New York Transmission Owners
Task Force on Tie-Line Ratings

Final Report

2019

FINAL REPORT

NEW YORK TRANSMISSION OWNERS TASK FORCE

ON

TIE-LINE RATINGS

PRESENTED TO NYISO TRANSMISSION PLANNING ADVISORY SUBCOMMITTEE
February 3, 2020

PRESENTED TO NYISO SYSTEM OPERATIONS ADVISORY SUBCOMMITTE
January 9, 2020

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New York Transmission Owners Task Force on Tie-Line Ratings

SECTION I

Introduction

INTRODUCTION

The 2019 Tie-Line Rating Report represents the fourth time the methodology for determining equipment rating has been investigated by the NY Transmission Owners (NYTO). The purpose of the original Task Force was to establish a clear and common methodology for determining equipment thermal ratings. This action would resolve the problem of non-uniformity regarding the determination of tie-line equipment ratings. The results could be used to establish ratings on equipment connecting different electric utilities within NYCA. Should a NY Transmission Owner determine an engineering need to make exceptions from these methodologies or assumptions, the onus is on the Transmission Owner to provide adequate technical justification for that method.

The following gives an historical perspective of these efforts:

1969 Original Report

- Developed a uniform and acceptable method of determining thermal equipment ratings.
- Set key definitions.
- Established ambient weather conditions for the calculation of summer and winter ratings.
- Originated "Table of Rating Factors for transmission System Components".
- Equipment ratings were derived from ANSI Standards and loading guides.

1982 Report Revisions

- Changed assumed conductor life from 25 years to 40 years.
- Changed the long-term-emergency (LTE) period to 4 hours.
- Increased the wind speed from 2 feet/second to 3 feet/second (Overhead transmission lines only) based on a NEPOOL Weather Study.
- Decreased the maximum ambient temperature from 40ºC to 35ºC

1995 Report Revisions

- Determined a generally accepted appropriate effective wind speed to be 3 feet/second
- Added tables of thermal ratings factors from -40°C to +40°C
- Added a new section with Regional Weather Data from 1983-1992
- Included Changes to STE Ratings of disconnect switches and power transformers
- Information on adjusting ratings based on real-time weather conditions
- Added a new section on Current Limiting Reactors

2019 Report Revisions

- Added new conductor types
- Updated rating factors for Current Transformers
- Updated rating factors for Circuit Breakers
- Updated Transformer section
- Updated references to Standards
- Provided links for weather data
- Eliminated 1995 Report Appendix C, D & E

This latest review was requested by the NYISO as the NYISO was reviewing Manual 24 - Reliability Analysis Data Manual aka RAD Manual. The first meeting was held in January 2019 and membership of the Task Force was established. Below is the list of members who participated in this endeavor:

Kofi Nimako	Avangrid
Paul Didsayabutra	Avangrid
Richard Wright, PE	Central Hudson Gas & Electric
Thomas Villani	Consolidated Edison of NY
Michael Lee	Consolidated Edison of NY
Edgar Gonzalez	Consolidated Edison of NY
Rollie Mangonon	Orange and Rockland Utilities
Robert Eisenhuth	Public Service Electric & Gas
Franco DiDomizio	Public Service Electric & Gas
John Savio	Public Service Electric & Gas
Mohammed Yousuf	Public Service Electric & Gas
Ali Iravani	New York Power Authority
William McQuillan	New York Power Authority
Xia Jiang	New York Power Authority
Nick Gibson	NY Transco
Philip Tatro, PE	NY Transco
Adam Barnello	National Grid
Mark F Domino, PE (Chair)	National Grid

At this time, the Chair would like to acknowledge the extra ordinary efforts of the Task Force and thank the members for their commitment to excellence. The Executive Summary of this report documents the decisions made by this Task Force.

To assist the user of this report, the definitions of important terms, established and refined by the previous Task Forces, are presented below.

A. DEFINITIONS:

Tie Line

A tie line consists of all series components, including line conductors, bus taps and all equipment and apparatus that are in one electrical path between two buses.

Ampacity

Current carrying capacity in amperes.

Rating Factor

NYTO rating in percent of nameplate rating.

Normal(operating) Rating

Capacity in amperes which may be carried through consecutive twenty-four-hour load cycles without exceeding agreed upon conductor or hottest spot equipment temperatures for this mode of operation.

Long Term Emergency (LTE) Rating

Capacity in amperes which may be carried through infrequent non-consecutive, appropriate four-hour periods without exceeding agreed-upon maximum conductor or hottest spot equipment temperatures for this mode of operation. Also known as Long Time Emergency rating in certain references.

Short Term Emergency (STE) Rating

Capacity in amperes which may be carried through very infrequent non-consecutive, periods of fifteen minutes or less duration without exceeding agreed upon maximum conductor temperatures for this mode of operation. Also known as Short Time Emergency rating certain references.

Assumed Daily Load Factor

The load factor is the ratio of the average load in kilowatts during a 24-hour period to the peak or maximum hourly load occurring in that period. A ratio of 80% is representative for rating purposes, but for those circuits whose load factor is known to differ substantially from this ratio, the actual load factor should be used.

Assumed Hours of Operation at Rated Temperatures for Overhead Conductors and strain bus

It is assumed that only when the rated limiting temperatures are reached will annealing and loss of strength occur. In general, an environment more favorable than assumed, and operating and reliability considerations, result in a system whose line conductors are rarely operating near their thermal limit under normal operation. No more than 10 percent loss of life/strength is assumed over the life of the conductor. The estimated number of hours of operation at rated temperatures for each mode of operation over the 40-year assumed life of conductor.

Normal	7665 hours
Long Term Emergency Rating	300 hours
Short-Term Emergency Rating	12 1/2 hours

To estimate loss of strength of overhead conductors, annealing is assumed to occur only during operation at one of the three limiting (rated) temperatures that correspond to the normal, LTE, STE ratings for an assumed number of hours.

New York Transmission Owners Task Force on Tie-Line Ratings

SECTION II

Executive Summary

EXECUTIVE SUMMARY

The Task Force recognized equipment changes and new conductor types have been developed since the last report. The most critical parameters which impact equipment thermal ratings are ambient temperature and wind speed assumptions. Below is a summary of the weather criteria for the 1995 report:

Table 2-1.

SEASON	Ambient Temperatures[1]		Wind Speed Feet/Second	
	Maximum	Average	Conductor	Bus Section
Summer	35˚C	30˚C	3ft/sec	2ft/sec
Winter	10˚C	5˚C	3ft/sec	2ft/sec
1) Interpolated values may be used for spring and fall.				

The summer season is from June to September and the winter season is December through February with interpolated values between them or the TO may choose to define the shoulder months as Summer or Winter. The following table defines other critical assumptions which form the basis of this report:

- Assumed life of equipment is 40 years
- The Ratings assume that line and terminal equipment are maintained in as “new condition”
- A normal preload is used in establishing short-term emergency (STE) rating
- The maximum duration for the STE rating is 15 minutes; totaling not more than 12.5 hours over the life of the equipment
- The maximum duration for the long-term emergency (LTE) rating is four (4) hours, totaling not more than 300 hours over the life of the equipment

The equipment criteria described above also represents no change from the 1995 final report, which is a complement to the previous Task Forces. The 2019 report includes additional ratings for new technologies. The following section summaries represent the highlights and revisions to the 2019 report.

SECTION SUMMARIES

Introduction

- Updated team members
- Updated LTE & STE definitions for consistency with NYSRC & NYISO Manuals

New York State Regional Weather Data

- Links added for historic weather data
- Historic Data tables removed.

Air Disconnect Switches & High Voltage Power Circuit Breakers

- Updated references for ANSI standards.

Power Transformers

- Major rewrite.
- Updated references to standards.

Current Transformers

- Addition of discussion on CT secondary circuitry.
- Change in STE rating factor for freestanding CTs.
- Name change in references #2 and #3.
- Removed ratings for GE and Westinghouse relays

Line Traps

- Major rewrite.
- Updated references to standards.

Substation Bus Conductor

- Updated references to standards
- Inclusion of temperature limits for equipment connections.

Current Limiting Reactors & Series Capacitors

- Updated references to standards.

Appendix A
Appendix B

RATING FACTORS FOR TRANSMISSION SYSTEM COMPONENTS

TABLE 1

Season	**Page #**	**Summer**			**Winter**		
Operating Conditions		**Normal**	**LTE**	**STE** (1)	**Normal**	**LTE**	**STE** (1)
Overhead Conductors - Maximum Temperatures							
ACSR (1350 Alloy, Steel Core)		95°C	115°C	125°C	95°C	115°C	125°C
SAC (1350 Alloy)		85°C	95°C	105°C	85°C	95°C	105°C
ACAR, AAC (6201 Alloy)		95°C	110°C	120°C	95°C	110°C	120°C
Copper		75°C	100°C	125°C	75°C	100°C	125°C
ACSS/ACCC/ACCR		Determined by Owner's Engineer					
Cable System - Finite Element Analysis		Determined by Owner's Engineer					
Current Transformers - Bushing Types		Use Same Factors as Associated Equipment					
Current Transformers - Free-Standing Types (2)		100%	128%	150%	122%	148%	150%
Air Disconnect Switches (SF6, See NOTE #6)							
30°C Temp. Rise		108%	153%	200%	141%	178%	200%
53°C Temp. Rise		105%	127%	160%	125%	144%	174%
Circuit Breakers		104%	116%	133%	122%	134%	149%
Line Traps		101%	111%	141%	107%	118%	150%
Transformers (See NOTE #5)							
55°C Rise		See Section VII		150%	See Section VII		150%
65°C Rise				150%			150%
Current Limiting Reactors (3)		100%	100%	121%	118%	118%	142%
Series Capacitors		See Section XII					
Substation Rigid and Strain Bus:							
Max Conductor Temperature (See NOTE #5)							
Aluminum		85°C	95°C	105°C	85°C	95°C	105°C
ACSR		95°C	115°C	125°C	95°C	115°C	125°C
Copper		75°C	100°C	125°C	75°C	100°C	125°C
Equipment Connections		85°C	95°C	105°C	85°C	95°C	105°C

Conditions: Summer: June through September Winter: December through February
Ambient Air Temp: Summer - 35°C Max. 30°C Average Winter - 10°C Max. 5°C Average Spring & Fall: Use interpolated values
Ambient Wind Speed: 3fps Overhead Conductors
2fps Terminal Equipment

Notes to Table 1:

1. NESC Clearances must be maintained @ STE temperatures.
2. Owner's Engineer may determine higher ratings factors are acceptable based on Manufacturer's recommendations.
3. 55°C rise dry type, self-cooled, 30°C Summer, 5°C Winter, 30 Minute STE
4. LTE: An infrequent emergency condition that should last no more than four hours.
5. STE: An infrequent emergency condition that should last no more than 15 minutes.
6. If known conditions (i.e., still air) require more conservative criteria, the member company should rate their equipment accordingly.
7. If a manufacturer's rating recommendation for a specific piece of equipment is found to conflict with the above, the manufacturer's rating should be followed.
8. Temperature limitations of bus conductors connected to electrical power equipment should be coordinated with the thermal limits of the terminal equipment. If equipment thermal limits are unknown, apply the temperature limitations shown in Table 1.
9. SF6 disconnect switches should be rated in the same manner as power circuit breakers.

New York Transmission Owners Task Force on Tie-Line Ratings

SECTION III

N.Y.S. Regional Weather Data

NEW YORK STATE REGIONAL WEATHER DATA

The 2019 Task Force recognizes the efforts of the 1994 Task Force. Weather data can be found at the following:

https://www.ncdc.noaa.gov/societal-impacts/wind/

http://www.ncdc.noaa.gov/cdo-web/datatools

https://www.climate.gov/maps-data/dataset/past-weather-zip-code-data-table

The reader is to be reminded of the caution in the 1995 Report:

> "A word of caution regarding the 0-4 feet/sec wind speeds. The actual values within this bandwidth, which includes the recommended wind speed for the NYPP rating calculation, is uncertain because of the starting inertia and bearing friction of individual anemometers. The Task Force was unable to obtain this information from the locations presented."

Discussion

A. WIND SPEEDS

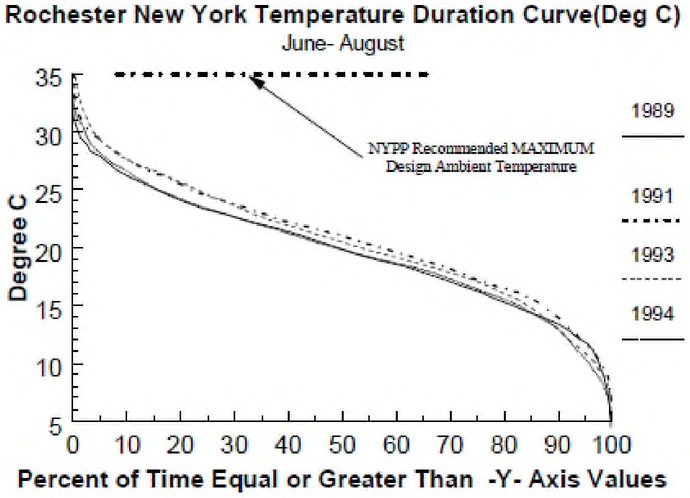
This parameter primarily impacts the rating of overhead conductors and buses. Changes in wind have a greater impact on the rating of a conductor than changes in ambient temperature. The 1995 report cited that since the 1982 report, research has demonstrated significant variability in wind speeds along a right-of-way caused by topography and structures, which adds to the uncertainty of a conductor rating. The Task Force concluded that insufficient data was available to quantify a state-wide adjustment in the 3 ft/sec wind speed that was adopted for conductor ratings in the 1982 report.

Also from the 1995 Report, the NEPOOL report that was the basis for adoption of the 3ft/sec wind speed for NYPP in 1982 concluded that the coincidence of high temperature and wind speed less than 3 ft/sec was 0.04% of the monitoring period.

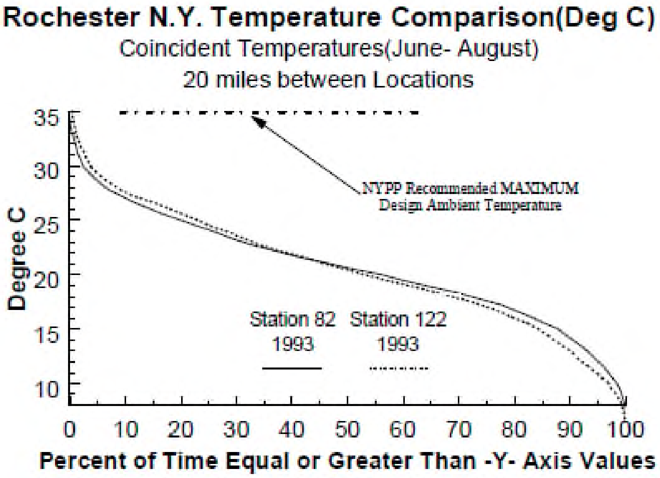
One should recall that for certain areas at night, the frequency of the 'no wind condition' increases. The cooler temperatures which may occur at night do not offset the loss of cooling effect by the low wind condition.

B. AMBIENT TEMPERATURES

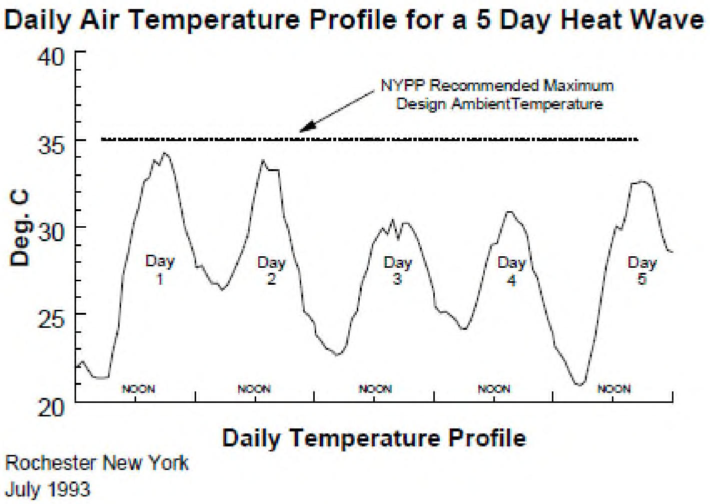
The 1995 Task Force expanded the report to include rating adjustment factors for ambient temperatures other than those recommended for maximum summer or maximum winter temperatures. The following duration curve of summer ambient temperatures demonstrates an almost non-existent occurrence of 35^{o}C in the selected years. Secondly, this family of curves shows that the temperature distribution is relatively constant for these years. Based upon this graph, there is potential to increase ratings, particularly on equipment whose rating is not impacted by wind. The graphs on the following pages were provided by Cornell University for the previous reports.



A second characteristic that makes ambiently adjusted ratings appealing is the relatively little variation in temperature across an area. This is shown below:



Another example of the conservatism of the recommended 35°C ambient temperature for rating calculation is shown below, which will typically result in a record energy use.



The following tables are a summary of the weather data obtained for the 1995 report and the recommended summer and winter ambient temperatures occurrences.

WIND SPEED OCCURRENCES WITH TEMPERATURES AT OR ABOVE NYPP AMBIENTS FOR T1E-LINE RATINGS, 10-YEAR PERIOD 1983-92

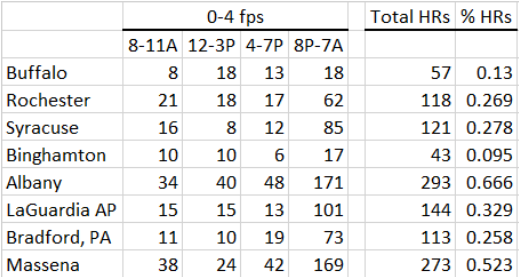
Summer (MAY-OCT) TEMPERATURE 35°C or above

	0-4 fps				4-6 fps				6-8 fps				>8 fps				Total HRs	% HRs
	8-11A	12-3P	4-7P	8P-7A	8-11A	12-3P	4-7P	8P-7A	8-11A	12-3P	4-7P	8P-7A	8-11A	12-3P	4-7P	8P-7A		
Buffalo	0	0	0	0	0	0	0	0	0	1	1	0	0	4	1	0	7	0.016
Rochester	0	0	0	0	0	0	0	0	0	1	1	0	0	23	6	0	31	0.071
Syracuse	0	0	0	0	0	0	0	0	0	2	2	0	0	19	6	0	29	0.066
Binghamton	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	4	0.009
Albany	0	1	0	0	0	0	0	0	0	2	2	0	0	12	9	0	26	0.059
LaGuardia AP	0	0	0	0	0	0	0	0	0	3	3	0	2	69	36	0	113	0.255
Bradford, PA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Massena	0	0	0	0	0	0	0	0	0	0	0	0	0	7	3	0	10	0.029

	0-4 fps				Total HRs	% HRs
	8-11A	12-3P	4-7P	8P-7A		
Buffalo	0	0	0	0	0	0
Rochester	0	0	0	0	0	0
Syracuse	0	0	0	0	0	0
Binghamton	0	0	0	0	0	0
Albany	0	1	0	0	1	0.002
LaGuardia AP	0	0	0	0	0	0
Bradford, PA	0	0	0	0	0	0
Massena	0	0	0	0	0	0

Winter (NOV-APR) TEMPERATURE 10°C or above

	0-4 fps				4-6 fps				6-8 fps				>8 fps				Total HRs	% HRs
	8-11A	12-3P	4-7P	8P-7A	8-11A	12-3P	4-7P	8P-7A	8-11A	12-3P	4-7P	8P-7A	8-11A	12-3P	4-7P	8P-7A		
Buffalo	8	18	13	18	15	23	18	22	33	46	40	64	820	1281	1109	1787	5315	12.13
Rochester	21	18	17	62	42	28	28	80	36	43	60	112	747	1293	1096	1541	5224	11.92
Syracuse	16	8	12	85	42	35	49	124	66	75	100	179	742	1293	1059	1359	5244	11.99
Binghamton	10	10	6	17	8	10	17	19	22	32	29	47	684	1196	1042	1506	4655	10.62
Albany	34	40	48	171	8	10	15	24	57	63	81	108	718	1381	1125	1419	5302	12.1
LaGuardia AP	15	15	13	101	40	37	29	97	46	55	23	135	1553	2372	2167	3568	10266	23.42
Bradford, PA	11	10	19	73	4	10	12	30	18	24	29	82	658	1174	1058	1414	4626	10.55
Massena	38	24	42	169	5	3	4	2	7	9	11	21	492	963	823	818	3431	7.83



	0-4 fps				Total HRs	% HRs
	8-11A	12-3P	4-7P	8P-7A		
Buffalo	8	18	13	18	57	0.13
Rochester	21	18	17	62	118	0.269
Syracuse	16	8	12	85	121	0.278
Binghamton	10	10	6	17	43	0.095
Albany	34	40	48	171	293	0.666
LaGuardia AP	15	15	13	101	144	0.329
Bradford, PA	11	10	19	73	113	0.258
Massena	38	24	42	169	273	0.523

New York Transmission Owners Task Force on Tie-Line Ratings

SECTION IV

Overhead Conductor Ratings

OVERHEAD CONDUCTOR RATINGS

The conductor ratings parameters given in this report are the recommended factors to be used in determining the thermal ratings of overhead conductors. "The prime consideration in thermal rating determination is that the conductor not sustain more loss of strength due to annealing over its useful life than some agreed upon percentage, usually approximately ten percent.” This statement from the Overhead Conductor Section of the 1970 report states the criteria that were used to develop allowable conductor temperatures. The limits were retained in future revisions.

Allowable conductor temperatures for each operating condition were determined based on the loss-of-strength criteria and the assumed number of hours of operation at each condition. The procedure was as follows: (1) the number of hours of operation at each operating condition was selected; (2) a tentative choice was made of the conductor operating temperature for each operating condition; (3) the time durations and temperatures from (1) and (2) were applied to laboratory data, giving loss of strength at a fixed temperature as a function of time to find the cumulative loss of strength which was then tested against the criterion. If the cumulative loss was too far over or under the 10 percent criterion, new conductor temperatures were chosen and the process repeated.

The 1995 Task Force reviewed the existing recommended conductor operating temperatures as they relate to loss of strength, annealing and clearances, and reviewed industry experience in a meeting with Glenn Davidson of Stone & Webster. It was determined that conductors in service suffer little strength loss since they seldom operate near rated temperatures and that the governing factor for a change in conductor rating would be clearance to ground or other wires. Given the uncertainty of actual field clearances, no reason was found to change the conductor temperatures indicated in the 1970 report, so they remain the same for each conductor type. It must be noted here that for lines built under the 1977 and more recent editions of the National Electrical Safety Code (NESC), clearances must be maintained at the highest (STE) conductor temperatures recommended in this report. For lines built under NESC editions prior to 1977, the owning utility may determine that in certain cases temperatures lower than recommended may be required to maintain clearances.

Overhead conductor ratings are determined by calculations based on the conductor temperatures and other parameters with the most important ones being AC resistance, ambient wind speed and temperature. No industry standard ratings exist for overhead conductors, but rating calculation methods for steady-state conditions (normal and LTE) and a transient thermal rating are contained in the IEEE Standard 738-2012 (Reference #2). NYTO ratings should be calculated in accordance with this standard. The Task Force recommends obtaining and using this standard for overhead rating calculations. The method is applicable to all the conductor types found in NYTO systems, using the proper values of AC resistance and other parameters. It can also be used to calculate conductor ratings for ambient conditions other than those recommended herein.

The rating calculation requires that values be chosen for a number of parameters as input to the calculation. Conductor emissivity, latitude and wind angle are examples. Each utility must select input values appropriate for their lines. If identical parameters are not assumed by two parties making the calculation for the same line, the ratings calculated will be different.

Ampacity for special conductor types can be calculated by the IEEE method, but the manufacturer should be consulted regarding temperature limits.

Points to consider with respect to practical application are as follows:

- Thermal Ratings: The NYTO ratings provide thermal limits only, and do not recognize the increased sag and reduced ground clearance that occurs with higher conductor temperatures. **Some line ratings may be limited by clearance limits rather than thermal limits.**

- Physical Conditions: The NYTO ratings assume conductors and accessories to be in a condition so that conductor temperatures are not increased by broken strands, faulty connectors and splices and similar conditions.

- High Conductor Temperatures: Conditions are recognized that can cause conductor temperature to exceed the selected limits during any given period of operation. All such conditions require the coincidence of high ambient temperatures and high-power transfer, with the following modifying or additional events:

    A. Ambient temperature exceeding assumed ambient.

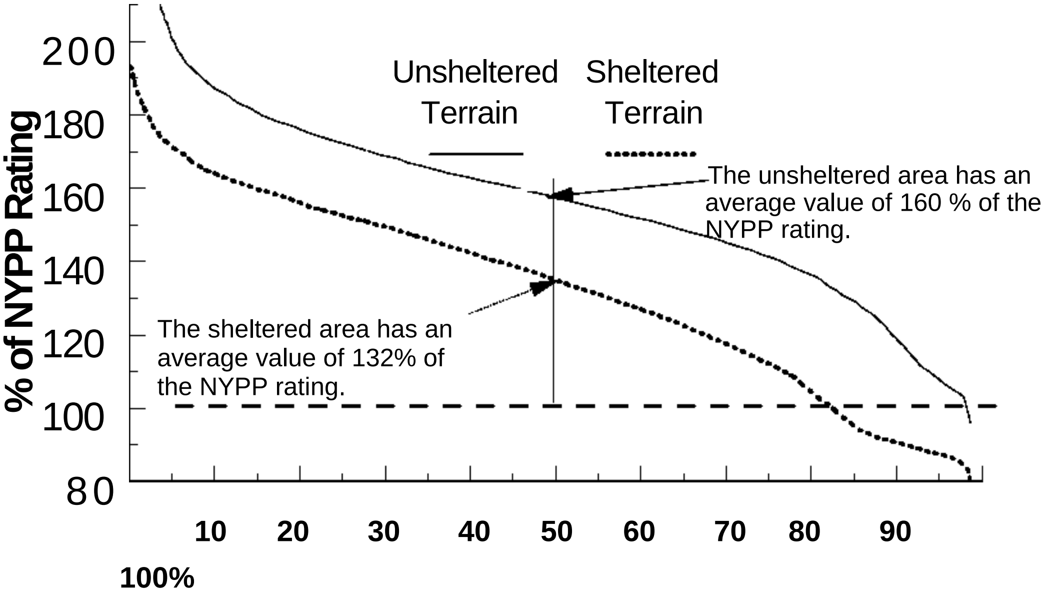
    B. Wind speed less than 3 ft/sec.

    C. Wind direction parallel to conductors which reduces heat loss by convection (conventional industry practice is to assume wind perpendicular to conductors in rating calculations). The IEEE Standard 738-2012 incorporates formulae which allows the user to define a wind angle other than perpendicular. It can be demonstrated that a change in wind angle from perpendicular to 20˚ will reduce the rating by 10%. Consideration of using wind angle for ratings would include review of wind direction data for low wind/high temperature conditions. Application of wind angle to rating calculations is left an option to be decided by each utility.

D. Emergency power flow that exceeds the STE rating due to system conditions at the time.

E. A "sheltered area" of very low wind speed may exist somewhere in a line.

The graph below presents coincident wind speed data (ft/second) obtained from a sheltered and unsheltered location in the Rochester Gas & Electric franchise area. Similar data could be collected and curves developed by other utilities. These curves could be used to develop a " wind sheltering factor" to account for lower effective wind speeds along a transmission line. Comparison of coincident ratings (% of NYPP) based on wind speeds obtained from a valley location and open flat location



The unsheltered area has an average value of 160 % of the NYPP rating.

The sheltered area has an average value of 132% of the NYPP rating.

Impact of Topography on Overhead Conductor Rating

0 **of Occurrences in Excess of -Y- Axis**

May through Septembe1988,
hourly values 90 Degree wind
angle

The curve in the figure above for "unsheltered terrain" is typical of wind speeds usually obtained from airport weather stations. Since temperature differences were small between the locations, most of the difference in ratings was due to reduced wind speed at the sheltered location. The rating was below the NYTO rating for approximately 18% of this period. If this was considered excessive by the utility, the rating could be adjusted to reduce the period of exposure to operating above the rating.

Favorable conditions are also possible that are taken into account in rating calculations, including:

A. Ambient temperatures that are different than those chosen for the calculation of the NYPP summer or winter rating. The table below contains factors to adjust the ratings for different ambient air temperatures:

SAMPLE RATING FACTORS
(LTE)

Ambient Temperature °C	Ambient Temperature Adjustment Factors (%)		
	4/0 Cu 7 strand "AA"Class	Conductor Types Aluminum 37 strand	1431kcm ACSR 45/7
40	95	95	96
35	100	100	100
30	104	104	103
25	107	108	106
20	111	112	109
15	115	116	112
10	118	120	114
5	121	123	117
0	125	127	119
-5	127	130	122
-10	131	134	125
-15	134	137	127
-20	136	140	129
-25	139	143	132
-30	142	146	134
-35	145	148	136
-40	147	151	138

B. Wind exceeding 3ft./sec.

C. Cloud cover or darkness that reduces or eliminates solar heating. The following table shows an approximate 5% increase in rating when sun is not present. It also demonstrates lesser increases as the conductor gets smaller:

IMPACT OF SOLAR RADIATION ON CONDUCTOR RATING

Conductor Type	**Summer LTE Rating with SUN**	**Summer LTE Rating Without SUN**	**%Increase with no SUN**
2493kcmil ACSR 66/6	2686 amperes	2877 amperes	7.1%
1431kcmil ACSR 45/7	1787 amperes	1888 amperes	5.6%
795kcmil ACSR 26/7	1258 amperes	1322 amperes	5.0%
336kcmil ACSR 26/7	724 amperes	755 amperes	4.2%

D. Rain.

E. Cooling due to vertical air current caused by heating of the wires or the earth.

F. Pre-disturbance power flow below the normal rating.

The frequency and duration of excess temperature occurrences is assumed to below enough that the lifetime 10 percent loss of strength criterion will not be exceeded.

STE RATING, PRELOADING

The STE rating calculation in this report is based on the assumption that the conductor has been operating at the temperature associated with its normal current rating prior to the incident. This assumption is needed to define the temperature rise that occurs during STE operation, in which a step change in loading is followed by a transient increase from the normal conductor temperature to the STE temperature. Since the conductor time constant is generally greater than 15 minutes, the conductor temperature will still be rising at the end of the STE period. A transient calculation is required to determine current that will cause the specified temperature rise in 15 minutes. The STE rating is the only one of the three ratings (Norm, LTE, STE) which takes advantage of the conductor's time constant. That is, following a step change in loading, it will take a while (minutes) for the conductor to reach a new steady-state temperature. Thus, the lower the starting point, the less "damage" is done in 15 minutes.

If the conductor is operating at less than normal steady-state temperature, the STE rating would increase. Conversely, if the conductor was operating at greater than the normal steady-state temperature, the STE rating would decrease.

Individual Companies may choose to use non-standard STE ratings for known actual operating conditions. This could be accomplished the same way dynamic ratings for known ambient conditions are accomplished today. The latest IEEE Standard can be used to calculate STE ratings for pre-load currents other than the normal rating value.

OVERHEAD CONDUCTOR
(References)

1. Current Carrying Capacity of ACSR-by H.E. House and P.D. Tuttle - AIEE Transactions, Power Apparatus and Systems, Vol.77, Part III, 1958, pp.1169-77.

IEEE Standards

2. IEEE Standard for the Calculating the Current-Temperature Relationship of Bare Overhead Conductors - IEEE Standard 738-2012

New York Transmission Owners
Task Force on Tie-Line Ratings

SECTION V

Air Disconnect Switches

AIR DISCONNECT SWITCHES

Synopsis

The standard requirements for high voltage air disconnect switches are covered in ANSI Standards C37.30 to C37.37. These standards specify, in addition to other requirements, the rated current, the conditions under which the rated current is determined, and the maximum allowable temperature rise limitations of the various components in the switch. For example, the maximum temperature rise for silver-to-silver contacts in air is 53˚C. A formula is provided in ANSI Standard C37.30 for the calculation of the allowable continuous current at ambient temperature at which the switch can operate without exceeding its temperature rise limitations.

Prior to 1971, ANSI Standards allowed a 30˚C temperature rise over a maximum ambient of 40˚C, for a maximum overall temperature of 70˚C. Switches manufactured in accordance with the 30˚C temperature rise limit have a higher loading capability than switches manufactured in accordance with standards published in 1971 and later.

Two switch ratings are listed in the table. The ratings listed under 30˚C rise apply to those switches designed in accordance with the 30˚C rise limitation. The ratings listed under 53˚C rise apply to those switches with silver-to-silver contacts designed in accordance with standards published in 1971 and later. The user must determine the criteria under which the switch was designed and determine the appropriate ratings.

A review of the switch formula for STE ratings in 1982 report disclosed that it was inconsistent with the design criteria recommended by ANSI. A formula developed by PJM member companies (Reference #2) has been adopted in this report. This formula yielded more conservative ratings, which resulted in a small reduction in STE ratings in certain instances.

The rating factors for air disconnects are based on switches that are maintained in "factory new" condition. Any operation above nameplate rating imposes additional duty on switch contacts. If regular maintenance is not performed, a more conservative rating factor may be obtained by taking only 50 percent of the increase over the nominal rating. (Reference #3).

Discussion

The nameplate current ratings for all switches are based on a 40˚C ambient temperature, no wind, and a finite temperature rise for the switch part at nameplate current rating. The allowable continuous-current ratings at conditions other than specified in the standards can be determined from the following equation.

$$I_{max} = I_{rated}\sqrt{\frac{\theta_{max} - \theta_a}{\theta_r}}$$

Where I_{max} = maximum allowable continuous current (amperes)

I_{rated} = nameplate rating (amperes)

θ_{max} = maximum allowable temperature for switch part (˚C)

θ_a = ambient temperature (˚C)

θ_r = limit of observable temperature rise (°C) at Nameplate rating of the switch part.

For switches manufactured in accordance with the 30˚C rise temperature limit, the nameplate rating was based on a temperature rise of 30˚C(θ_r) at the rated nameplate current (I_r) over a 40˚C ambient temperature (θ_a) giving a maximum allowable temperature (θ_{max}) of 70˚C. For the emergency rating, silver to silver contacts were assumed and the maximum allowable temperature was limited to 105˚C. With a maximum Summer ambient of 35˚C and winter ambient of 10˚C, the normal and LTE ratings of these switches in percent of nameplate rating are as follows:

Seasonal Rating Factors (%) 30˚C Rise
Disconnect Switches

Ambient Temperature (θ_a)	**Max Temp of Switch Part (θ_{max})**	**Allowable Loading**
35˚C	70˚C	108% (*Summer Normal*)
35˚C	105˚C	153% (*Summer LTE*)
10˚C	70˚C	141% (*Winter Normal*)
10˚C	105˚C	178% (*Winter LTE*)

For switches manufactured in accordance with ANSI C37.30-1971 and later standards, the normal rating was based on switches with silver-to-silver contacts having a 53˚C temperature rise over a 40˚C ambient, giving a maximum allowable temperature of 93˚C at nameplate rating. For emergency operation the maximum allowable temperature of 120˚C as accepted for silver-to-silver contacts based on IEEE Transactions Paper F78213-1 published July-August 1979 (Reference #1). The normal and LTE ratings of these switches at 35˚C and 10˚C ambient as a percent of nameplate rating are:

Seasonal Rating Factors (%) 53˚C
Rise Disconnect Switches

Ambient Temperature (θ_a)	Max Temp. of Switch Part (θ_{max})	Allowable Loading in % Of Nameplate
35˚C	93˚C	105% (*Summer Normal*)
35˚C	120˚C	127% (*Summer LTE*)
10˚C	93˚C	125% (*Winter Normal*)
10˚C	120˚C	144% (*Winter LTE*)

When factory tests are available, the actual temperature rise θ_r at the nameplate rating of the switch can be used. Generally, this factor will be less than the factor specified in ANSI C37.30, resulting in an increased loading capability.

Short Term Emergency Ratings

Short term emergency ratings are determined based on the switch thermal time constant which is a function of the heat storage capacity of the switch. Switch loading prior to applying the short time emergency rating is assumed to be 100% of the normal rating with switch contacts at normal allowable maximum temperature. An emergency allowable maximum temperature is utilized. The loss of tensile strength of copper and aluminum alloys due to annealing is expected to be negligible.

The short term 15 minute ratings were calculated, using the following formulae silver-to-silver contacts. However, in all cases, the short term rating has been limited to 200% of nameplate ratings of all 30˚C rise switches and 180% of nameplate ratings of the 53˚C switches.

$$I_{et}^{*} = I\left[\frac{1}{\theta_r}\left(\frac{\theta_{maxe2} - \theta_{\max_n}}{1 - e^{-t/T}} + \theta_{\max_n} - \theta_a\right)\right]^{1/\eta}$$

Note: *Rating is limited to 180% of normal rating for 53°C rise designs

Where

I_{et} = Emergency rating of less than 2 hours (amperes)
I = Rated Continuous Current
Θ_{maxn} = Normal allowable temperature for switch part (°C)
Θ_{maxe2} = STE allowable maximum temperature (20°C higher than maximum allowable LTE temperature for switch part)
Θa = ambient temperature (°C)
t = STE Duration time (15 minutes)
T = thermal time constant of switch in minutes. This may be conservatively assumed to be 30 minutes.
η = empirical temperature rise exponent = 1.8

Because the calculated value is greater than the maximum recommended in the standard, the short term emergency rating would be 180I.

RATINGS FACTORS (%) FOR
30 Degree Rise Switch

Ambient ˚C Temp.	Normal Loading	LTE Loading	STE Loading
-40	191	200	200
-35	187	200	200
-30	183	200	200
-25	178	200	200
-20	173	200	200
-15	168	200	200
-10	163	196	200
-5	158	191	200
0	153	187	200
5	147	183	200
10	141	178	200
15	135	173	200
20	129	168	200
25	122	163	200
30	115	158	200
35	108	153	200
40	100	147	200

Normal maximum allowable temperature = 70˚C
LTE maximum allowable temperature limit =105˚C
Limit of observable temperature rise=30˚C

RATINGS FACTORS (%) FOR
53 Degree Rise Switch

Ambient ˚C Temp.	Normal Loading	LTE Loading	STE Loading
-40	158	174	180
-35	155	171	180
-30	152	168	180
-25	149	165	180
-20	146	163	180
-15	143	160	180
-10	139	157	180
-5	136	154	180
0	132	150	180
5	129	147	180
10	125	144	180
15	121	141	180
20	117	137	180
25	113	134	180
30	109	130	180
35	105	127	180
40	100	123	180

Normal maximum allowable temperature=93˚C
LTE maximum allowable temperature limit=120˚C
Limit of observable temperature rise=53˚C

AIR DISCONNECT SWITCHES
(References)

1. Loading of Substation Electrical Equipment with Emphasis on Thermal Capability, Part II-Application by I.S.Bendo, D.E.Cooper, D.O.Craghead, P.Q.Nelson - IEEE Transactions, Power Apparatus and Systems,Vol.PAS-98,No.4,July/Aug.1979, pp. 1403-19.
2. Determination of Disconnecting Switch Ratings for the Pennsylvania - New Jersey-Maryland Interconnection, by J.V. Barker,Jr, W.J. Beran, K.D.Hendrix, M.D. Hill,P.L. Kolarik, D.E. Massey – IEEE Transactions, Power Apparatus and Systems,Vol.PAS-91, Jan/June, 1972, pp.404-411.
3. Continuous Overload Capability of Kearney Switches, by J.H. Ashton, Technical Paper 229-738, Kearney-National (Canada) Limited, September 23,1977.

ANSI Standards

4.	C37.30.5-2018	Requirements for AC High-Voltage Air Switches Rated Above 1000V
5.	C37.32-2002[1]	High Voltage Switches, Bus Supports, and Accessories Schedules - of Preferred Ratings, Construction Guidelines, and Specifications
6.	C37.34-1994	Test Code for High Voltage Air Switches
7.	C37.35-1995	Application, Installation, Operation and Maintenance of High Voltage Air Disconnecting and Interrupter Switches
8.	C37.37-1996	Loading Guide for AC High-Voltage Air Switches (in excess of 1000 volts)

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[1] *This standard replaces C37.33-1987 Rated Control Voltages and Their Ranges for High Voltage Air Switches*

New York Transmission Owners Task Force on Tie-Line Ratings

SECTION VI

High Voltage Power Circuit Breakers

HIGH VOLTAGE POWER CIRCUIT BREAKERS

Synopsis

The rating factors for circuit breakers are based on ANSI standard C37.010-2016, *'Application Guide for AC High Voltage Circuit Breakers'* which covers the STE and LTE conditions. Continuous-current temperature limits of breaker components are not exceeded during normal loading. During LTE and STE loading, breaker component temperatures rise 15˚C above the continuous-current limits are allowed, and some loss of life may result. Rating factors include the required adjustment for the NYTO summer and winter ambient temperatures, and remain the same as in the 1995 Tie Line Ratings Report. Optional short-term rating factors are given as provided for in the application guide.

Discussion

A. RATING FACTORS FOR NORMAL OPERATION

Rating factors for normal operation are obtained by adjusting the nameplate continuous load current capability for ambient temperatures other than 40˚C as indicated in Section 4.4.3.2 of C37.010. The formula is:

$$\frac{I_a}{I_r} = \left[\frac{\theta_{\max} - \theta_a}{\theta_r}\right]^{1/1.8}$$

I_a = Allowable load current at ambient temperature θ_a

I_r = Rated continuous current (nameplate)

θ_{Max} = Allowable hottest spot total temperature = $\theta_r + 40$˚C

θ_a = Actual ambient temperature; ˚C

θ_r = Allowable hottest spot rise at rated current

The exponent of 1/1.8 in the formula is derived from the relationship, based on testing experience, that the temperature rise of a current-carrying component is proportional to current raised to an exponent that varies from 1.6 to 2. An average value of 1.8 for the exponent is used throughout the guide.

The formula indicates that the rating factor at actual ambient temperature θ_a depends on the limits of total temperature and temperature rise, θ_{max} and θ_r, of critical circuit breaker components. Temperature limits are listed in Table1 of the guide, which is reproduced below as Table1, columns 1-5, with the addition of calculated rating factors for NYPP summer and winter ambient temperatures. The application guide requires that for actual ambient temperatures less than 40˚C,

θ_{max} and θ_r for the circuit breaker components with the highest temperature limit should be used to calculate rating factors. NYPP normal rating factors are for silver contacts in air (θ_{max} = 105˚C). In assigning breaker ratings, utilities should note that manufacturing practice may result in some units having components with higher capabilities than the nameplate rating. If load on a breaker is near its rating, an inquiry to its manufacturer may be advisable concerning the unit's actual capability.

B. RATING FACTORS FOR LTE CONDITIONS

Emergency load-carrying ability is achieved in the application guide by increasing the allowable total temperature and temperature rise of breaker components above the values allowed for continuous operation. The guide states that this may reduce the operating life of the breaker. Some conditions for using the emergency rating factors include:

1) Application is to outdoor breakers (metal-clad switchgear will have its own application guide).
2) The circuit breaker shall have been maintained in essentially new condition.
3) For a minimum of 2 hours following the emergency period, load current shall be limited to 95% of I_a, the rated continuous current for the selected ambient temperature (normal rating).
4) Mandatory inspection and maintenance procedures in the standard are required following emergency operation.
5) During and after emergency operation and prior to maintenance, the circuit breaker shall be capable of one operation at its rated short-circuit current.

The guide provides rating factors for four-hour and eight-hour periods of emergency operation. The factors are based on increased operating temperatures of 15˚C for four hours and 10˚C for eight hours, above the temperature limits for continuous operation. The four-hour and eight-hour periods must be separate, with inspection and maintenance required when the duration of separate periods of emergency operation totals 16 hours.

Rating factors are adjusted for ambient temperatures other than 40˚C using the following formula:

$$I_a = I_r\left(\frac{\theta max - \theta a}{\theta r}\right)^{1/1.8}$$

Where

I_a = allowable continuous load current in amperes at the actual ambient temperature
I_r = rated continuous current in amperes
Θ_{max}=allowable hottest spot total temperature (Θ_{max}=Θ_r+40°C) in degrees Celsius
Θ_a = actual ambient temperature expected (between -30°C & 60°C) in degrees Celsius
Θ_r = allowable hottest spot temperature rise at rated current, in degrees Celsius

THE RATING FACTOR SHOULD NOT EXCEED 200% UNDER THIS APPLICATION GUIDE. The 40˚C ambient rating factors are shown in table 2(a) of the standard corresponding to the limiting temperatures of breaker components. Table 1, columns 6-11, provide four-hour and eight-hour rating factors calculated for the 35˚C and 10˚C NYPP summer and winter ambient conditions. NYPP LTE rating factors are taken from Table 1, columns 7 and 8, for silver contacts in air.

C. RATING FACTORS FOR STE CONDITIONS

The same 15˚C increase is allowed in the total temperature of circuit breaker components as for the four-hour emergency rating. Conditions for use of the short-term rating factors are:

1) Initial current shall not be greater than the normal rating.
2) Following application of a short-term emergency current, current must be reduced to below the four-hour emergency current (LTE rating) for the remainder of the four-hour period, or to not more than 95% of the rated continuous current (Normal rating) for a minimum of two hours.
3) Regarding inspection and maintenance requirements, each isolated short-term emergency event shall be considered equal to one four-hour emergency period unless it is part of a four-hour emergency period.

A value is required for the circuit breaker thermal time constant t; t=30min. is used, which the guide says is typical. The rating factor defines the current level for which the total temperature will reach the θ_{max} + 15˚C level within a specified period which is 15 minutes for the NYTO STE rating. The resulting NYTO STE rating factors based on the temperature limit for silver contacts in air are: summer = 133% and winter = 149%.

The rating factors are calculated for θ_{max} = 105˚C, the limit for silver contacts in air. The factors are applicable to oil and SF_6 breakers also, and are probably more conservative for those types than for air breakers.

TABLE 1: Breaker Component Temperature Limits and Rating Factors (% Nameplate) Calculated for NYPP Summer and Winter Ambient Conditions

Column #	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
Component		Θ_r	Θ_{max}	Summer Normal Rating Factor Θ_a=35°C	Winter Normal Rating Factor Θ_a=10°C	Θ_{max}	4 Hour Rating Factor Θ_a=35°C	4 Hour Rating Factor Θ_a=10°C	Θ_{max}	8 Hour Rating Factor Θ_a=35°C	8 Hour Rating Factor Θ_a=10°C
Circuit breaker parts handled by the operator in the normal course of their duties		10°C	50°C	125	200						
Copper contacts, copper-in-copper conducting joints, external surfaces accessible to the operator in the normal course of his/her duties, external terminal connected to bushing		30°C	70°C	109	147	85°C	133	166	80°C	125	160
Top oil		40°C	80°C	107	136	95°C	125	151	90°C	119	146
Breaker terminals to be connected to 85°C insulated cable		45°C	85°C	106	132	100°C	122	146	95°C	117	141
Hottest spot of parts in contact with oil		50°C	90°C	105	129	105°C	119	141	100°C	115	137
Silver (or equal) contacts in air		65°C	105°C	104	123	120°C	116	133	115°C	112	133
External surfaces not accessible to an operator in the normal course of his/her duties		70°C	110°C	104	122	125°C	116	132	120°C	111	132
Hottest spot winding temperature of 80°C dry-type current transformers		110°C	150°C	103	114	165°C	111	121	160°C	108	119

D. OPTIONAL SHORT-TERM RATINGS BASED ON THE STANDARDS

In addition to NYTO rating factors, ANSI standards for circuit breakers provide for other types of ratings that are included in this report for information. One type is the eight-hour rating already covered in part B of this section. Another is short-term ratings provided in C37.010 that may be employed when the initial current is at or below the normal ratings.

The short-term load current capability tables given in Table 2 are based on C37.010, in which total temperatures are limited to the continuous rating values from C37.010 Table 1. Use of higher temperature limits should be infrequent and should be limited to the LTE and STE ratings. The table provide rating factors for a range of ambient temperatures, so advantage may be taken of favorable ambient conditions. The rating factors may be applied under the following conditions:

1. Initial current is less than the rated current.
2. Short-term load current is limited to the indicated time period.

$$\frac{I_s}{I_r} = 100\left[\frac{I_i}{I_r}\right] x \left[1 + \frac{\theta_{\max} - Y - \theta_a}{Y(1 - e^{-t_s/\mathrm{T}})}\right]^{1/1.8}$$

$$Y = (\theta_{\max} - 40)\left[\frac{I_i}{I_r}\right]^{1.8}$$

Rating factors are calculated from the following equations based on C37.010 section 4.4.3.3.2: An example application of Table 2 is as follows:

Known conditions:	Pre-contingency (initial) current I_i = 1125 amperes
	Ambient temperature θ_a = 6˚C
	Breaker Rated Current at 40˚C I_r = 3000 amperes
	Breaker θ_{max} =105˚C (from Table 1 for type of breaker)
Assumed condition:	Anticipated short-term period t_s = 20 minutes

To obtain Short-term Rating Factor:

1) Calculate I_i/I_r 1125/3000 = .375
2) Round I_i/I_r and θ_a up to 0.4 and 10˚C.
3) Enter Table 2 section for θ_{max} = 105˚C and t_s = 20min., in the column for I_i/I_r = .4 and the row for ambient temperature θ_a = 10˚C, find the rating factor I_s/I_r = 177%.

Table 2 Short term rating factors (100*I_s/I_r) for circuit breakers for selected values of initial current ratio

I_i/I_r, θ_{max}, θ_a and t_s

			θ_{max}=105°C t_c=30minutes							θ_{max}=90°C t_c=30minutes						
t_s MIN	θ_a deg C	I_i/I_r=	.8	.7	.6	.5	.4	.3	.2	.8	.7	.6	.5	.4	.3	.2
10	40		140	155	167	177	186	192	197	140	155	187	177	186	192	197
	30		162	176	186	196	200			188	181	192	200	200		
	20		181	194	200					192	200					
	10		199													
15	40		126	136	144	151	157	161	176	126	136	144	151	157	161	155
	30		143	152	160	166	171	178	179	148	156	164	170	176	180	183
	20		169	167	174	180	185	189	192	167	175	182	188	193	197	200
	10		173	181	187	193	198	200	200	185	193	199	200			
	0		187	194	200	200				200						
	-10		199	200												
20	40		118	125	131	137	141	144	147	118	125	131	137	141	144	147
	30		133	139	145	150	154	157	158	137	143	149	154	157	181	169
	20		146	152	158	162	166	169	171	154	160	165	169	173	176	178
	10		159	164	169	174	177	180	182	169	175	180	184	187	190	192
	0		171	176	181	185	188	191	193	184	189	193	197	200	200	
	-10		182	187	191	195	198	200	200	197	200					
	-20		192	197	200	200										
	-30		200													
25	40		113	119	123	127	131	133	135	113	119	123	127	131	138	135
	30		126	131	136	139	143	145	147	130	135	139	143	146	148	150
	20		139	143	147	151	154	156	158	145	150	154	157	180	182	184
	10		150	154	158	161	164	166	168	159	164	167	170	173	175	177
	0		160	165	168	171	174	176	178	173	176	180	183	185	187	189
	-10		171	175	178	181	183	185	187	185	183	192	195	197	199	200
	-20		180	184	187	190	193	195	196	197	200					
	-30		189	193	196	199	200									
	-40		198	200												
30	40		110	114	118	121	124	126	128	110	114	118	121	124	126	128
	30		122	126	130	132	135	137	138	126	129	133	136	138	140	141
	20		133	137	140	143	145	147	148	140	143	146	149	151	153	154
	10		144	147	150	153	155	157	158	153	158	159	161	163	116	166
	0		154	157	160	162	164	166	167	165	168	171	173	175	177	178
	-10		163	168	169	171	173	175	176	176	179	182	184	186	187	189
	-20		172	175	178	180	182	183	184	187	190	192	195	196	198	199
	-30		181	183	186	188	190	191	193	198	200					
	-40		189	192	194	196	198	199	200							

40	40		106	109	111	113	116	117	118	106	109	111	113	115	117	118
	30		117	120	122	124	125	126	127	120	123	125	127	128	129	130
	20		127	129	131	133	135	136	137	133	135	137	138	140	141	142
	10		136	138	140	142	144	145	146	144	146	148	150	151	152	153
	0		145	147	149	151	152	153	154	155	157	159	160	162	163	164
	-10		154	156	157	159	160	161	162	165	167	169	171	172	173	174
	-20		162	164	165	167	168	168	170	175	177	179	180	181	182	183
	-30		169	171	173	174	175	176	177	185	187	188	189	191	191	192
	-40		177	179	180	182	183	184	184	194	195	197	198	199	200	200

CIRCUIT BREAKERS
(References)

ANSI Standards

1. C37.010-2016	Application Guide for AC High Voltage Circuit Breakers Rated on a Symmetrical Current Basis

New York Transmission Owners
Task Force on Tie-Line Ratings

SECTION VII

Power Transformers

Power Transformers

Synopsis

The determination of overload ratings for power transformers is a rather complex problem, not unlike the rating of cables, which must be solved by careful engineering and coordination. In the case of new transformer installations being planned, it is recommended that the required load cycle information and complete transformer performance criteria for all modes of operation (normal, LTE, STE) be provided to the manufacturers during the specification stage of the procurement so that appropriate overload requirements will be addressed in the design stage.

The larger problem remains to reliably rate existing system transformers. The recommended practice is to consult the transformer manufacturer for overload ratings, particularly for STE ratings. A utility engineer cannot be expected to have the resources to obtain and analyze the detailed design data required to determine the leakage flux heating limitation for STE loading for instance, which is the limiting criterion in most contemporary transformer designs. In cases where this is not possible, it is recommended that a contemporary computer rating program which factors in the individual design parameters of the unit and the required load cycle and ambient temperature data and using IEEE C57.91 Table 9, to determine both the normal transformer load capability under defined load cycle operation and the 4 hour LTE rating. A transformer rating analysis program is available in Annex G of IEEE PC57.91/D9 and the EPRI computer program 'PTLOAD' also has these capabilities plus a transformer gas bubble evolution module. Sample outputs for selected transformers are contained in Appendix D**.** The use of these programs is encouraged.

The information contained in this section is intended to be used as a guide to aid discussions between engineering teams and with equipment manufacturers to help determine transformer ratings. Final transformer ratings should be rated based on each owner's internal company practice including any associated loss-of-life risks.

Discussion

Power transformers are designed and constructed with varying characteristics, depending upon the class and type of service, environmental considerations, and the economic value of transformer losses. The three major classes of service are:

- Generation step-up
- System tie
- Substation

Generation step-up (GSU) service normally involves well-defined load patterns with GSU units being sized to the maximum capability of the associated generator on a continuous basis. Emergency overload conditions are rare except for multi-bank GSU configurations in which one of the banks fails without an available spare and the remaining units are loaded as much as possible until a replacement becomes available.

System tie service encompasses all major transmission system tie transformers. These transformers are typically over 100 MVA. System tie service also includes tie-line phase-angle regulators, voltage-regulators and combination voltage/phase angle regulators.

Substation service comprises power and regulating transformers directly serving load, typically rated below 100 MVA.

Further design distinctions involve the type of cooling system used:

Liquid-Immersed Air-Cooled

ONAN	self-
ONAN/ONAF	self-cooled/forced air-cooled
ONAN/ONAF/ONAF	self-cooled/forced air-cooled/forced-air cooled

Liquid-Immersed Air-Cooled/Forced Liquid-Cooled

- ONAN/ONAF/OFAF[1] self-cooled/forced air-cooled/forced liquid air-cooled
- ONAN/OFAF[1]/OFAF[1] self-cooled/forced air-forced liquid-cooled/forced air-forced liquid-cooled

Liquid-Immersed Water-Cooled

OW	water-cooled
OW/A	water-cooled/self-cooled

Liquid-Immersed Forced Liquid-Cooled

OFAF[1]	forced liquid-cooled with forced air-cooler
FOW	forced liquid-cooled, water-cooled

[1] OFAF can be either **ODAF(directed OFAF)** or **NDFOA(non-directed OFAF)**

Finally, design distinctions exist among autotransformers, two- and three-winding transformers, single-phase versus three-phase units, tap-changers and ancillary equipment and the types of oil-preservation systems being used.

The IEEE loading guide in effect:

- **ANSI/IEEE C57.91-2011** *Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators.*

Those distribution transformers whose characteristics are known and which have established successful overload patterns over the years should continue to be operated in the manner recommended by the manufacturer and/or the individual company's engineer. This may imply STE operation at up to 2.0 per unit load.

Note that stay flux heating remains the STE design limitation for many transformers, especially those 100 MVA and larger and/or 345kV and up. In particular, this applies to three-phase shell-form designs. The proposed guide lists a new Table 8 with a "other metallic hot-spot temperature limit of 200°C for STE loading," but then misleadingly describes a short-term emergency load method which neglects stray-flux heating. Utilities are not normally able to quantify the load saturation effects and stray-flux hot-spot temperatures in the core and other metallic parts. This would be necessary to evaluate the validity of assuming, for instance, 180°C insulated conductor hottest-spot temperature as the limiting risk in calculating an STE rating. PC57.91 states "Usually the limits on other metallic hot-spot temperature not in contact with heating are design limits and calculated by the manufacturer when an overload specification is submitted as part of the purchasing specifications." Therein lies the problem: many of the transformers in service today were not purchased with an overload specification, invalidating a generic "180°C" approach to an STE rating calculation and reinforcing the generic limits of Table 3 listed above.

Loss-of-Life Criteria/Limiting Temperatures for Engineered Ratings

Within the constraints of the maximum absolute loading limits, it is possible to determine normal, LTE and STE transformer ratings based on limiting temperature rises of the winding insulation hot-spot and the top-oil. The recommended “loss-of-life” criterion for emergency operation is **0.25% per occurrence,** which is equivalent to approximately 19 days loss-of-life for the one day in which the emergency occurs, using the method described in IEEE PC57.91/D9. This value will not be reached for STE operation given the short 15-minute time period and the other limiting criteria. Normal transformer operation should entail normal winding insulation loss-of-life.

The recommended limiting temperature rises for all modes of operation are listed in the following tables for 65^{o}C and 55^{o}C average winding rise rated transformers respectively:

Power Transformers Rated 65ºC AWR (Average Winding Rise)
80ºC Hottest-Spot Rise

(extracted from IEEE PC57.91 Table 8)

Temperature Limit	**Normal Life Expectancy Loading**	**Long-Time Emergency Loading**	**Short-Time Emergency Loading**
Insulated conductor hottest-spot temperature, °C	120*	140	180**
Other metallic hot-spot temperature (in contact and not in contact with insulation), °C	140	160	200
Top oil temperature, °C	105	110	110

* 110°C on a continuous 24-hour basis or; equivalent 24-hour variable temperature with 120°C maximum.

**** Gassing may produce a potential risk to the dielectric strength of the transformer. This risk should be considered when this guide is applied refer to Annex A.**

Power Transformers Rated 55ºC AWR (Average Winding Rise)
65ºC Hottest-Spot Rise

(Some Data from ANSI/IEEE C57.92-1981, Par. 5.2.2.4)

Temperature Limit	**Normal Life Expectancy Loading**	**Long-Time Emergency Loading**	**Short-Time Emergency Loading**
Insulated conductor hottest-spot temperature, °C	105*	140	150**
Other metallic hot-spot temperature (in contact and not in contact with insulation), °C	N/A	N/A	N/A
Top oil temperature, °C	95	100	100

* 95°C on a continuous 24-hour basis or; equivalent 24-hour variable temperature with 105°C maximum.

** **Gassing may produce a potential risk to the dielectric strength of the transformer. This risk should be considered**.

Application of Transformer Ratings

Transformer load capability is traditionally stated in terms of MVA. The true thermal loading of a transformer is determined by its load-side current, in amperes. The fact that a transformer can have “full capacity” taps has led to the misnomer that transformers are “constant MVA” devices. It is true that a transformer with “full capacity taps” has “full MVA” at each tap setting, however, ***at any given tap position a transformer has a fixed ampere rating for a particular mode of operation***. This can best be demonstrated by means of an example. For any given "full-capacity tap equipped" transformer MVA rating, the **true tap ampacity** will vary inversely with off-nominal rated voltage. For example, take a three-phase autotransformer rated 200 MVA at 345 kV/115 kV nominal, with ± 5% NLTC in 2.5% steps, used in step-down service. The nameplate ampacity at rated nominal 115 kV voltage is simply calculated as:

$$Iratedamperes = \frac{MVA3\oslash}{\sqrt{3} \times kVratedtap} \times 1000 = \frac{200}{\sqrt{3} \times 115} \times 1000 = 1004amperes$$

The complete ampacity table for the transformer as a function of tap position, which would be shown on the transformer nameplate, is as follows:

Ampacity as a Function of Tap Position

Tap Position	Rated kV @ Tap Position	Rated Tap Current, Amperes
-5%	109.25	1057
-2.5%	112.125	1030
Neutral	115	1004
+2.5%	117.875	980
+5%	120.75	956

It is significant to note that for any given mode of transformer operation, in this case normal nameplate rating, the real thermal capability is dependent on the tap position of the transformer. There is no “constant MVA” capability unless the transformer happens to be operating at a system voltage equal to the output tap rated voltage, which is seldom the case. Indeed, transformers whose operating tap position voltage ratings are below the operating system voltage will achieve a “greater than nameplate” MVA for the tap-rated current. Conversely, transformers whose operating tap position voltage ratings are above the actual system operating voltage will realize a “less than nameplate” MVA for the tap-rated current.

Reduced Capacity Taps

Some transformers are purchased with "reduced capacity taps", in which the inverse current capability is limited at some absolute value, greater than or equal to the rated neutral tap current.

These limitations can be due to winding current limits or tap-changer, bushing, internal cable or other related restrictions.

Tap-Position Impact on Overall Circuit Ratings

Given the significance of the variability of the tap rated current for any transformer (equal in percentage to the percentage tap range), tap positions must be factored into the transformer circuit ratings. In cases where no-load tap changers (NLTC) are involved, a simple static rating for each operating mode (Normal, LTE, STE, both Summer and Winter) at a stated fixed tap position will suffice. For transformers with load tap changers (LTC), a table of transformer circuit ampacity vs. tap position is required. It is important for system operators to view transformers as current(ampere)-limited devices, in the same manner as say cables. In determining quasi-megawatt ratings, it is necessary to ascertain a minimum typical system operating voltage and to assume a minimum load power-factor judiciously based on operating experience.

Voltage Regulators and/or Phase Shifting Transformers

Voltage regulators, phase-angle regulators and combination voltage & phase angle regulators have rated transformer ampacities which are a function of tap position. The rating analyses for such devices should result in a tabulation of the circuit ratings as a function of the full range of tap positions. A phase angle regulator consists of both a series transformer and an exciting transformer. As phase shift increases from zero degrees, the exciting transformer progressively carries more current. In most cases the exciting transformer limits the phase shifter output resulting in the minimum rating at maximum phase shift.

POWER TRANSFORMERS
(References)

ANSI Standards

1.	C57.92-1981	Guide for Loading Mineral-Oil-Immersed Power Transformers up to and Including 100MVA with 55˚C or 65˚C Winding Rise, **Reaffirmed in 1991**.
2.	C57.115-1991	(Redesignation of IEEE STD 795): IEEE guide for loading mineral-oil-immersed power transformers rated in excess of 100MVA (65C winding rise)
3.	C57.19.101-1989	Trial-Use Guide for Loading Power Apparatus Bushings
4.	PC57.91/D9-2010	Draft Guide for Loading Liquid Immersed Transformers and Voltage Regulators

New York Transmission Owners
Task Force on Tie-Line Ratings

SECTION VIII

Current Transformers

CURRENT TRANSFORMERS

Synopsis

Thermal ratings of current transformers will usually require a review of each application and each manufacturer's and owner's practice. A single set of rating factors cannot be expected to cover the variety of installations that are possible. Thermal overload of devices in the secondary circuit must be considered. A careful review of the application is mandatory for any current transformer that is the limiting component in rating a transmission facility.
Methods of rating current transformers recommended in this report are based on ANSI/IEEE Standards, including: ANSI/IEEEC57.13-2016 (Reference #1), ANSI Standards C57.91(2011) (Reference #2), guides for transformer loading.

CT Secondary Circuitry

The effective thermal circuit limits imposed by relay components installed on secondary CT circuits should be coordinated so as not to impose a limit on the overall transmission circuit. In existing cases where relay circuits are limiting, action should be taken, where feasible, to remove these restrictions.

Discussion

To develop normal ratings for all types of current transformers, the continuous thermal current rating factor (CTCRF) must be used. The CTCRF is defined in standard C57.13, and is one of the required ratings. Manufacturers design their products with rating factors per their own usual practice, or the owner may specify a rating factor when the unit is purchased. The normal ratings in the table are taken from Figure No.1 of C57.13, using the curve for a CTCRF of 1.0 and average daily ambient temperatures of 30˚C and 5˚C respectively for summer and winter. For CTCRF values other than 1.0, the curve for the proper CTCRF value from Figure 1 of C57.13 should be used to determine normal rating factors at 30˚C and 5˚C.

Standard C57.13 does not provide methods to determine LTE and STE ratings, so these are discussed separately for free-standing and bushing-type current transformers.

Limits on emergency ratings may be imposed by relay coils, meter coils and like devices in the CT secondary circuit that may be thermally overloaded by secondary current in excess of normal values. The secondary circuit should be included in any review of specific installations.

Free Standing CTs

The LTE and STE rating factors in the table are for oil filled units installed separately from other equipment. Since these units are similar in construction to power transformers, the equations for transient heating that are found in Section 9.6 of Standard C57.91(2011) were used to develop LTE and STE ratings.

Parameter values and the calculations are the same as for power transformers in this report, assuming a 55°C average winding rise in accordance with the limit given in C57.13 for instrument transformers. With no requirements stated in C57.13, current and power transformers were assumed to have the same parameter values for hottest-spot temperature related to loss of life and ratio of load to no-load loss. Thermal time constant was assumed equal to that of a forced air coiled power transformer.

Bushing-Type CTs

The LTE and STE ratings of bushing-type current transformers will normally be at least as great as the rating of the circuit breaker or power transformer in which the CTs are installed. The manufacturer of the major equipment can provide CTs with thermal performance that is adequate, taking into account the ambient temperature at which they will operate in or on the equipment and other factors. Confirmation of the LTE and STE ratings should be sought from the equipment manufacturer.

If the tap used on a bushing CT is less than its maximum ratio, additional continuous thermal capability, beyond the tap rating, may be available. A curve used to determine the additional capacity has the equation:

$$\frac{I_a}{I_{tr}} = \sqrt{\left[\frac{I_r}{I_{tr}}\right]}$$

Where I_a = allowable secondary current for connected tap
I_{tr} = rating of connected tap
I_r = rating of full winding

If the connected tap is 50% of the full winding, for example, the CT will have a continuous rating of 141% of the tap rating. One manufacturer recommends a limit of 200% on the rating factor so determined. This higher rating can be treated in the same manner as a nameplate rating and can be multiplied by the LTE and STE rating factors to obtain emergency ratings. Confirmation should be obtained from the manufacturer before using this rating.

CURRENT TRANSFORMER RATINGS FACTORS

Current Transformers	Summer			Winter		
	N	LTE	STE	N	LTE	STE
Bushing Type	Same rating factors as transformer or breaker					
Free-Standing	100%	128%	150%	122%	148%	150%

CURRENT TRANSFORMERS

ANSI Standards

1. C57.13-1978 Requirements for Instrument Transformers, (**Reaffirmed in 1986**)
2. C57.91-2011 Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators

THERMAL CAPABILITIES OF COMPONENTS IN THE CURRENT CIRCUIT STARTING AT THE CT TERMINALS

Protective Relays

Please consult with the manufacturer.

New York Transmission Owners Task Force on Tie-Line Ratings

Section IX

Line Traps

LINE TRAPS

A line trap usually consists of an air-core inductance coil in series with a power line conductor and tuned to parallel resonance by means of a tuning pack.

At the time of the release of the 1995 Report, there was no formal standard for this piece of equipment – the previous standard (C93.3-1981) having been withdrawn during that report's review period. Since the 1995 report, an updated version of C93.3-2017 has been approved.

Table A-1 has been transcribed from IEEE C93.3-2017 (Reference #2). For formal discussion of the formulae used to derive these ratings factors, refer to section A.1.1 of that document:

TABLE-A-1

Normal and Emergency Overload Current is a Percentage of Rated Continuous Current					
Ambient	**Emergency Period**				**Normal**
Temperature (˚C)	**15 Minutes**	**30 Minutes**	**1 Hour**	**4 Hours**	**Continuous**
45	138	128	118	108	98
40	140	130	120	110	100
35	141	131	121	111	101
20	145	135	125	115	105
10	150	139	129	118	107
0	150	140	130	120	110
-20	155	145	135	125	110
-40	160	150	140	130	110

The rating factors to be used for line traps are:

Season	**Normal**	**LTE**	**STE**
Summer (35˚C)	101%	111%	141%
Winter (10˚C)	107%	118%	150%

LINE TRAPS

ANSI Standards

1. C93.3-2017 <u>Requirements for Power-Line Carrier Line Traps</u>

New York Transmission Owners Task Force on Tie-Line Ratings

Section X

Substation Bus Conductors

SUBSTATION BUS CONDUCTORS

Synopsis

Ampacity requirements for bus conductors are usually determined by the full-load ratings of the attached equipment or transmission lines. Temperature limitations of the connected equipment may be a factor in determining conductor loading limits when operation of conductors at excessive temperatures may cause damage to the connected equipment by transfer of heat. Bus conductor ampacity limits are affected by conductor size, material, wind velocity, insulation, ambient temperature, convective heat loss, radiation heat loss and solar heat gain.

Ampacity rating factors for air insulated rigid bus conductors are based on information given in ANSI/IEEE Std. 605-2008 (Reference #1). Ampacity rating factors for bare cable bus conductors are determined using the rating factors used for transmission line conductors, except that for substation bus conductor ampacity calculations, a wind velocity to two feet per second (fps) should be utilized.

Discussion

Substation electric power equipment have full-load ratings which are set by the limitations of the actual operating temperature. Accordingly, bus conductors should not be operated at temperatures which would cause heat to flow into the equipment. This requires that the calculated bus conductor ampacity ratings and operating temperatures be closely coordinated with the full-load ratings and thermal limitations of any connected equipment.

The general temperature rise equation for calculation of bus conductor loading amperes for normal and LTE operating conditions can be found in ANSI/IEEE Std. 605-2008 (Reference #1).

An important factor in the computation of bus conductor ampacity is the assumption of a wind velocity in connection with forced convection losses. For substation bus conductor ampacity calculations at 2 fps wind velocity is recommended as a conservative, but realistic approach (Reference #1 and #2).

The appropriate equations for determination of the ampacity factors for rigid bus conductors are defined in Appendix B on substation bus conductors. The ampacity factors for bare cable conductors are defined in Appendix A on transmission line conductors except that a wind velocity of 2 fps should be utilized.

The temperature limitation rating factors apply for both rigid bus and strain bus conductors. More conservative temperature limitation rating factors may be required for bus conductors directly connected to electrical equipment. Conductors connected to electrical equipment should not be operated at temperatures which would cause heat to flow into equipment. If the thermal limits of the equipment are unknown, the following conductor temperature limitations should be applied for conductors connected to electrical equipment.

Table 10-1: BUS CONDUCTOR TEMPERATURE LIMITATIONS

	Summer			Winter		
	N	LTE	STE	N	LTE	STE
Aluminum	85˚C	95˚C	105˚C	85˚C	95˚C	105˚C
ACSR	95˚C	115˚C	125˚C	95˚C	115˚C	125˚C
Copper	75˚C	100˚C	125˚C	75˚C	100˚C	125˚C
Equipment Connections	85°C	95˚C	105˚C	85˚C	95˚C	105˚C

SUBSTATION BUS CONDUCTORS

1. **ANSI/IEEE Std 605-2008**, IEEE Guide for Bus Design in Air Insulated Substations

2. Loading of Substation Equipment with Emphasis on Thermal Capability, Part I: Principles, by B.J. Conway, D.W. McMullen, A.J. Peat and J.M. Scofield - IEEE Transactions, Power Apparatus and Systems Vol. PAS-98, No.4, July/Aug.1 979 pp. 1394-1402

3. Loading of Substation Equipment with Emphasis on Thermal Capability, Part II: Application, by I.S.Benko, D.E.Cooper, D.O.Craghead and P.Q.Nelson - IEEE Transactions, Power Apparatus and Systems Vol. PAS-98, No.4, July/Aug.1979 pp.1403-1419

New York Transmission Owners Task Force on Tie-Line Ratings

Section XI

Current Limiting Reactors

SERIES REACTORS

The use of series reactors on the existing NY Bulk Power System is limited to a few locations. The standard covering the use of series reactors in the American Standard Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors, C57.16-2011.

One NYTO member's practice is to request the reactor manufacturers to match the rating of the transmission lines containing the planned series reactor(s). After the series reactor is installed, the rating used for the reactor supplied by the manufacturers Is used. Presently, the NYTO systems have a limited use of series reactors. The Task Force recommends the use ratings provided by the manufacturers.

In the 1995 NYPP Tie-Line Rating Report, ANSI's Appendix C57.99, the Guide for Loading Dry-Type and Oil-Immersed Current-Limiting Reactor published in 1965 is referenced. It provides general recommendations for loading both Dry-Type and Oil-Immersed current limiting reactors. It covers physical limitation, reactor life expectancy, rated load, effect of temperature of loading, etc.

The following example shows one of the many tables from the guide. It indicates the "Daily Peak Loads Above Name Plate Rating to Give Normal Life Expectancy in 30C Average Ambient for Dry-Type 55°C or 80°C Rise Self-Cooled":

Peak Load Time in Hour	Time Rated Amperes Dry-Type 55˚C or 80˚C Rise Self-Cooled(AA) Following and Followed by a Constant Load of		
	90 Percent	**70 Percent**	**50 Percent**
1/2	1.21	1.51	1.70
1	1.09	1.25	1.34
2	1.04	1.09	1.13
4	1.00	1.01	1.03
8	1.00	1.00	1.00

Other tables in the guide have similar data for Forced-Air-Cooled, Forced-Oil etc.

The thermal time constant formula for a Dry-Type reactor at rated load is shown below:

$$T_r = \frac{C\theta_{rl}}{w_t}$$

T_r= Time constant at rated load.
C= 0.06(weight of coil assembly in pounds, less weight of bottom disc and mounting insulators).
Θ_{rl}= Temperature at rated load.
W_r= Watts loss at 75˚C at rated load.

The following table indicates the "Daily Peak Loads Above Name Plate Rating to Give Normal Life Expectancy in 30C Average Ambient":

Peak Load Time in Hour	Time Rated Amperes Oil-Immersed self-cooled or water-cooled (OA or OW)* Following and Followed by a Constant Load of		
	90 Percent	70 Percent	50 Percent
1/2	1.64	1.78	1.89
1	1.39	1.49	1.58
2	1.24	1.32	1.37
4	1.13	1.17	1.19
8	1.06	1.07	1.08

*Average ambient of 25˚C for water-cooled reactors. Minimum water temperature must be 0˚C.

The thermal time constant formula for Oil-Immersed reactor for any load and for any specific temperature differential between the ultimate oil rise and the initial oil rise is given by the equation:

$$T = \frac{C(\theta hu - \theta hi)}{Wi - Wu}$$

T: Thermal time constant
C: Thermal capacity of reactor, watts-hours per degree C

Θhu: Ultimate hottest-spot winding temperature

Θhi: Initial hottest-spot winding temperature
Wi: Initial watts loss at 75˚C
W_u: Ultimate watts loss at 75˚C

Table 11-x: DRY TYPE CURRENT LIMITING REACTORS -- RATING FACTORS(%) --

Season	*SUMMER*				*WINTER*			
Operating Conditions	Ambient	Normal/ 8 hour	LTE 4 hours	STE 30 min.	Ambient	Normal/ 8 hours	LTE 4 hours	STE 30 min.
55ºC rise - dry-type, self-cooled * Following and followed by a constant load of 90 percent * Altitude does not exceed 3,300 feet	35ºC	96%	96%	116%	10ºC	114%	114%	140%
	30ºC	100%	100%	121%	5ºC	118%	118%	142%
	25ºC	104%	104%	125%	0ºC	121%	121%	146%
80ºC rise - dry-type, self-cooled * Following and followed by a constant load of 90 percent * Altitude does not exceed 3,300 feet	35ºC	98%	98%	118%	10ºC	109%	109%	109%
	30ºC	100%	100%	121%	5ºC	111%	111%	136%
	25°C	102%	102%	124%	0ºC	114%	114%	137%

NOTE 1: The shaded area numbers are taken from the Guide. Other numbers are calculated.

NOTE 2: The following factors from the Guide are used for the calculations:

For 55ºC RISE DRY-TYPE: 0.85% decrease for each degree C temperature ABOVE 30ºC
0.70% increase for each degree C temperature BELOW 30ºC

For 80ºC RISE DRY-TYPE: 0.50% decrease for each degree C temperature ABOVE 30ºC
0.45% increase for each degree C temperature BELOW 30ºC

SERIES REACTORS
(References)

ANSI Standards

1. C57.16-1958 Requirement, Technology, and Test Code for Current-Limiting Reactors.
2. Appendix C57.99-1965. Application Guide for Loading Dry-Type and Oil-Immersed Current-Limiting Reactors.
3. C57.16-2011 Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors.

New York Transmission Owners Task Force on Tie-Line Ratings

Section XII

Series Capacitors

SERIES CAPACITORS

Synopsis

The standard requirements for series capacitors are covered in ANSI Standard 824-2004. This standard applies to capacitors and assemblies of capacitors, insulation means, switching and protective equipment, and control accessories that form a complete installation for inserting in series with a transmission or distribution line.

The capacitor bank shall be designed for continuous operation in outdoor locations with unrestricted ventilation and direct sunlight under the ambient temperatures in accordance with applicable ANSI Standards.

The series capacitor bank shall be capable of withstanding the rated continuous current, system swing, emergency loading, continuous current as specified by the user in the general form illustrated in Fig 1.

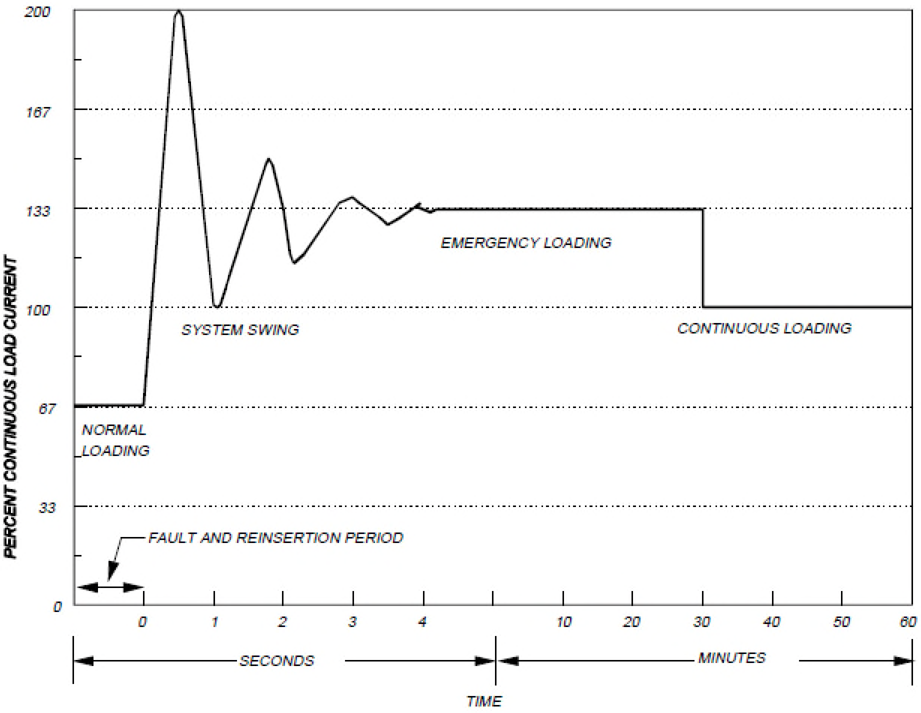

Figure 1
Typical Time-Current Profile on Reinsertion of Capacitor Bank
(After Fault and Loss of Parallel Line)

The life of a capacitor may be shortened by overstressing, overheating, or physical damage. Therefore, the life depends upon the control of operating conditions involving voltage, temperature limits, and physical care. Table 1 indicates the short-time capability based on the occurrence of overvoltage when the internal temperature of the capacitor unit is less than 0˚C.

Table 1 Transient Overvoltage and Overcurrent

Probable No. of Switching Operations Per Year	Permissible Peak Transient Voltage (Multiplying Factor to be Applied to RMS Rated Voltage)	Permissible Peak Transient Current (Multiplying Factor to be Applied to RMS Rated Current)
4	5	1500
40	4	1150
400	3.4	800
4000	2.9	400

New York Transmission Owners Task Force on Tie-Line Ratings

Appendix
A

Calculation of Overhead Conductor Ampacities

MANUAL METHOD OF CALCULATING CONDUCTOR AMPACITY

This is the method presented in the 1995 Tie-Line Rating Report and is based on the 1993 Standard. Newer versions of the Standard can be used as determined by each Transmission Owner. Calculating the ratings of a conductor involves steady-state and transient heat flow calculations. What follows is a brief review of the basic steps involved in making such calculations. *The IEEE Std 738-1993 includes both a computer program listing (basic) and a floppy disk containing the runtime version for calculating steady-state and transient conductor ratings.* The manual methods presented are based on the IEEE Standard.

The fundamental relationships for steady-state convected heat loss for horizontal wires discussed in the House and Tuttle AIEE Paper Current Carrying Capacity of ACSR are also covered in the book Heat Transmission by W. H. McAdams, McGraw-Hill Book Co.; and in an Alcoa booklet, Section 6 of Alcoa Conductor Engineering Handbook Series, titled: Current - Temperature Characteristics of Aluminum Conductors. A third reference, Principles of Heat Transfer by Frank Kreith, the International Textbook Company, Scranton, Pennsylvania, covers the subject of thermal transients. The material which follows was drawn primarily from these four references, and from *the IEEE Standard 738-2006, Calculating the Current Temperature Relationship of Bare Overhead Conductors. This standard includes a wind angle factor formula. The angle used is that between the wind and the conductor (0^{o}=parallel, 90^{o}=perpendicular). This factor was added to this section of the 1995 report.*

A conductor under transient loading conditions may be classified as a heat flow system with negligible internal thermal resistance. A justifiable assumption is that the thermal resistance between the surface of the system and the surrounding air (the film resistance) is so large compared to the internal thermal resistance of the system that it controls the heat transfer process.

Terms used in this appendix are defined hereunder:

CONDUCTION	A process by which heat flows from a region of higher temperature to a region of lower temperature within a medium (solid, liquid, or gaseous) or between different mediums, in direct physical contact. The subscript for conduction is "k".
RADIATION	A process by which heat is transferred from a high temperature body to a body at a lower temperature when the bodies are separated in space, even when a vacuum exists between them. The subscript for radiation is "r".
CONVECTION	A process of energy transfer by combined action of heat conduction, energy storage and mixing motion. It is most important as a mechanism of energy transfer between a solid surface and a liquid or a gas. The subscript for convection is "c".
HEAT RADIATED q_r	$q_r = \sigma(A_s)\epsilon[(T_1)^4 - (T_2)^4]$ where σ (sigma) is the Stefan-Boltzmann constant with a value equal to 0.5275×10^{-8} Watts per square foot per $^{o}K^4$ and ϵ (Epsilon) is the emissivity factor, with an agreed upon average value of 0.6 to be used for NYCA ratings.
HEAT ABSORBED q_s (sun effect)	Energy absorbed from the sun's radiation which results in a temperature of a conductor.

HEAT CAPACITY, Conductor	The quantity of heat energy required to raise the temperature of one linear foot of conductor by 1 degree in a specified way, Watt-sec/ft-ºC
SPECIFIC HEAT	The quantity of heat required to raise the temperature of a unit of weight of material by 1 degree, Cal/gm-ºC or Watt-sec/lb-ºC.
TRANSIENT FLOW	A heat flow process in a system is transient when the temperature at various points in the system changes with time

Since there are many variables involved, Table I has been included and is a complete listing of all physical quantities with brief definitions, symbols and a consistent system of units.

TABLE I SYMBOLS, DEFINITIONS AND UNITS

I = Conductor current - amperes at 60 Hz.

q_c = Convected heat loss - watts per lineal foot of conductor

q_r = Radiated heat loss - watts per lineal foot of conductor

q_s = Heat gain from the sun - watts per lineal foot of conductor

Q_s = Total solar and sky radiated heat - watts per sq. ft. (Table III)

$r_{ac}(T_c)$ = 60 Hz. AC resistance per lineal foot of conductor at temperature T_c (Table VII)

T_a = Ambient temperature - degreec C

$°K_a$ = Ambient temperature - degrees Kelvin = $T_a + 273$

T_c = Conductor temperature - degrees C

$°K_c$ = Conductor temperature - degrees Kelvin = $T_c + 273$

T_f = Air film temperature - degrees C; $T_f = (T_c + T_a)/2$

ΔT = Temperature difference - degrees C

Δt = Time increment

D = Diameter of conductor - inches

D_o = Diameter of conductor - feet

A = Cross sectional area - square feet

A_s = Conductor surface area - square feet per foot = $\pi D/12$

A' = Projected area of conductor - square feet per lineal foot = $D/12$

V = Velocity of air stream - feet per hour

K_{ang} = wind direction factor

ρ_f = Density of air at film temperature - lbs/cubic foot (Table II)

μ_f = Absolute viscosity of air at film temperature - lbs/(hr) (ft) (Table II)

k_f = Thermal conductivity of air at film temperature - watts/(sq. ft.) (°C) (Table II)

ϵ = Coefficient of emissivity, 0.23 - 0.91; use 0.6 for average value

α = Coefficient of absorption, 0.23 - 0.95; use 0.6 for average value

Note: above values are recommended for consistency of NYCA calculations

θ = Effective angle of incidence of sun's rays

H_c = Altitude of sun - degrees (Table III)

Z_c = Azimuth of sun - degrees (Table III)

Z_l = Azimuth of line - degrees (Table III)

c = Specific heat of conductor metal - cal./gm.-°C (Table IX)

W = Weight of conductor - lbs./lineal foot (Table VIII)

ϕ = Angle between the wind and conductor axis

τ = Time constant - minutes

Al = Subscript for aluminum

St = Subscript for steel

AMPACITY CALCULATION PROCEDURE

The ampacity ratings may be determined as follows:

1. For a particular conductor, it is first necessary to calculate the Normal and LTE ratings as described in the House and Tuttle reference for steady-state conditions, section 6 of the Alcoa Conductor Engineering Handbook, and IEEE Standard 738-1993, making use of the following equations:

Fundamental Steady-State Heat Balance Equation

$q_c + q_r = q_s + I^2 r_{ac}$ This equation states that at steady state the heat input due to conductor current and the sun is equal to heat loss by convection and radiation.

The ampacity rating is the value of current that satisfies this equation. Note that q_c, q_r and r_{ac} (T) must be calculated for the relevant design conductor temperature (Normal or LTE).

$$I = \sqrt{\frac{q_c + q_r - q_s}{r_{ac}(T)}}$$

Forced Convection Heat Loss

Air density ρ_f , air viscosity, μ_f , and coefficient of thermal conductivity of the air film at the conductor surface, k_f , are taken from Table II at air film temperature T_f where:

$$T_f = \frac{T_c + T_a}{2}$$

The convective heat loss term now includes the wind direction factor K_{ang}, where ϕ is the angle between the wind direction and the conductor axis:

$$K_{ang} = 1.194 - \cos(\phi) + 0.194 \cdot \cos(2\phi) + 0.368 \cdot \sin(2\phi)$$

The following sample values were generated from this formula:

ϕ	K_{ang}
90^o	1.000
45^o	0.855
30^o	0.744
20^o	0.639
0^o	0.388

Two formulas are used to calculate convection heat loss as follows:

The first formula

$$q_c = K_{ang}\left[1.01 + 0.371\left[\frac{D_o\rho_f V}{\mu_f}\right]^{0.52} k_f(T_c - T_a)\right] \text{ Watts/ft. of conductor}$$

is for values of $\left[\frac{D_o\rho_f V}{\mu_f}\right] = 0.1\ to\ 1{,}000$, where D_o = Conductor diameter in feet.

The second formula

$$q_c = 0.1695 \cdot K_{ang}\left[\frac{D_o\rho_f V}{\mu_f}\right]^{0.6} k_f(T_c - T_a) \text{ Watts/ft.ofconductor}$$

is for of $\left[\frac{D_o\rho_f V}{\mu_f}\right]$ $v$alues ranging between 1,000 to 18,000 (i.e. for higher values of wind speed, V)

The IEEE Standard 738 recommends using the <u>larger</u> of the two q_c values for a given conductor diameter.

A formula for natural convection heat loss is also provided in this standard. It is recommended to use the larger of the natural or forced convection heat loss. No combined effect is considered. Natural convection heat loss is numerically about the same as forced convection loss with a wind speed of 3 ft/sec and a wind angle of zero degrees.

Radiated Heat Loss

$$q_r = \sigma\epsilon A_s({}^\circ K_c^4 - {}^\circ K_a^4) = 0.5275 \text{ x } 10^{-8}\left[\frac{\pi D}{12}\right]\epsilon[({}^\circ K_c^4 - {}^\circ K_a^4)]$$

$$q_r = 0.138 \cdot D\epsilon\left[\left(\frac{{}^\circ K_c}{100}\right)^4 - \left(\frac{{}^\circ K_a}{100}\right)^4\right] \text{ Watts/ft. of conductor}$$

Solar Heat Gain

$$q_s = \alpha Q_s (\sin\theta) A'$$

Effective angle of incidence of solar radiation (see Tables III through VI)

$$\theta = \cos^{-1}[(\cos H_c)\cos(Z_x - Z_l)]$$

solar absorptivity:

$\alpha = 0.6$

2. From the above calculate the net rate of heat loss:

$$q_{Normal} = (q_c + q_r)_{Normal} - q_s \text{ Watts/ft of conductor}$$

and

$$q_{LTE} = (q_c - q_r)_{LTE} - q_s \text{ Watts/ft of conductor}$$

Calculate normal and LTE current ratings:

$$I_{Normal} = \sqrt{\frac{q_{Normal}}{r_{ac}(T_{Normal})}} \text{ Amperes} \qquad I_{LTE} = \sqrt{\frac{q_{LTE}}{r_{ac}(T_{LTE})}} \text{ Amperes}$$

CALCULATING THE SHORT-TERM RATING

Because the short-term rating period is limited to 15 minutes, most conductors can actually carry a heavier current without exceeding a selected maximum temperature than they would if the current were allowed to continue flowing until steady-state conductor heating was reached. The relationship between the changing conductor temperature and time is given by the "time constant" equation. The equation is:

$$\mathrm{T_c(t) = T_i + (T_{ult} - T_t)\left(i - e^{-t/\tau}\right)}$$

As the equation shows, the rate of conductor temperature rise depends on T_{ult}, the ultimate steady-state temperature that would result if the STE current was continuous, and time constant τ. Time constant is defined as the time required, after the step increase to STE current, for the temperature to equal 63% of the difference between T_{ult} and initial temperature T_i. For NYCA ratings, T_i is the Normal rating conductor temperature limit.

1. Computer Calculation

The STE current ratings and the T_{ult} and τ parameters can be determined by use of the IEEE Std. 738-1993 software. The STE time period and limiting temperature, and T_i are input, and the program starts an iterative procedure. A trial starting value of STE current is selected by the program, and the temperature rise ΔT_c during a time increment Δt is calculated from:

$$\Delta \mathrm{T_c} = \frac{(\mathrm{I}^2\mathrm{R} + \mathrm{q_s} - q_r - \mathrm{q_c})\Delta \mathrm{t}}{\mathrm{CW}} = \frac{\text{Net Heat Input}}{\text{Heat Capacity}}$$

The values of q_s, q_r and q_c are calculated from the same equations as for steady-state with the assumption that these are valid for the transient period. Temperature increment ΔT_c is added to T_i to get a new conductor temperature $T_c = T_i + \Delta T_c$. Heat input I^2R and losses q_r and q_c are then recalculated for the new T_c and ΔT_c is calculated for the next time increment using the new q_r and q_c. The process continues to the end of the STE time period. The resulting conductor temperature is then compared to the STE limiting temperature. If they are not sufficiently close, the program selects a new STE current and calculates another temperature vs time curve. The process continues until the curve passes through the temperature limit at t = 15 minutes. The current for this curve is the STE rating.

Having found the STE current, parameters T_{ult} and τ can then be found by the following steps, using the IEEE Std. program:

1. Calculate the steady state conductor temperature due to the STE current using NYCA ambient conditions. This is parameter T_{ult}.

2. Calculate conductor temperature $T_c = T_i + 0.63(T_{ult} - T_i)$

3. From the temperature vs time curve provided by the program, find the time corresponding to the T_c value. This is the time constant τ.

Another way to calculate the time constant is from IEEE Std 738-1993, Annex F; equation F3, which provides a good approximation for most conductors and an underestimate for small conductors (4/0 and smaller).

STE rating calculations for a range of ACSR conductors, Table A-1 and figure A-1, show that for 477 kcm and larger conductors, the temperature vs time curves are very similar during the 15 minute period (note temp. @ 5 min). This is true even though there is considerable variation in T_{ult} and τ. Temperature rise is more rapid for small conductors, which are seen in figure A-1 to reach steady-state within 15 minutes. Wind angle and wind speed also have small effect on the rate of temperature rise (see Table A-1), although they greatly affect convective heat loss, due to time and temperature constraints of the STE rating.

It is expected that the IEEE Std. method of calculating STE ratings will be more accurate than the method included in the 1982 NYPP Tie Line Rating Report. The IEEE method is easily handled by a computer, and is recommended in place of the 1982 report method.

Table A-1
Calculated values of T_{ult}, T_i and conductor temperature at 5 minutes after the start of STE operation, IEEE method, ambient 35ºC.

ACSR Conductor	Stranding	Wind Speed Ft/sec	Wind Angle Degrees	T_{ult} Degree C	τ Min.	T_c @ t=5 min. Degree C
1/0	6/1	3	90	125	2.9	119.7
4/0	6/1	3	90	127	4.9	115.5
477	30/7	3	90	132	8.9	110.9
795	26/7	3	90	137	11.9	109.4
795	26/7	1	90	145	16.2	108.3
795	26/7	3	20	143	15.2	108.5
2385	72/7	3	90	157	22.4	107.4

While it is not required, the mean conductor temperature during the STE transient period can be calculated from a formula obtained by integrating the time constant equation:

$$\overline{T_c} = T_{ult} + \frac{\tau}{\Delta t}\left(T_{ult} - T_t\right)\left(e^{-\Delta t/\tau} - 1\right) \text{ where } \Delta t = \text{duration of STE operation}$$

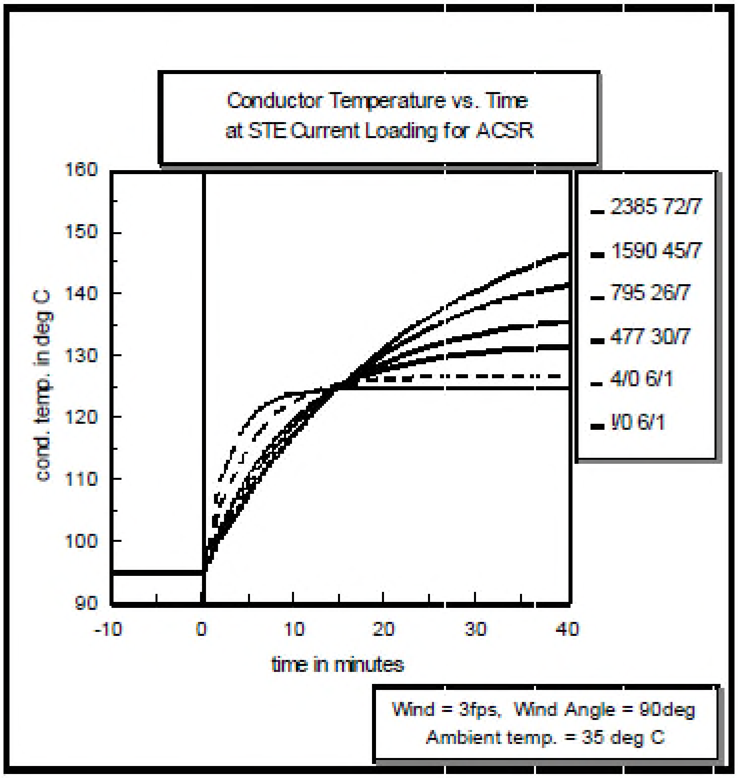

Figure A-1 Temperature vs Time for STE operation for a range of ACSR conductors, NYCA summer ambient.

2. **Manual Calculation**

The STE Rating for overhead conductors can be estimated by a manual method based on equations used in the IEEE Standard. A manual method can only provide an approximation. Simplifying assumptions must be made to handle the non-linear variation of radiated heat loss with conductor temperature. Results within a few percent of computer calculated ratings are still attainable.

The following empirical calculation method makes use of the observation that temperature vs. time curves such as those in figure A-1, fall in a narrow range for a number of common conductor sizes. This is due to the time and conductor temperature constraints of STE operation. Consequently, the mean conductor temperature during the STE transient period is nearly the same for each conductor type. For the manual STE rating calculation it is assumed that heat input and losses are constant for the full STE period. Heat input and losses are assumed to have values corresponding to a fixed temperature that is near the mean value of conductor temperature during the STE time period. The formula below can then be used to equate conductor temperature rise during a specified time to net heat energy input divided by the conductor heat capacity. The temperature rise is the increase from the Normal to the STE temperature limits (e.g. for ACSR, 95°C to 125°C). The equation is

$$\Delta T_c = T_{STE} - T_n = \frac{(I^2 r_{ac}(T_c) + q_s - q_c - q_r)\Delta t}{CW}$$

Solving the equation for current I results in a formula for I_{STE}:

$$I_{STE} = \sqrt{\frac{1}{r_{ac}(T_c)}\left[\frac{CW(T_{STE} - T_n)}{\Delta t} - q_s + q_r + q_c\right]}$$

where Δt = duration of the STE current = 15 minutes or 900 sec. The term $\frac{CW(T_{STE} - T_n)}{\Delta t}$

is the constant rate of heat input required to raise the conductor temperature from T_n to T_{STE} in time Δt.

In using the formula, parameters q_c, q_r, $r_{ac}(T_c)$ and CW are calculated at the fixed temperature for the conductor type. The temperatures are:

Conductor Type	T, Deg. C
ACSR	110
SAC	95
ACAR	110
Copper, CWC	100

Solar heat gain q_s is the same for Normal and LTE calculations. In calculating heat capacity CW, the specific heat value from Table IX must be multiplied by the factor 1898.76 to convert the units to Watt--sec/lb-^{o}C. For ACSR and other composites the sum of the heat capacities of each material is used, i.e.

$$CW = C_{Al}W_{Al} + C_{St}W_{St}$$

Results from the above procedure will be within a few percent of the computer calculation. For mid-range and larger conductors the manual results will be on the high side. If assured conservative values of I_{STE} are required, results from the formula can be reduced by 3-5 percent.

For small conductors that closely approach or reach steady-state by the end of the STE time period, another method must be used. A reasonable estimate of the STE rating can be calculated by the method used for Normal and LTE ratings. Heat losses and $r_{ac}(T_c)$ are calculated at the STE temperature limit.

TABLE A-II
Viscosity, Density and Thermal Conductivity of Air

Temperature			(^{o}K/100)^{4}	Absolute Viscosity (1) lb/hr-ft μ_r	Density (2) Air lb/ft^{3} ρ_f				Thermal Conductivity of Air (3) Watts/ft^{2}-^{o}C k_f
^{o}F	^{o}C	^{o}K			Sea Level	5,000 ft	10,000 ft	15,000 ft	
32	0	273	55.55	0.0415	0.0807	0.0671	0.0554	0.0455	0.00739
41	5	278	59.73	0.0421	0.0793	0.0660	0.0545	0.0447	0.00750
50	10	283	64.14	0.0427	0.0779	0.0648	0.0535	0.0439	0.00762
59	15	288	68.80	0.0433	0.0765	0.0636	0.0526	0.0431	0.00773
68	20	293	73.7	0.0439	0.0752	0.0626	0.0517	0.0424	0.00784
77	25	298	78.86	0.0444	0.0740	0.0616	0.0508	0.0417	0.00795
86	30	303	84.29	0.0450	0.0728	0.0606	0.0500	0.0411	0.00807
95	35	308	89.99	0.0456	0.0716	0.0596	0.0492	0.0404	0.00818
104	40	313	95.98	0.0461	0.0704	0.0586	0.0484	0.0397	0.00830
113	45	318	102.26	0.0467	0.0693	0.0577	0.0476	0.0391	0.00841
122	50	323	108.85	0.0473	0.0683	0.0568	0.0469	0.0385	0.00852
131	55	328	115.74	0.0478	0.0672	0.0559	0.0462	0.0379	0.00864
140	60	333	122.96	0.0484	0.0661	0.0550	0.0454	0.0373	0.00875
149	65	338	130.52	0.0489	0.0652	0.0542	0.0448	0.0367	0.00886
158	70	343	138.41	0.0494	0.0643	0.0535	0.0442	0.0363	0.00898
167	75	348	146.66	0.0500	0.0634	0.0527	0.0436	0.0358	0.00909
176	80	353	155.27	0.0505	0.0627	0.0522	0.0431	0.0354	0.00921
185	85	358	164.26	0.0510	0.0616	0.0513	0.0423	0.0347	0.00932
194	90	363	173.63	0.05115	0.0608	0.0506	0.0418	0.0343	0.00943
203	95	368	183.40	0.0521	0.0599	0.0498	0.0412	0.0338	0.00952
212	100	373	193.57	0.0526	0.0591	0.0492	0.0406	0.0333	0.00966

(1) (605) HH Senrath and Touloukian, "The Viscosity, Thermal Conductivity and Prandtl Number for Air and Other Gases," *ASME Transactions*, Vol 76, 1954, pp. 967-981

(2) (606) Richard D. Madison, Editor, *Fan Engineering*, 5th edition, Buffalo Forge Company, Buffalo, New York, 1948.

(3) (604) W. H. McAdams, *Heat Transmission*, 3rd edition, McGraw-Hill Book Company, New York, 1954

TABLE A-III
FACTORS FOR DETERMINING SUN EFFECT WHEN CALCULATING TRANSMISSION LINE AMPACITY SUMMER AND WINTER CONDITIONS NEW YORK STATE AREA

Factors	Summer	Winter
Latitude (1)	42°	42°
Longitude (1)	76°	76°
Declination (2)	+23°	-23°
Altitude of Sun (H_c) 10:00am and 2:00 pm (2)	59°	19°
Altitude of Sun (H_c) 12:00 N (2)	71°	25°
Average Altitude (2)	65°	22°
Azimuth of Sun (Z_c) 10:00 am (2)	118°	152°
Azimuth of Sun (Z_c) 12:00 N (2)	180°	180°
Average Azimuth, 10:00am and 12:00 N	149°	166°
Effect of Sun, Q_s Watts/ft^2 (3)	94	67
Assumed Direction of Line	E to W	E to W
Azimuth of Line Z_ℓ	270°W	270°W

(1) For a point in vicinity of Binghamton, NY.

(2) Declination and sun's altitude are averages for June 10 and July 13 for summer; and December 13 and January 2 for winter. Data obtained from SIGHT REDUCTION TABLES FOR AIR NAVIGATION, U.S. Navy Hydrographic Office, H.O. Publication No. 29, Volume III.

(3) From Table III, CURRENT CARRYING CAPACITY OF ACSR, by House and Tuttle, AIEE Transactions, Power Apparatus and Systems, Volume 77, Part III, 1959, page 1170.

TABLE A-IV
ALTITUDE AND AZIMUTH IN DEGREES OF THE SUN AT VARIOUS LATITUDES DECLINATION 23.0° - NORTHERN HEMISPHERE - JUNE 10 AND JULY 3

Degrees North Latitude	Local Sun Time					
	10:00 am		12:00 N		2:00 pm	
	H_c	Z_c	H_c	Z_c	H_c	Z_c
20	62	78	87	0	62	282
25	62	88	88	180	62	272
30	62	98	83	180	62	262
35	61	107	78	180	61	253
40	60	115	73	180	60	245
45	57	122	68	180	57	238
50	54	128	63	180	54	232
60	47	137	53	180	47	233
70	40	143	43	180	40	217

TABLE A-V
TOTAL HEAT RECEIVED BY A SURFACE AT SEA LEVEL NORMAL TO THE SUN'S RAYS

Solar Altitude Degrees H_c	Q_s watts / ft^2 (See Table VI)	
	Clear Atmosphere	Industrial Atmosphere
5	21.7	12.6
10	40.2	22.3
15	54.2	30.5
20	64.4	39.2
25	71.5	46.6
30	77.0	53.0
35	81.5	57.5
40	84.8	61.5
45	87.4	64.5
50	90.0	67.5
60	92.9	71.6
70	95.0	75.2
80	95.8	77.4
90	96.4	78.9

TABLE VI
SOLAR HEAT MULTIPLYING FACTORS FOR HIGH ALTITUDES

Elevation Above Sea Level, feet	Multiplier for Values in Table V
0	1.00
5,000	1.15
10,000	1.25
15,000	1.30

TABLE A-VII

Note: See also tables in EPRI Transmission Line Reference Book 345kV and Above , 1975 for conductor tables containing a-c resistance. A newer version of the book is available.

RESISTANCE AND STRANDING OF BARE ACSR

Code Name	Alum. Area MCM	Stranding			AC Resistance 60 cps - ohms per miles *			
		No. of Wires		Layers of Alum.	25°C	50°C	75°C	100°C
		Alum.	Steel					
Starling	715.5	26	7	2	0.1260	0.1390	0.1510	0.1640
Redwing	715.5	30	19	2	0.1260	0.1390	0.1510	0.1640
Tern	795.0	45	7	3	0.1160	0.1280	0.1390	0.1510
Condor	795.0	54	7	3	0.1150	0.1270	0.1380	0.1500
Drake	795.0	26	7	2	0.1140	0.1250	0.1370	0.1480
Mallard	795.0	30	19	2	0.1140	0.1250	0.1370	0.1480
Crane	874.5	54	7	3	0.1050	0.1160	0.1260	0.1370
Canary	900.0	54	7	3	0.1020	0.1120	0.1220	0.1330
Rail	954.0	45	7	3	0.0978	0.1080	0.1170	0.1270
Cardinal	954.0	54	7	3	0.0963	0.1060	0.1160	0.1250
Ortian	1,033.5	45	7	3	0.0905	0.0996	0.1090	0.1180
Curlew	1,033.5	54	7	3	0.0893	0.0983	0.1070	0.1160
Bluejay	1,113.0	45	7	3	0.0844	0.0929	0.1010	0.1100
Finch	1,113.0	54	19	3	0.0832	0.0915	0.0999	0.1080
Bunting	1,192.5	45	7	3	0.0792	0.0871	0.0951	0.1030
Grackle	1,192.5	54	19	3	0.0778	0.0856	0.0934	0.1010
Bittern	1,272.0	45	7	3	0.0746	0.0821	0.0896	0.0970
Pheasant	1,272.0	54	19	3	0.0732	0.0805	0.0879	0.0952
Dipper	1,351.5	45	7	3	0.0705	0.0776	0.0846	0.0917
Martin	1,351.5	54	19	3	0.0692	0.0761	0.0831	0.0900
Bobolink	1,431.0	45	7	3	0.0668	0.0735	0.0802	0.0869
Plover	1,431.0	54	19	3	0.0657	0.0723	0.0739	0.0855
Nuthatch	1,510.5	45	7	3	0.0636	0.0700	0.0764	0.0827
Parrot	1,510.5	54	19	3	0.0625	0.0688	0.0750	0.0813
Lapwing	1,590.0	45	7	3	0.0608	0.0669	0.0730	0.0791
Falcon	1,590.0	54	19	3	0.0589	0.0648	0.0707	0.0766
Chukar	1,780.0	84	19	4	0.0548	0.0603	0.0658	0.0713

* The 60 cycle AC resistance is for ACSR conductors with two or four layers of aluminum of 62 per cent conductivity and allows for skin effect in the aluminum and losses in the steel core. For ACSR conductors with three layers of aluminum, the values in the table should be multiplied by the following factors when greater accuracy is desired: (a) for current densities of 1000 amperes per 1000 MCM multiply by 1.006 for 45/7 conductors and by 1.025 for 54/7 and 54/19 (b) for current densities of 1300 amperes per 1000 MCM multiply by 1.0075 for 45/7 conductors and by 1.03 for 54/7 and 54/19. Additional information on this subject is available in the source reference Alcoa Engineering Data Handbook, Section 5, Resistance and Reactance of Aluminum Conductors

TABLE A-VIII

Code Word	PHYSICAL PROPERTIES											
	Size and Area, ACSR			Standing Individual Wires				Diameter Inches		Weight Pounds Per Ft		
	Aluminum		Alum. and Steel Square Inches	Aluminum		Steel				Aluminum	Steel	
	CM	Square Inches		No.	Dia. Inches	No .	Dia. Inches	Steel Core	Over All	Alum	Steel	Total
Mallard	795,000	0.6244	0.7668	30	0.1628	19	0.0977	0.489	1.140	.752	.483	1.235
Ruddy	900,000	0.7069	0.7558	45	0.1414	7	0.0943	0.283	1.131	.849	.166	1.015
Canary	900,000	0.7069	0.7985	54	0.1291	7	0.1291	0.387	1.162	.849	.310	1.159
Rail	954,000	0.7493	0.8011	45	0.1456	7	0.0971	0.291	1.165	.900	.175	1.075
Cardinal	954,000	0.7493	0.8464	54	0.1329	7	0.1329	0.399	1.196	.900	.329	1.229
Ortotan	1,033,500	0.8117	0.8678	45	0.1515	7	0.1010	0.303	1.212	.975	.190	1.165
Curlew	1,033,500	0.8117	0.9169	54	0.1383	7	0.1383	0.415	1.245	.975	.356	1.331
Blue Jay	1,113,000	0.8742	0.9346	45	0.1573	7	0.1049	0.315	1.258	1.050	.205	1.255
Finch	1,113,000	0.8742	0.9851	54	0.1436	19	0.0862	0.431	1.293	1.055	.376	1.431
Bunting	1,192,500	0.9366	1.001	45	0.1628	7	0.1085	0.326	1.302	1.125	.219	1.344
Grackle	1,192,500	0.9366	1.055	54	0.1486	19	0.0892	0.446	1.338	1.130	.463	1.533
Bittern	1,272,000	0.9990	1.068	45	0.1681	7	0.1121	0.336	1.345	1.200	.234	1.434
Pheasant	1,272,000	0.9990	1.126	54	0.1535	19	0.0921	0.461	1.382	1.206	.429	1.635
Dipper	1,351,500	1.061	1.134	45	0.1733	7	0.1155	0.346	1.386	1.275	.248	1.523
Martin	1,351,500	1.061	1.195	54	0.1582	19	0.0949	0.475	1.424	1.281	.456	1.737
Bobolink	1,431,000	1.124	1.202	45	0.1783	7	0.1189	0.357	1.426	1.350	.263	1.613
Plever	1,431,000	1.124	1.266	54	0.1628	19	0.0977	0.489	1.465	1.357	.483	1.840
Nuthatch	1,510,500	1.186	1.268	45	0.1832	7	0.1221	0.366	1.466	1.425	.277	1.702
Parrot	1,510,500	1.186	1.336	54	0.1672	19	0.1003	0.502	1.505	1.432	.510	1.942
Lapwing	1,590,000	1.249	1.335	45	0.1880	7	0.1253	0.376	1.504	1.499	.293	1.792
Falcon	1,590,000	1.249	1.407	54	0.1716	19	0.1030	0.515	1.545	1.507	.537	2.044
Chukar	1,780,000	1.398	1.512	84	0.1456	19	0.0874	0.437	1.602	1.687	.387	2.074
Bluebird	2,156,000	1.693	1.831	84	0.1602	19	0.0961	0.491	1.762	2.044	.467	2.511
Kiwi	2,167,000	1.702	1.776	72	0.1735	7	0.1157	0.347	1.735	2.054	.249	2.303
HIGH STRENGTH ACSR												
Grouse	80,000	0.0628	0.0947	8	0.1000	1	0.1670	0.167	0.367	.075	.074	.149
Petrel	101,800	0.0800	0.1266	12	0.0921	7	0.0921	0.276	0.461	.096	.158	.254
Minorca	110,800	0.0870	0.1378	12	0.0961	7	0.0961	0.288	0.481	.105	.172	.277
Leghorn	134,600	0.1057	0.1674	12	0.1059	7	0.1059	0.318	0.530	.127	.209	.336
Guinea	159,000	0.1249	0.1977	12	0.1151	7	0.1151	0.345	0.576	.150	.247	.397
Dotterel	176,900	0.1389	0.2199	12	0.1214	7	0.1214	0.364	0.607	.167	.275	.442
Dorking	190,800	0.1499	0.2373	12	0.1261	7	0.1261	0.378	0.631	.180	.296	.476
Brahma	203,200	0.1596	0.3020	16	0.1127	19	0.0977	0.489	0.714	.192	.485	.677
Cochin	211,300	0.1660	0.2628	12	0.1327	7	0.1327	0.389	0.664	.199	.328	.527

TABLE A-IX
SPECIFIC HEAT
Variation With Temperature

°C	Pb	Za	Al	Ag	Au	Cu	Ni	Fe	Co	Quartz
0°C	0.0350	0.0878	0.2220	0.0573	0.0317	0.1008	0.1005	0.1055	0.0912	
100	0.0336	0.0965	0.2297	0.0583	0.0320	0.1014	0.1200	0.1168	0.0998	0.2372
200	0.0313	0.1052	0.2374	0.0594	0.0322	0.1020	0.1305	0.1282	0.1073	0.2416
300	0.0200	0.1139	0.2451	0.0605	0.0325	0.1026	0.1409	0.1396	0.1154	0.2460
400	0.0266	0.1226	0.2529	0.0616	0.0328	0.1032	0.1294	0.1509	0.1235	0.2504
500	0.0259	0.1173	0.2606	0.0627	0.0330	0.1038	0.1294	0.1623	0.1316	0.2548
600	0.0252	0.1141	0.2683	0.0638	0.0333	0.1045	0.1294	0.1737	0.1396	0.2592
700	0.0246	0.1100	0.2523	0.0649	0.0335	0.1051	0.1295	0.1850	0.1477	0.2636
800	0.0239	0.1076	0.2571	0.0660	0.0338	0.1057	0.1295	0.1592	0.1558	0.2680
900	0.0233	0.1044	0.2619	0.0671	0.0341	0.1063	0.1295	0.1592	0.1639	0.2724
1000	0.0226	0.1012	0.2667	0.0637	0.0343	0.1069	0.1295	0.1448		0.2768
1100				0.0694	0.0329	0.1028	0.1296	0.1448	0.1424	0.2812
1200				0.0750	0.0346	0.1159	0.1296	0.1448	0.1454	0.2856
1300				0.0807	0.0364	0.1291	0.1296	0.1449	0.1483	0.2900
1400							0.1296	0.1449	0.1512	0.2944
1500							0.1388	0.2142	0.1472	0.2988
1600								0.1501	0.1472	

Variation With Temperature (Interpolated Values) CAL./gm-°C

°F	°C	Aluminum	Steel	Copper
32	0	0.2220	0.10450	0.10080
68	20	0.2235	0.10700	0.10092
167	75	0.2278	0.11388	0.10125
176	80	0.2282	0.11450	0.10128
185	85	0.2285	0.11513	0.10131
194	90	0.2289	0.11575	0.10134
203	95	0.2293	0.11638	0.10137
212	100	0.2297	0.11700	0.10140
221	105	0.2301	0.11763	0.10143
230	110	0.2305	0.11825	0.10146
239	115	0.2309	0.11888	0.10149
248	120	0.2312	0.11950	0.10152
257	125	0.2316	0.12013	0.10155

To convert to Watt-sec/lb-ºC, multiply by $1898.76 = \left(4.186\ \frac{Watt-sec}{Cal}\right)\left(453.6\ \frac{g}{lb}\right)$

NUMERICAL EXAMPLE OF MANUAL CALCULATION NYCA SUMMER NORMAL, LTE AND STE RATINGS

Assume Lapwing ACSR Conductor [1590 MCM ACSR (45/7)]

D = 1.504”

Weight/ft		
	Aluminum	1.500 lbs
	Steel	0.292 lbs
	Total	1.792 lbs

α = 0.6

T_a = 35°C Summer Ambient

T_c = 95°C Operating

T_c = 115°C Emergency

T_c = 125°C Short-Time

$r_{ac\,@\,25^oC}$ = 0.0622 Ohms/mi

$r_{ac\,@\,100^oC}$ = 0.0791 Ohms/mi

ϕ = 90°

ϵ = 0.6

V = 3 ft/sec x 3600 = 10,800 ft/hr

Change in resistance/°C:

$(\mathrm{r_{ac\,@\,100^oC}} - \mathrm{r_{ac\,@\,25^oC}})/75 = 0.000224$

$$\mathrm{r_{ac\,@\,95^oC}} = \frac{0.0790 - 5(0.000224)}{5280} = 14.8\mathrm{x}10^{-6}\,\frac{\mathrm{Ohms}}{\mathrm{ft}}$$

$$\mathrm{r_{ac\,@\,115^oC}} = \frac{0.0790 - 15(0.000224)}{5280} = 15.6\mathrm{x}10^{-6}\,\frac{\mathrm{Ohms}}{\mathrm{ft}}$$

$$\mathrm{r_{ac\,@\,110^oC}} = \frac{0.0790 - 10(0.000224)}{5280} = 15.39\mathrm{x}10^{-6}\,\frac{\mathrm{Ohms}}{\mathrm{ft}}$$

FACTORS FOR NORMAL RATING

^oK_c = 95°C + 273° = 368°

^oK_a = 35°C + 273° = 308°

$T_f = \dfrac{95^o + 35^o}{2} = 65^oC$

From Table II for T_f = 65°C

ρ_f = 0.0652 lb/ft^3

μ_f = 0.0489 lb/ hr-ft

k_f = 0.00886 Watts/ft^2-°C

FACTORS FOR LTE RATING

^oK_c = 115°C + 273° = 388°

^oK_a = 35°C + 273° = 308°

$T_f = \dfrac{115 + 35^o}{2} = 75^oC$

From Table II for T_f = 75°C

ρ_f = 0.0634 lb/ft^3

μ_f = 0.0500 lb/ hr-ft

k_f = 0.00909 Watts/ft^2-°C

FACTORS FOR SHORT-TIME RATING

From Table II for $T_f = 72.5^oC$

^oK_c = $110^oC + 273^o = 383^o$

^oK_a = $35^oC + 273^o = 308^o$

T_f = $\dfrac{110^o + 35^o}{2} = 72.5^oC$

ρ_f = 0.0638 lb/ft^3

μ_f = 0.0498 lb/hr-ft

k_f = 0.00904 $watts/ft^2$-^oC

CALCULATING THE SUMMER NORMAL RATING

A. Convection Heat Loss

$$q_c = K_{ang}\left[1.01 + 0.371\left(\frac{D_o\rho_f V}{\mu_f}\right)^{0.52} k_f(T_c - T_a)\right] \text{Watts/ft. of conductor}$$

$$q_c = (1.0)\left[1.01 + 0.371\left(\frac{(1.504)(0.0652)(10800)}{0.0489}\right)^{0.52}\right](0.00886)(95-35)$$

$$q_c = 35.98 \text{ Watts/ft of conductor}$$

Note that for this particular conductor, the two alternative formulas give the same value for q_c. Normally the higher value from the two formulas should be used for a given conductor. Since the wind angle is 90^o in this example, $K_{ang} = 1.0$.

B. Radiated Heat Loss

$$q_r = 0.138D\epsilon\left[\left(\frac{^oK_c}{100}\right)^4 - \left(\frac{^oK_a}{100}\right)^4\right] \text{Watts/ft. of conductor}$$

$$q_r = 0.138(1.504)(0.6)\left[\left(\frac{368}{100}\right)^4 - \left(\frac{308}{100}\right)^4\right]$$

$$q_r = 11.63 \text{ Watts/ft of conductor}$$

C. Assume line runs E-W at latitude 42°N in clear atmosphere. Take average altitude and average azimuth of sun between 10:00 am and noon.

$H_c = 65°$ $Z_c = 149°$ - from Table III: $Q_s = 94.0$ Summer

from Table III

$$\theta = \cos^{-1}[(\cos 65^o)\cdot\cos(149^o - 270^o)] = 102.5^o$$

$$\sin 102.5^{o} = 0.976$$

Solar Heat Gain

$$q_s = \alpha Q_s (\sin\theta) A' \quad \text{Assume coefficient of absorption } \alpha = 0.6$$

$$q_s = (0.6)(94.0)(0.976)\left(\frac{1.504}{12}\right) = 6.88\,\frac{\text{Watts}}{\text{ft}}.\text{of conductor}$$

D. Summer Normal Rating

(a) With Sun:

$$I_{\text{Normal}} = \sqrt{\left[\frac{q_c + q_r - q_s}{r_{ac\,@\,95C}}\right]} = \sqrt{\left[\frac{35.98 + 11.63 - 6.88}{14.8\text{x}10^{-6}}\right]} = 1659 \text{ Amperes}$$

(b) Without Sun:

$$I_{\text{Normal}} = \sqrt{\left[\frac{q_c + q_r}{r_{ac\,@\,95C}}\right]} = \sqrt{\left[\frac{35.98 + 11.63}{14.8\text{x}10^{-6}}\right]} = 1794 \text{ Amperes}$$

CALCULATING THE LTE RATING

Max Conductor Temperature for ACSR = 115°C

$$q_c = K_{ang}\left[1.01 + 0.371\left(\frac{D_o \rho_f V^{0.52}}{\mu_f}\right) k_f (T_c - T_a)\right] \text{Watts/ft. of conductor}$$

$$q_c = (1.0)\left[1.01 + 0.371\left(\frac{(1.504)(0.0634)(10800)}{0.0500}\right)^{0.52}\right](0.00909)(115 - 35)$$

$$q_c = 47.96\,\frac{\text{Watts}}{\text{ft}}.\text{of conductor}$$

$$q_r = (0.138)(1.504)(0.6)\left[\left[\frac{388}{100}\right]^4 - \left[\frac{308}{100}\right]^4\right]$$

$$q_r = 17.02 \frac{\text{Watts}}{\text{ft}}$$

The sun effect is unchanged $q_s = 6.88$ Watts/ft

Summer LTE Rating:

(a) With Sun:

$$I_{LTE} = \sqrt{\left[\frac{q_c + q_r - q_s}{r_{ac\,@\,115C}}\right]} = \sqrt{\left[\frac{47.96 + 17.02 - 6.88}{15.7x10^{-6}}\right]} = 1924 \text{ Amperes}$$

(b) Without Sun:

$$I_{LTE} = \sqrt{\left[\frac{q_c + q_r}{r_{ac\,@\,115C}}\right]} = \sqrt{\left[\frac{47.96 + 17.02}{15.7x10^{-6}}\right]} = 2034 \text{ Amperes}$$

CALCULATINGTHE STE RATING

Since the conductor is ACSR, $r_{ac}(T)$, CW, q_c and q_r will be calculated at $T_c = 110^oC$.

A. Since $\phi = 90^o$, $K_{ang} = 1.0$

$$q_c = K_{ang}\left(1.01 + 0.371\left(\frac{D_{\ o}\rho_f\ V}{\mu_f}\right)^{0.52}\right) k_f\ (T_C - T_a)\ \text{Watts/ft. of conductor}$$

$$q_c = 1.0\ x\left(1.01 + 0.371\left(\frac{1.504\ x\ 0.0638\ x\ 10800}{0.0498}\right)^{0.52}\right) x\ 0.00904\ x\ (110 - 35)$$

$$q_c = 44.95\ \text{Watts/ft. of conductor}$$

B.

$$q_r = (\sigma)\ (\epsilon)\ (A_{surface})\left[\left(\frac{^\circ K_c}{100}\right)^4 - \left(\frac{^\circ K_a}{100}\right)^4\right]$$

$$\mathrm{q_r} = (0.138) \text{ x } (1.504) \text{ x } (0.6)\left[\left(\frac{383}{100}\right)^4 - \left(\frac{308}{100}\right)^4\right]$$

$$\mathrm{q_r} = 15.59 \ \text{Watts/ft. of conductor}$$

C.

$$\mathrm{CW} = \left((\mathrm{C}_{\mathrm{Al\,@\,110C}} \text{ x } \omega_{\mathrm{Al}}) + (\mathrm{C}_{\mathrm{St\,@\,110C}} \text{ x } \omega_{\mathrm{St}})\right) \text{ x } \left[1898.76 \ \frac{\frac{\mathrm{Watt \cdot sec}}{\mathrm{lb \cdot \ ^oC}}}{\frac{\mathrm{Cal}}{\mathrm{gm - \ ^oC}}}\right]$$

$$\mathrm{CW} = \left((0.2305 \text{ x } 1.500) + (0.11825 \text{ x } 0.292)\right) \text{ x } 1898.76$$

$$\mathrm{CW} = 722.06 \ \frac{\mathrm{Watt \cdot sec}}{\mathrm{lb \cdot \ ^oC}}$$

D.

$$\mathrm{I_{STE}} = \sqrt{\frac{1}{\mathrm{r}_{\mathrm{ac\,@\,110C}}}\left[\frac{\mathrm{CW \text{ x } (T_{STE} - T_n)}}{900} + \mathrm{q_c} + \mathrm{q_r} - \mathrm{q_s}\right]}$$

$$\mathrm{I_{STE}} = \sqrt{\frac{1}{15.39\text{x}10^{-6}}\left[\frac{722.06 \text{ x } (125 - 95)}{900} + 44.95 + 15.59 - 6.88\right]}$$

$$\mathrm{I_{STE}} = \sqrt{\frac{77.73}{15.39\text{x}10^{-6}}}$$

$$I_{STE} = 2247 \ Amperes$$

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Appendix

B

Calculation of
Rigid Bus Conductor
STE Ampere Rating

APPENDIX ’B’

Manual Method of Calculating Substation Rigid Bus Conductor Short-Time Current Rating

The general temperature rise equation for calculation of bus conductor loading amperes for normal and LTE operating conditions is:

$$I = \sqrt{\left[\frac{q_c + q_r - q_s}{R \cdot F}\right]}$$

Where:

I = Conductor loading amperes
q_c = Convective heat loss
q_r = Radiation heat loss
q_s = Solar heat gain
R = Direct current resistance at the conductor temperature
F = Skin effect coefficient for 60 Hz. current

An important factor in the computation of bus conductor ampacity is the assumption of a wind velocity in connection with forced convection losses. For substation bus conductor ampacity calculations, a 2 fps wind velocity is recommended as a conservative but realistic approach (Ref. #1) (Ref. #2).

Convective Heat Loss (q_c)

A bus conductor loses heat through natural or forced convection. Natural convection is a function of:

(1) the temperature difference between the conductor surface and the ambient air temperature;
(2) the orientation of the conductor’s surface;
(3) the width of the conductor’s surface and
(4) the conductor’s surface area.

Forced convective heat loss is a function of:

(1) the temperature difference between the conductor’s surface and the ambient air temperature;
(2) the length of flow path over the conductor;
(3) the wind velocity and
(4) the conductor’s surface area.

For rigid tubing bus conductors the summation of natural forced convection losses is determined by:

$$q_c = 0.377 \cdot \Delta t \cdot d^{0.6} \left(\frac{\text{Watts}}{\text{ft}}\right)$$

where
Δt = temperature difference between conductor temperature and ambient temperature (^{o}C)
d = outside diameter of tubing (inches)

Radiation Heat Loss (q_r)

A conductor loses heat through the emission of radiated heat. The heat lost is a function of:

(1) the difference in the absolute temperature of the conductor and the surrounding bodies;
(2) the emissivity of the conductor's surface; and
(3) the conductor's surface area.

For rigid tubing bus conductors, the radiation heat loss is determined by:

$$q_r = 1390 \cdot \epsilon \cdot d(T_c^4 - T_a^4)x10^{-12} \left(\frac{\text{Watts}}{\text{ft}}\right)$$

where

ϵ = emissivity coefficient which varies with the surface condition of the conductor. Typical values are $\epsilon = 0.5$ for weathered aluminum and $\epsilon = 0.8$ for weathered copper.
d = outside diameter of tubing (inches)
T_c = conductor temperature (°K) = °C + 273°
T_a = ambient temperature (°K) = °C + 273°

Solar Heat Gain (q_s)

The amount of solar heat gained is a function of:

(1) the total solar and sky radiation;
(2) the coefficient of solar absorption for the conductor surface;
(3) the projected area of the conductor;
(4) the altitude of the conductor and
(5) the orientation of the conductor with respect to the sun's rays.

For rigid tubing bus conductors, the solar heat gain is determined by:

$$q_s = 0.00695 \cdot \epsilon' Q_s A' K(\sin \emptyset) \left(\frac{\text{Watts}}{\text{ft}}\right)$$

where ϵ' = coefficient of solar absorption, usually somewhat higher than emittance, but generally taken as equal to that used for radiation loss ($\epsilon = 0.5$ for weathered aluminum and $\epsilon = 0.8$ for weathered copper).

Q_s = total solar sky radiated heat on a surface normal to sun's rays, (Watts/ft^2), based on the altitude of the sun. From Table III (Appendix A) the average altitude of the sun for New York State is 65° (summer) and 22° (winter). From Table 1 (reference 1), this corresponds to 94 Watts/ft^2 (summer) and 67 Watts/ft^2 (winter).

A' = projected area of conductor (square inches per foot), based on area casting shadow.

K = heat multiplying factor for high altitude.

Elevation above Sea Level (ft)	K
0	1.00
5,000	1.15
10,000	1.25
15,000	1.30

ϕ = effective angle of incidence of sun = $\cos^{-1}[\cos H_c \cdot \cos(Z_c - Z_i)]$

where:
H_c = altitude of sun (degrees)
Z_c = azimuth of sun (degrees)
Z_i = azimuth of conductor line (degrees)

0 or 180 for N-S
90 or 270 for E-W

From Table III (Appendix A)

	Summer	Winter
H_c	65^o	22^o
Z_c	149^o	166^o

Direct Current Resistance (R)

The direct current resistance (R) of a conductor may be obtained from published data or calculated as follows:

For copper and copper alloys

$$R = \frac{8.145x10^{-4}}{C'A_2}\left[1 + \frac{0.00393 \cdot C'}{100}(T_2 - 20)\right]$$

For aluminum alloys

$$R = \frac{8.145x10^{-4}}{C'A_2}\left[1 + \frac{0.00403 \cdot C'}{100}(T_2 - 20)\right]$$

Where C' = conductivity as % IACS
A_2 = cross-sectional area (square inches)
T_2 = conductor temperature (^{o}C)

Skin Effect Coefficient for 60 Hz. Current (F)

Skin effect coefficients are a function of resistance, frequency and geometry. The factors are readily available for simple shapes from published data such as Alcoa Bus Conductor Handbook.

Bus Conductor Temperature Limits

Bus conductor temperature limits are found in Section X: Substation Bus conductors.

Sample calculations of rigid bus conductor ampacity.

I. Determination of summer "normal operating condition" conductor loading amperes for 3-1/2" aluminum tubing, 6063-T6, Schedule 40, 35°C ambient and 85°C conductor temperature. Bus orientated east-west.

% IACS = 53%
O.D. = 4"
Wall thickness = 0.226" ∴ I.D. = 3.548”
Area = 2.6795 in^2 $= \pi\left[\left(\frac{4}{2}\right)^2 - \left(\frac{3.548}{2}\right)^2\right]$
$\epsilon = 0.5$

A. Conductive heat loss (q_c)

$$q_c = 0.377 \cdot \Delta t \cdot d^{0.6}$$

$\Delta t = 85^{\circ} - 35^{\circ} = 50^{\circ}$
d = 4.0

$$q_c = 0.377(50)(4.0)^{0.6} = 43.31\ \text{Watts/ft.}$$

B. Radiation heat loss (q_r)

$$q_r = 1390 \cdot \epsilon \cdot d(T_c^4 - T_a^4)x10^{-12}$$

$\epsilon = 0.5$
d = 4.0"
$T_c = 85^{\circ}C + 273 = 358^{\circ}K$
$T_a = 35^{\circ}C + 273 = 308^{\circ}K$

$$q_r = 1390(0.5)(4)[358^4 - 308^4]x10^{-12} = 20.65\ \text{Watts/ft.}$$

C. Solar heat gain (q_s)

$$q_s = 0.00695 \cdot \epsilon \cdot Q_s \cdot A' \cdot K \cdot \sin\phi$$

$\epsilon = 0.5$
$Q_s = 94$ watts/ft^2

$A' = 4'' \times 12'' = 48\ \text{inch}^2$
$K = 1.0$
$\phi = \text{Cos}^{-1}\ [\text{Cos}\ H_c\ \text{Cos}\ (Z_c - Z_i)]$
$= \text{Cos}^{-1}\ [\text{Cos}\ 65^\circ\ \text{Cos}\ (145 - 90)] = 77.4^\circ$

$$q_s = 0.00695(0.5)(94)(48)(1.0)(\sin 77.4°) = 15.30\ \frac{\text{Watts}}{\text{ft}}$$

D. Direct current resistance at 85°C

$$R = \frac{8.145\text{x}10^{-4}}{C' \cdot A_2}\left[1 + \frac{0.00403 \cdot C'}{61}(T_c - 20)\right]$$

$C' = 53$
$A_2 = 2.6795\ \text{inch}^2$
$T_c = 85$

$$R = \frac{8.145\text{x}10^{-4}}{(53)(2.6795)}\left[1 + \frac{0.00403(53)}{61}(85 - 20)\right] = 7.04x10^{-6}\,\frac{\text{Ohms}}{\text{ft}}$$

E. Skin effect coefficient F based on Alcoa Handbook, Figure 34

determine (1) $\frac{\text{wall}-\text{thickness}}{\text{diameter}} = \frac{0.226}{4.0} = 0.06$

determine (2) $\sqrt{\left[\frac{f}{R_{dc}}\right]}$

f = 60 Hz.
R_{dc} = Ohms per 1000 ft = R x 10^3

$$\sqrt{\left[\frac{60}{7.04\text{x}10^{-6}\text{x}10^{9}}\right]} = 92$$

determine (3) From figure 34, F = 1.0

F. Calculated ampacity of tubing

$$\mathrm{I} = \sqrt{\frac{\mathrm{q_c} + \mathrm{q_r} - \mathrm{q_s}}{\mathrm{R} \cdot \mathrm{F}}} = \sqrt{\frac{43.31 + 20.65 - 15.30}{(7.04\mathrm{x}10^{-6})(1.0)}}$$
$$= 2629\ Amperes$$

II. Determination of summer "LTE Operating Condition" conductor ampere loading where conductor temperature = 95ºC

A. q_c = 51.96 Watts/ft.

B. q_r = 25.97 Watts/ft.

C. q_s = 15.30 Watts/ft.

D. R = 7.24 x 10-6 Ohms/ft.

E. F = 1.0

F. $$\mathrm{I} = \sqrt{\frac{\mathrm{q_c} + \mathrm{q_r} - \mathrm{q_s}}{\mathrm{R} \cdot \mathrm{F}}} = \sqrt{\frac{51.96 + 25.97 - 15.30}{(7.24\mathrm{x}10^{-6})(1.0)}} = 2941\ \mathrm{Amperes}$$

III. Determination of summer "STE Operating Condition" conductor ampere loading where conductor temperature limit = 105ºC. Ampacity calculation based on methodology for calculation of short-time rating described in Appendix A.

Initial Conductor Temperature = 85ºC
Maximum Conductor Temperature = 105ºC
Average Conductor Temperature = (85 + 105)/2 = 95ºC
Weight of Conductor = 3.151 lb/ft
Specific heat of aluminum = 0.2305
The heat storage capacity per foot of conductor equals:

$$\mathrm{C} = \left(\frac{(4.186)(453.6)(0.2305)(3.151)}{60}\right) = 22.99\ \frac{\mathrm{Watt-minutes}}{\mathrm{lb}-{}^{\circ}\mathrm{C}}$$

Calculation for q_c and q_r using rigid bus factors

$$q_c = 0.377(95 - 35)4.0^{0.6} = 51.97\,\frac{\text{Watts}}{\text{ft}}$$

$$q_r = 1390(0.5)(4)[368^4 - 308^4]\text{x}10^{-12} = 25.97\,\frac{\text{Watts}}{\text{ft}}$$

I_{STE} calculations by Appendix A methods give:

Using the IEEE Std. computer program, I_{STE} = 4664 Amperes

Using the manual calculation formula,

$$I_{STE} = \sqrt{\frac{1}{r_{ac\ @\ 95C}}\left[\frac{C \cdot W\ \text{x}\ (T_{STE} - T_n)}{900} + q_c + q_r - q_s\right]}$$

$$I_{STE} = \sqrt{\frac{1}{7.24\text{x}10^{-6}}\left[\frac{(22.99)(3.151)(105 - 85)}{15} + 51.96 + 25.97 - 15.30\right]}$$

$$I_{STE} = \sqrt{\frac{159.22}{7.24\text{x}10^{-6}}} = 4690\ \text{Ampere}$$