_s}{W_c} = \left(\frac{I_s}{I_c}\right)^2 \frac{R_s}{R_{ac}} \text{ (equation F6 of NEMA WC50-1988/ICEA P-53-426)}$$

therefore

$$Q_s = 1 + \left(\frac{I_s}{I_c}\right)^2 \times \frac{R_s}{R_{ac}}$$

where

W_s = shield loss due to circulating currents in W/ft
W_c = conductor loss including skin and proximity effects in W/conductor ft
I_s = current in metallic shield
I_c = current in phase conductor

$$\left(\frac{I_{s_1}}{I_c}\right)^2 = \frac{(P^2+3Q^2)+2\sqrt{3}\,(P-Q)+4}{4\,(P^2+1)\,(Q^2+1)}$$

$$\left(\frac{I_{s_2}}{I_c}\right)^2 = \frac{1}{Q^2+1}$$

$$\left(\frac{I_{s_3}}{I_c}\right)^2 = \left(\frac{(P^2+3Q^2)-2\sqrt{3}(P-Q)+4}{4(P^2+1)(Q^2+1)}\right)$$

where

$$P = \frac{R_s}{Y} \text{ and } Q = \frac{R_s}{Z}$$

and

$$Y = X_M + a$$

$$Z = X_M - (a/3)$$

$$a = 15.93$$

$$Y = 54.15 + 15.93 = 70.08$$

$$Z = 54.15 - (15.93/3) = 48.84$$

$$P = \frac{272.93}{70.08} = 3.895$$

$$Q = \frac{272.93}{48.84} = 5.588$$

$$\left(\frac{I_{s_1}}{I_c}\right)^2 = \frac{(3.895)^2+3(5.588)^2+3.464(3.895-5.588)+4}{4(3.895^2+1)(5.588^2+1)} = 0.0513$$

$$\left(\frac{I_{s_2}}{I_c}\right)^2 = \frac{1}{5.588^2} = 0.0310$$

$$\left(\frac{I_{s_3}}{I_c}\right)^2 = \frac{(3.895)^2+3(5.588)^2+3.464(3.895-5.588)+4}{4(3.895^2+1)(5.588^2+1)} = 0.05695$$

$$Q_{s_1} = 1 + \left(\frac{I_{s_1}}{I_c}\right)^2 \times \frac{R_s}{R_{AC}}$$

$$Q_{s_1} = 1 + \frac{0.0513(272.93)}{89.07}$$

$$Q_{s_1} = 1.157$$

$$Q_{s_2} = 1 + \left(\frac{I_{s_2}}{I_c}\right)^2 \times \frac{R_s}{R_{ac}}$$

$$Q_{s_2} = \frac{1 + 0.0310\,(272.93)}{89.07}$$

$$Q_{s_2} = 1.095$$

$$Q_{s_3} = 1 + \left(\frac{I_{s_3}}{I_c}\right)^2 \times \frac{R_s}{R_{AC}}$$

$$Q_{s_3} = 1 + \frac{0.05695\,(272.93)}{89.07}$$

$$Q_{s_3} = 1.175$$

Thermal resistances

Insulation

$$\bar{R}_i' - 0.012\bar{\rho}_e \log\frac{D_i}{D_c} \text{ thermal ohm feet (TOF)} \quad \text{(equation 38)}$$

$$\bar{R}_i' = 0.012\,(350)\log\frac{1.358}{0.558}$$

$$\bar{R}_i' = 1.662 \text{ TOF}$$

Cable jacket

$$\bar{R}_j' = 0.0104\bar{\rho}_j n\left(\frac{t}{D-t}\right) \text{TOF} \quad \text{(equation 40)}$$

$$\bar{R}_j' = 0.0104\,(500)\;(1)\;\left(\frac{0.080}{1.646 - 0.080}\right)$$

$$\bar{R}_j' = 0.266 \text{ TOF}$$

Cable surface to conduit

$$\bar{R}_{sd}' = \frac{n'A}{1 + (B + CTm)\,D_s'} \text{ TOF} \quad \text{(equation 41)}$$

$$\bar{R}_{sd}' = \frac{1\,(17)}{1 + [2.3 + 0.024\,(70)\,]\;(1.646)}$$

$$\bar{R}_{sd}' = 2.251 \text{ TOF}$$

Conduit wall

$$\bar{R}_d{}' = 0.0104\rho_c n' \left(\frac{t}{D-t}\right) \text{TOF (equation 40)}$$

where

D = 3.5 in
t = 0.216 in
$\bar{R}_d{}' = 0.0104\,(600)\;(1)\left(\frac{0.216}{3.5-0.216}\right)$
$\bar{R}_d{}'$ = 0.410 TOF

Earth thermal resistance

$$\bar{R}_e{}' = 0.012\rho_e n' \left[\log\frac{D_x}{D_e} + LF\log\left(\frac{4L}{D_x}\right)F\right] \text{(equation 44)}$$

where

n' = 1
LF = 1

$$\bar{R}_e{}' = 0.012\rho_e\log\frac{D_x}{D_e} + 0.012\rho_e\log\frac{4L}{D_x} + 0.012\rho_e\log F$$

where

F = the mutual heating term in equation 46 (center cable hottest)

$$F = \frac{D_{21}{}'}{D_{21}} \times \frac{D_{23}{}'}{D_{23}} \text{ (equation 46)}$$

$$D_{21}{}' = D_{23}{}' = \sqrt{72^2+7.5^2} = 72.4 \text{ in}$$

$$D_{21} = D_{23} = 7.5 \text{ in}$$

$$\frac{D_{21}{}'}{D_{21}} = \frac{72.4}{7.5} = 9.65$$

$$\frac{D_{23'}}{D_{23}} = 9.65$$

Thermal diffusivity (equation 45)

$$D_x = 1.02\sqrt{\alpha \times 24 \text{ h}}$$

where

$$\alpha = \frac{104}{\rho_e^{0.8}}$$

$$\alpha = \frac{104}{60^{0.8}} = 3.93 \text{ in}^2/\text{h}$$

$$D_x = 1.02\sqrt{3.93 \times 24} = 9.91 \text{ in}$$

$$\text{Let } \bar{R}_e{}' = \bar{R}_{e_1}{}' + \bar{R}_{e_2}{}' + \bar{R}_{21}{}' + \bar{R}_{23}{}'$$

$$\bar{R}_{e_1}{}' = 0.012\rho_e \log\frac{D_x}{D_e} \text{ TOF (equation 44 refined)}$$

$$\bar{R}_{e_1}{}' = 0.012\,(60)\log\left(\frac{9.91}{3.5}\right)$$

$$\bar{R}_{e_1}{}' = 0.325 \text{ TOF}$$

$$\bar{R}_{e_2}{}' = 0.012\rho_e \log\left(\frac{4L}{D_x}\right) \text{ TOF (equation 44 refined)}$$

$$\bar{R}_{e_2}{}' = 0.012\,(60)\log\left(\frac{4 \times 36}{9.91}\right)$$

$$\bar{R}_{e_2}{}' = 0.837 \text{ TOF}$$

$$\bar{R}_{21}{}' = 0.012\rho_e \log\left(\frac{D_{21}{}'}{D_{21}}\right) \text{ (equation 44 refined)}$$

$$\bar{R}_{21}{}' = 0.012\,(60)\log 9.65$$

$$\bar{R}_{21}{}' = 0.709 \text{ TOF}$$

$$\bar{R}_{23}{}' = 0.709 \text{ TOF}$$

Total thermal resistance (center cable hottest)

$$\bar{R}_{ca}{}' = \bar{R}_i + Q_{s2}\,(\bar{R}_j{}' + \bar{R}_{sd}{}' + \bar{R}_d + \bar{R}_{e1}{}' + \bar{R}_{e2}{}') + Q_{s1}\,(\bar{R}_{21}{}') + Q_{s3}\,(\bar{R}_{23}{}') \text{ (equation 8 refined)}$$

$$\bar{R}_{ca}{}' = 1.622 + 1.095\,(0.266 + 2.251 + 0.410 + 0.325 + 0.837) + 1.157\,(0.709) + 1.175\,(0.709)$$

$$\bar{R}_{ca}{}' = 7.752 \text{ TOF}$$

Temperature rise due to dielectric loss

$$\Delta Td = W_d\bar{R}_{da}{}' \text{ °}C \text{ (equation 6)}$$

where

$$\bar{R}_{da}' = \bar{R}_i'/2 + \bar{R}_j' + \bar{R}_{sd}' + \bar{R}_d' + \bar{R}_e' \text{ at unity loss factor}$$

$$\bar{R}_{da}' = \frac{1.622}{2} + 0.266 + 2.251 + 0.410 + 2.580$$

$$\bar{R}_{da}' = 6.318 \text{ TOF}$$

$$W_d = \frac{0.00276\, E^2 \varepsilon_r \tan\delta}{\log D_i/D_c} \text{ (equation 36 for 60 Hz)}$$

where

E = voltage across dielectric = 20 kV
ε_r = SIC of insulation 2.3
δ = dissipation factor 0.1%
D_i = diameter over insulation
D_c = diameter over conductor

$$W_d = \frac{0.00276 \times (20)^2 (2.3)\ (0.001)}{\log \dfrac{1.278}{0.588}}$$

W_d = 0.0075 W/ft
ΔT_d = $W_d \bar{R}_{da}'$ °C
ΔT_d = (0.0075) (6.318)
ΔT_d = 0.048 °C (negligible)

Ampacity calculation

$$I = \sqrt{\frac{T_c - (T_a + \Delta T_d)}{T_{dc}(1 + Yc)\ (\bar{R}_{ca}')}} \text{ kA (equation 9)}$$

$$I = \sqrt{\frac{90 - (25)}{(89.07)\ (7.752)}} = 0.307 \times 10^3$$

I = 307 A

A.2.3 Example 3: 3-1/c 2000 kcmil copper, 15 kV, tape shielded, EPR cables installed in a 6 inch PVC in still air

Calculation example for:

3-1/c 2000 kcmil copper conductor cables, 15 kV, EPR insulated (0.220 inch wall), half lapped 0.005' copper tape shield, with 0.110 inch PVC jacket over each cable. Circuit installed in one 6 inch PVC conduit in a horizontal position in still air (no sun)

Ambient temperature: 40 °C
Operating temperature: 90 °C
Cable shield are multipoint bonded and grounded

Cable dimensions

O.D. over conductor: 1.583 in
O.D. over conductor shield: 1.653 in
O.D. over insulation: 2.093 in
O.D.over insulation shield: 2.193 in
O.D. over metallic shield: 2.237 in
O.D. over jacket: 2.457 in
Circumscribed diameter: 2.15 × 2.457 = 5.283 in

Conductor resistance

R_{dc} of 2000 kcmil copper (class B): 5.39 μΩ/ft @ 25 °C

Temperature correction

$$\frac{234.5+90}{234.5+25}\times 5.39 = 6.74\ \mu\Omega/\text{ft @ } 90\ ^\circ\text{C}$$

Skin effect

$$Y_{cs} = F_{sp}(x)$$

where

$$ks = 1$$

$$x = \frac{R_{cd}}{ks}$$

$$Fsp(x) = \frac{11.0\,(1-0.1102/x)}{\left(x+\frac{4}{x}-\frac{2.56}{x^2}\right)^2}$$ (equation F3 of NEMA WC50-1988/ICEA P-53-426)

and

$$x = \frac{6.74}{1} = 6.74$$

$$F_{sp}(x) = \frac{11(1-0.102/6.74)}{\left(6.74+\frac{4}{6.74}-\frac{2.56}{(6.74)^2}\right)^2}$$

$$F_{sp}(x) = 0.2043$$

Proximity effect

where

$$F(xp) = F_{sp}(x)$$

$$x = \frac{R_{dc}}{k_p}$$

and

$$k_p = 1$$

$$Y_{cp} = F(xp)\left(\frac{D_c}{S}\right)^2 \times \left[\frac{1.18}{F(xp)+0.27}+0.312\left(\frac{D_c}{S}\right)^2\right] \text{ (equation 24)}$$

$$Y_{cp} = 0.2043\left(\frac{1.583}{2.457}\right)^2 \times \left[\frac{1.18}{0.2043+0.27}+0.312\left(\frac{1.583}{2.457}\right)^2\right]$$

$$Y_{cp} = 0.222$$

AC resistance

$$R_{ac} = R_{dc}(1+Y_{cs}+Y_{cp}) \text{ (equation 20)}$$

$$R_{ac} = 6.74(1+0.2043+0.222)$$

$$R_{ac} = 9.613\ \mu\Omega/\text{ft @ } 90\ ^\circ\text{C}$$

Shield resistance

$$R_s = \frac{\rho_s K}{4D_{sm}t} \text{ (equation E4 of NEMA WC50-1988/ICEA P-53-426)}$$

where

ρ_s = resistivity of coated copper (Ω cm/ft)
K = increase in resistance due to contact resistance of helical tape overlap = (2 normally used)
D_{sm} = mean diameter of metallic shield (in)
t = thickness (in)

$$R_s = \frac{(10.787)\ (2)}{4\,(2.227)\ (0.005)} = 484.37\ \mu\Omega/\text{ft @ } 25\ ^\circ\text{C}$$

$$R_s @\ 80\ ^\circ C = \frac{234.5+80}{234.5+25} \times 484.37$$

$$R_s = 587.03\ \mu\Omega/\text{ft @ 80m } ^\circ\text{C}$$

Shield losses

$$Q_s = 1 + \frac{Y_s}{1+Y_c}\ \text{(equation 18)}$$

where

$$Y_s = Y_{sc} + Y_{se}$$

Circulating current losses

$$Y_{sc} = \frac{R_s/R_{dc}}{1+\,(R_s/X_m)^2}\ \text{(equation 27)}$$

where

$$X_m = 0.882 f \log \frac{2S}{D_{sm}}\ \mu\Omega/\text{ft (equation 28)}$$

$$X_m = 0.882\ (60)\ \log \frac{2\ (2.457)}{2.227}$$

$$X_m = 18.19\ \mu\Omega/\text{ft}$$

$$Y_{sc} = \frac{587.03/6.74}{1+\ (587.03/18.19)^2}$$

$$Y_{sc} = 0.084$$

Eddy current effect

$$Y_{se} = \frac{3R_s/R_{dc}}{\left(\frac{5.2R_s}{f}\right)^2 + 0.2\left(\frac{2S}{D_{sm}}\right)} \times \left(\frac{D_{sm}}{2S}\right)^2 \times \left[1+0.417\left(\frac{D_{sm}}{2S}\right)^2\right] \times \left[\frac{R_s^2}{R_s^2+X_m^2}\right]\ \text{(equation 30)}$$

$$Y_{se} = \frac{3\ (587.03)\ /6.74}{\left(\frac{5.2\ (587.03)}{60}\right)^2 + 0.2\left(\frac{2\times 2.457}{2.227}\right)} \times \left(\frac{2.227}{2\times 2.457}\right)^2 \times \left[1+0.417\left(\frac{2.227}{2\times 2.457}\right)^2\right] \times \left[\frac{(587.03)^2}{(587.03)^2 + (18.19)^2}\right]$$

$$Y_{sc} = 0.023$$

Ratio of losses

$$Q_s = 1 + \frac{0.084 + 0.023}{1 + (0.2043 + 0.222)}$$

$$Q_s = 1.075$$

Thermal resistances

Insulation

$$\bar{R}_i' = 0.012\rho_i \log\frac{D_i}{D_c} \text{ TOF (equation 38)}$$

$$\bar{R}_i' = 0.012\,(350)\log\frac{2.193}{1.583}$$

$$\bar{R}_i' = 0.594 \text{ TOF}$$

Cable jacket

$$\bar{R}_j' = 0.0104\rho_j n'\left(\frac{t}{D - t}\right) \text{ TOF (equation 40)}$$

$$\bar{R}_j' = 0.0104\,(500)\;(1)\left(\frac{0.110}{2.457 - 0.110}\right)$$

$$\bar{R}_j' = 0.244 \text{ TOF}$$

Cable surface to conduit

$$\bar{R}_{sd}' = \frac{n'A}{1 + (B + CT_m)\,D_s'} \text{ TOF (equation 41)}$$

$$\bar{R}_{sd}' = \frac{3\,(17)}{1 + [2.1 + 0.016\,(70)\,]\;(5.283)}$$

$$\bar{R}_{sd}' = 2.83 \text{ TOF}$$

Conduit wall

$$\bar{R}_d' = 0.0104\rho_c n'\left(\frac{t}{D - t}\right) \text{ TOF (equation 40)}$$

$$\bar{R}_d' = 0.0104\,(600)\;(3)\left(\frac{0.280}{6.625 - 0.280}\right)$$

$$\bar{R}_d' = 0.826 \text{ TOF}$$

Conduit to ambient air

$$R_e' = \frac{n'\Delta T}{W_c + W_r} \text{ TOF}$$

where

$W_c = 0.072 d^{0.75} (\Delta T)^{1.25}$ W/ft (equation 5 of IEEE Std 738-1993)

$d = D_s'$ (Neher-McGrath effective diameter)

$\Delta T = 35\ °C$, wind velocity = 0

$W_r = 0.10256 D_s' \in \Delta T [1 + 0.0167 (T_m)]$ W/ft (equation 55A)

$\in\ = 0.92$

$\Delta T = 35\ °C$

$T_m = (75 + 40)/2 = 57.5$

$W_c = 0.072 (6.625)^{0.75} (35)^{1.25}$ W/ft = 25.31 W/ft

$W_r = 0.10256 (6.625) (0.92) (35) [1 + 0.0167 (57.5)]$ W/ft = 42.89 W/ft

$$R_e' = \frac{3(35)}{25.31 + 42.89} = 1.54 \text{ TOF}$$

Total thermal resistance

$\bar{R}_{ca}' = \bar{R}_i' + Q_s (\bar{R}_j' + \bar{R}_{sd}' + \bar{R}_d' + \bar{R}_e')$ (equation 8)

$\bar{R}_{ca}' = 0.594 + 1.075 (0.244 + 2.83 + 0.826 + 1.54)$

$\bar{R}_{ca}' = 6.431$ TOF

Temperature rise due to dielectric loss

$$\Delta T_d = W_d \bar{R}_{da}' \ {}^{\circ}C \text{ (equation 6)}$$

$$\bar{R}_{da}' = \bar{R}_i'/2 + \bar{R}_j' + \bar{R}_{sd}' + \bar{R}_d' + \bar{R}_e'$$

$$\bar{R}_{da}' = \frac{0.594}{2} + 0.244 + 2.83 + 0.826 + 1.54$$

$$\bar{R}_{da}' = 5.737 \text{ TOF}$$

$$W_d = \frac{0.00276 E^2 \varepsilon_r \tan\delta}{\log D_i/D_c}$$

where

E = applied voltage 8.7 kV

ε_r = SIC = 3

δ = dissipation factor 1.5%

$$W_d = \frac{0.00276\,(8.7)^2\,(3)\ (0.015)}{\log \frac{2.093}{1.553}}$$

W_d = 0.0725 W/ft (negligible)

Ampacity calculation

$$I = \sqrt{\frac{T_c - (T_a + \Delta T_d)}{R_{dc}\,(1 + Y_c)\,\bar{R}_{ca}}} \text{ kA (equation 9)}$$

$$I = \sqrt{\frac{90 - 40}{(9.613)\ (6.431)}} = 0.899 \times 10^3 \text{ A}$$

$$I = 899 \text{ A}$$

If these cables were operated with the shields open circuited, then

$$Y_S = Y_{SE}$$

where

$$Y_{SE} = 0.023$$

and

$$Q_S = 1 + \frac{0.023}{1 + (0.2043 + 0.222)}$$

$$Q_S = 1.016$$

and

$$\bar{R}_{ca}' = 0.594 + 1.016\,(0.244 + 2.83 + 0.826 + 1.53)$$

$$\bar{R}_{ca}' = 6.111$$

$$I = \sqrt{\frac{90-40}{(9.613)\,(6.111)}} = 922\text{ A (open-circuited)}$$

If the cable circuit, with open circuited shields, was operated in a wind of 2 ft/sec then the rating is recalculated as follows:

Thermal resistance of conduit to ambient @ 2 ft/s wind speed

Forced convection term

W_c = larger of W_{c1} and W_{c2}

where

$$W_{c1} = 1.01 + 0.371\left(\frac{d\rho_f V}{\mu_f}\right)^{0.52} \cdot k_f \cdot \Delta T\text{ W/ft (equation 3 of IEEE Std 738-1993)}$$

$$W_{c2} = 0.1695\left(\frac{d\rho_f V}{\mu_f}\right)^{0.6} \cdot k_f \cdot \Delta T\text{ W/ft (equation 4 of IEEE Std 738-1993)}$$

and

$$t_f = \frac{t_c - t_a}{2}$$

where

d = 6.625 in
t_c = 70 °C
t_s = 40 °C
t_f = 55 °C
ρ_f = 0.672 lb/ft^3 @ sea level @ t_f
V = 2 ft/sec × 3600 = 7200 ft/h
μ_f = 0.478 lb/h @ t_f
k_f = 0.00864 W/ft @ t_f
ΔT = 30 °C (NOTE—Calculated iteratively by computer program in tables.)

Thermal resistance from horizontal surface to air

$$\bar{R}_e' = \frac{n'\Delta T}{W_c + W_r}\ \text{TOF}$$

$$W_{c1} = 1.01 + 0.371\left(\frac{6.625 \times 0.0672 \times 7200}{0.0478}\right)^{0.52} \times 0.00864 \times 30 = 32.11\ \text{W/ft}$$

$$W_{c2} = 0.1695\left(\frac{6.625 \times 0.0672 \times 7200}{0.0478}\right)^{0.6} \times 0.00864 \times 30 = 34.57\ \text{W/ft}$$

$$W_R = 0.10256 D_s' \varepsilon \Delta T 1 + [0.0167\,(Tm)]\ \text{W/ft (equation 55A)}$$

where

$$\varepsilon = 0.92$$

$$\Delta T = 30$$

$$Tm = \frac{70+40}{2}$$

$$Tm = 55°$$

$$W_R = 0.10256 \times 6.625 \times 0.92 \times 30\,[1 + 0.0167\,(55)] = 35.98\ \text{W/ft}$$

$$\bar{R}_e' = \frac{3\,(30)}{34.57 + 35.98}\ \text{TOF}$$

$$\bar{R}_e = 1.27\ \text{TOF}$$

Total thermal resistance

$$\bar{R}_{ca} = 0.594 + 1.016\,(0.244 + 2.83 + 0.826 + 1.27)$$

$$\bar{R}_{ca} = 5.846\ \text{TOF}$$

$$I = \sqrt{\frac{90-40}{(9.613)\,(5.846)}} = 0.943 \times 10^3\ \text{A} = 943\ \text{A}$$

A.2.4 Example 4: 1-1/c #1/0 AWG aluminum 15 kV XLPE, URD cable, buried in the earth (1/2 of neutral current in shield)

Calculation example for:

1-1/c #10 AWG aluminum conductor cable 15 kV XLPE insulated, 8#14 AWG copper concentric wire shield.

Cable directly buried 36 inches in the earth.
Earth thermal resistivity: 90 °C cm/W
Ambient earth temperature: 25 °C
Load factor: 75%
Operating temperature: 90 °C

Cable dimensions

O.D. over conductor: 0.373 in
O.D. over conductor shield: 0.403 in
O.D. over insulation: 0.753 in
O.D. over insulation shield: 0.853 in
O.D. over metallic shield: 0.981 in

Conductor resistance

R_{dc} for #1/0 AWG aluminum: 168 µΩ/ft @ 25 °C (value from tables)

Temperature correction

$$R_{dc} = \frac{228.1 + 90}{228.1 + 25} \times 168 = 211.14\ \mu\Omega/\text{ft @ } 90\ ^\circ\text{C}$$

Skin effect

$$Y_{cs} = F_{sp}(x)$$

$$F_{sp}(x) = \frac{11}{\left(x + \frac{4}{x} + \frac{2.56}{x^2}\right)^2} \text{ (equation F3 of NEMA WC50-1988/ICEA P-53-426)}$$

where

$$k_s = 1$$

and

$$x = \frac{R_{dc}}{k_s}$$

$$x = \frac{211.14}{1}$$

$$F_{sp}(x) = \frac{11.0}{\left(211.14 + \frac{4}{211.14} - \frac{2.56}{(211.14)^2}\right)^2}$$

$$F_{sp}(x) = 0.0002$$

AC resistance

$$R_{ac} = R_{dc}(1 + Y_c)$$

$$R_{ac} = 211.14\,(1 + 0.0002)$$

$$= 211.18\ \mu\Omega/\text{ft @ } 90\ °\text{C}$$

Shield resistance

$$R_S = \frac{\rho_s Lf}{nd^2}\ \mu\Omega/\text{ft @ } 25\ °\text{C (equation E-1 of NEMA WC50-1988/ICEA P-53-426)}$$

where

ρ_s = resistivity of copper wire 10.575 Ω cm/ft

Lf = lay factor = 1.05 (increase in length due to helical application)

n = number of wires = 8

d = diameter of each wire (#14 AWG) = 0.0641

$$R_S = \frac{(10.575)\,(1.05)}{8\,(0.0641)^2} = 337.80\ \mu\Omega/\text{ft @ } 25\ °\text{C}$$

$$R_s \text{ @ } 80\ °\text{C} = \frac{234.5 + 80}{8\,(0.0641)^2}\ 337.80$$

$$R_S\text{@}80\ °C = 409.40\ \mu\Omega/\text{ft @ } 80\ °\text{C (1/2 neutral)}$$

Ratio of losses

$$Q_s = \frac{W_c + W_s}{W_c} = 1 + \frac{W_s}{W_c} \text{ (equation 18)}$$

$$\frac{W_s}{W_c} = \left(\frac{I_s}{I_c}\right)^2 \times \frac{R_s}{R_{ac}} \text{ (equation F6 of NEMA WC50-1988/ICEA P-53-426)}$$

therefore

$$Q_s = 1 + \left(\frac{I_s}{I_c}\right)^2 \times \frac{R_s}{R_{ac}}$$

when 1/2 of the total current is present in the neutral (metallic shield)

$$Q_s = 1 + \frac{R_s}{4R_{ac}}$$

therefore

$$Q_s = 1 + \frac{409.40}{4\,(211.18)} = 1.48$$

Thermal resistances

Insulation

$$\bar{R}_i' = 0.012\rho_i \log\frac{D_i}{D_c} \text{ TOF (equation 38)}$$

$$\bar{R}_i' = 0.012\,(350)\log\frac{0.853}{0.373}$$

$$\bar{R}_i' = 1.508 \text{ TOF}$$

Earth thermal resistance

$$\bar{R}_e' = 0.012\rho_e n'\left[\log\frac{D_x}{D_e} + LF\log\left(\frac{4L}{D_x}\right)F\right] \text{ (equation 44)}$$

$$\bar{R}_e' = 0.012\,(90)\;(1)\left[\log\frac{8.4}{0.853} + 0.62\log\left(\frac{4\times 36}{8.4}\right)1\right]$$

$$\bar{R}_e' = 1.89 \text{ TOF}$$

Total effective thermal resistance

$$\bar{R}_{ca}' = \bar{R}_i' + Q_s(\bar{R}_e') \text{ (equation 8)}$$

$$\bar{R}_{ca}' = 1.508 + 1.48\,(1.89)$$

$$\bar{R}_{ca}' = 4.31 \text{ TOF}$$

Ampacity calculation

$$I = \sqrt{\frac{T_c - T_a}{R_{dc}(1 + Y_c)\,(\bar{R}_{ca}')}} \text{ kA (equation 9)}$$

$$I = \sqrt{\frac{90 - 25}{(211.18)\,4.27}} = 0.267 \times 10^3 \text{ A}$$

$$I = 267 \text{ A}$$