VI.F

CURRENT TRANSFORMERS

GUIDE FOR DETERMINATION OF

CURRENT TRANSFORMER RATINGS

PJM INTERCONNECTION

Heritage MAAC Group

A task force of the Transmission and Substation Subcommittee

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SUBJECT

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REVISION HISTORY

December 1971:	Rev. 0 – Original Document
February 1999:	Rev. 1 – Format changes, general revisions.
April 2011:	Rev. 2 - General revision and document standardization and clarification of emergency and load dump ratings, and revision of associated equations.

SCOPE AND PURPOSE

This guide presents principles and procedures to be used in establishing normal, emergency 4 hour, and load dump current carrying capabilities for current transformers. The resulting thermal ratings can be used for selecting the most economical nameplate ratings for new current transformers. All current transformers built under prior standards; and the existing standards listed in the references of this report are included. The rating method applies to stand alone current transformers of either the bushing type, donut type or separately wound type. To calculate the rating of a current transformer that is mounted on a power transformer or circuit breaker bushing, follow method prescribed in the PJM report "Guide for Determination of Circuit Breaker Load Current Capability Ratings". Although this rating method is intended to be all-inclusive, it is recognized that exceptions such as those listed in the subheading entitled "Connected Equipment Limitations" may be necessary for special conditions.

BACKGROUND

The recognition that various designs of current transformers can carry different normal and emergency currents led to the establishments of ratings based on current transformer capabilities, operating procedures, physical environment, and special conditions.

The primary purpose of revising this document is to clarify certain definitions and bring documents up to date to the latest revision to the industry standards.

This report presents principles and procedures to be used in establishing normal and emergency ratings for current transformers. The resulting ratings can be used for selecting the most economical nameplate ratings for new current transformers. Current transformers built under C57.13-2008 and prior standards are included. Ratings are intended for use on all current transformers affecting the PJM Interconnection. Although this rating method is intended to be all inclusive, it is recognized that exceptions may be necessary for special conditions.

HISTORICAL BACKGROUND

Scope change from 1971 version to 1999

The primary difference between this revision and the original issue results from application of values from current IEEE standards as follows:

Original Issue: $n = 1.8$
Current Issue: $n = 2.0$

Scope change from 1999 version to 2011

The primary difference between the 2011 and 1999 version is ratings provided in this guide are now limited to Normal, Emergency and Load Dump to align with PJM operating practice. In addition normal ratings are now performed at 35 ^{o}C rather than 30 ^{o}C. The revision also includes document standardization, sample calculation corrections and clarification of emergency and load dump ratings, including revisions to associated equations.

DISCUSSION OF RATING METHOD

The rating methods established by this report represent compromises in the various factors included in the latest thinking (IEEE C57.13-2008) of the utility industry. The method developed is based primarily on the following:

1. Ambient temperature (θ_a).
2. Temperature rise as a function of the 2.0 power of the current.
3. Maximum temperature determined to be acceptable for various current transformer parts under normal and emergency conditions.
4. Acceptable loss of foreseeable life for emergency conditions.

It is assumed that power levels will be maintained and managed within the requirements of PJM Manual 3, Section 2, "Thermal Operating Guidelines". PJM operating philosophy strives to restore loads to below the Normal Rating in four hours or less. The intent of this guide is that equipment loading will not be above the Normal Rating for greater than four hours. It is understood that under a single event restoration, cumulative time of loading, in excess of the Normal Rating, beyond four hours may occur. Operating in excess of four hours above the Normal Rating for a single event restoration should be evaluated by the equipment owner.

DEFINITIONS

Following are definitions of terms used in this report for use in determining PJM current transformer ratings.

Adjusted Rated Continuous Current (I)

Rated continuous current capability of a current transformer corrected to Limit of Observable Temperature Rise using specific Test Observable Temperature Rise data. Note: $I = I_r$ when the specific temperature rise test data is not available.

Adjusted Rated Continuous Current of a Current Transformer Tap (Itap)

Rated continuous current of a specific tap of a current transformer corrected for connection on a reduced tap and to limit of observable temperature rise.

Ambient Temperature (θ_a)

Expected air temperature surrounding the rated current transformer.

Emergency Allowable Maximum Temperature (θmax_e)

Maximum temperature which any current transformer part can withstand for various emergency rating durations, e.g., θmax_{e4} = 4 hour maximum temperature, etc.

Emergency Current Rating (I_{ea})

Short time currents that can be carried for a specified period of time at selected ambient temperature without any current transformer part exceeding its emergency allowable maximum temperature. In PJM, the Emergency Current Rating is for a four hour duration, e.g., I_{ea4} = 0 to 4 hour emergency current.

Limit of Observable Temperature Rise (θ_r)
Maximum value of observable temperature rise of any part of a current transformer as limited by ANSI C57.13-2008. Values are listed in Table I of this report.

Load Dump Current Rating ($I_{s0.25}$)
In PJM, a Load Dump Current Rating is a Short Time Emergency Current Capability for 15 minutes duration e.g., $I_{s_{0.25}}$ is the current which can be carried 15 minutes, or a ¼ of an hour.

Normal Allowable Maximum Temperature (θmax)
Maximum temperature which any current transformer part can withstand continuously. In this report it is defined as $\theta_{max} = \theta_r + 40\,°C$.

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Normal Current Rating (I_n)
Current that can be carried continuously at a specific ambient temperature without any current transformer part exceeding its normal and allowable maximum temperature.

Rated Continuous Current (Nameplate Rating(full ratio)) (I_r)
Maximum current in amperes at rated frequency a current transformer can carry continuously without any part exceeding its limit of observable temperature rise.

Rated Continuous Current of a Current Transformer Tap ($Itap_r$)
Maximum current in amperes at rated frequency a specific tap of a current transformer can carry continuously without any part exceeding its limit of observable temperature rise.

Continuous Thermal Current Rating Factor (RF)
The specified factor by which the rated continuous current of any current transformer tap can be multiplied to obtain the primary current that can be carried continuously without exceeding the limit of observable temperature rise. Note: The primary current path's rating may limit the full use of the rating factor on the secondary windings.

Test Observable Temperature Rise (θ)
Measured steady-state temperature rise above ambient temperature of any part of a current transformer when tested at rated continuous current.

Thermal Time Constant (τ)
The length of time required in minutes, for the initial temperature to reach 63.2% of final value after a change in current in the current transformer. In practice, it is generally agreed that after 4 time constants the ultimate temperature is reached (actually 98.2% of its final value).
(This value is assumed to be 30 minutes minimum for all current transformers in this guide. If manufacturer provides a thermal time constant for the device being rated that time constant should be used.)

AMBIENT TEMPERATURE

Since maximum current transformer temperature is a function of prevailing ambient temperature, θ_a, the value of ambient temperature is important for determination of ratings. For short-time intervals, the maximum expected ambient temperature is of prime importance. Temperature records surveyed by the PJM Companies resulted in agreement on use of the following temperatures, which are consistent with those used for all PJM equipment ratings (Normal, Emergency and Load Dump).

Description	Summer	Winter
PJM Planning Basis Temperatures	35 °C	10 °C

PJM Operations utilizes ambient adjusted ratings in 5 °C increments. The method described in this document allows the calculation of these capabilities.

Bushing-type current transformers are designed to allow operation in the higher temperature environment of a circuit breaker or transformer. For simplification of calculation of current transformer ratings, the assumption is made that the temperature rise of the current transformer is equal to its allowable maximum temperature less the ambient temperature of the air surrounding the circuit breaker.

NORMAL RATINGS

The normal current rating of a current transformer is that current which can be carried continuously without any part exceeding its Normal Allowable Maximum Temperature. The prime considerations in defining the normal current rating of a current transformer are ambient temperature, the limit of observable temperature rise and continuous thermal current rating factor. The normal current rating of a current transformer tap is calculated by compensating the adjusted rated continuous current of the tap for a specific ambient temperature, or if a rating factor is given for the tap; use this rating factor to calculate the continuous current limit. The adjusted rated continuous current of any current transformer tap is calculated by compensating the rated continuous current (nameplate rating (full ratio)) of the tap as follows:

(a) If temperature rise data from a heat run test is not available, compensate the rated continuous current of the tap for the tap setting and continuous thermal current rating factor. (ref. Eq. 1)

(b) If temperature rise data from a heat run test is available and was made at the rated continuous current, compensate the rated continuous current of the tap for the tap setting and temperature rise data. (ref. Eq. 2)

(c) If temperature rise data from a heat run test is available and was made at the rated continuous current times the continuous thermal current rating factor; compensate the rated continuous current for the tap setting, temperature rise data, and continuous thermal current rating factor. (ref. Eq. 3)

EMERGENCY & LOAD DUMP CURRENT RATINGS

Emergency ratings for current transformers are not supported by IEEE standard C57.13, or by current transformer suppliers. The recommended procedure for new current transformers is to specify a transformer with a continuous thermal current rating factor that is sufficient to handle foreseeable emergencies. The calculations for emergency ratings are provided as a reference. These calculations may be used if the appropriate temperature rise information is provided for the current transformer.

Emergency ratings are determined based on operation up to the emergency allowable maximum temperature for the limiting current transformer part. These emergency allowable maximum temperature limits are listed in Table I. These temperature limits may result in slightly accelerated deterioration of some current transformer performance. Emergency ratings for duration of less than twenty-four hours are determined based on the current transformer thermal time constant, which is a function of the heat storage capacity of the current transformer.

Load dump current ratings, are determined based on the current transformer part's thermal time constant which is a function of the heat storage capacity of the part. Loading prior to applying emergency ratings, including load dump current ratings, shall be 100% or less of the normal rating for the ambient temperature. Ratings can be increased by assuming the pre-load current is less than 100% of the normal rating; however, safely operating to this type of rating is difficult and is not recommended.

The thermal time constant (τ) of a current transformer should be obtained by test or calculated according to the physical characteristics of the current transformer. Thirty minutes is a conservative approximation for other than oil-filled wound-type current transformers. The PJM report on Determination of Power Transformer Rating should be consulted for the method of calculating the time constant of an oil-filled transformer, based on its physical characteristics. The weight of the porcelain should not be used in calculating the thermal time constant.

DETERMINATION OF RATINGS

Current transformer ratings can be determined as follows:

(a) When current transformers are incorporated internally as parts of power transformers or power circuit breakers, they shall meet allowable average winding temperature limits under the specific conditions and requirements of the larger apparatus. To calculate the rating of a current transformer that is mounted on a power transformer or circuit breaker bushing, follow method prescribed in the PJM report "Guide for Determination of Circuit Breaker Load Current Capability Ratings".

(b) For current transformer not incorporated internally as parts of power transformers or power circuit breakers use the guidance of sections (c), (d) and (e) below.

(c) If no information is available on current transformer materials and rating factor: Assume RF = 1 and rating is Itap calculated in Appendix.

(d) If current transformer materials are known, refer to Table I and calculate rating from Appendix.

(e) If current transformer materials are known and temperature rise data from heat run tests is available, determine ratings from Appendix.

CONNECTED EQUIPMENT LIMITATIONS

When determining a current transformer thermal rating, all equipment connected to the secondary must be checked for thermal capability. Current transformer accuracy limitations will not be encountered within the emergency allowable maximum temperatures. However, accuracy curves should be consulted when operating current transformers at temperatures above the limit of normal allowable maximum temperature.

TABLE I

TEMPERATURE LIMITATIONS FOR STAND-ALONE CURRENT TRANSFORMERS

No.	Insulation	Limit of Observable Temperature Rise at Rated Current θr (°C)	Normal Allowable Maximum Temperature θmax_n (Note 1) (°C)	Emergency Allowable Maximum Temperature (θmax_4) Rating Duration: 4 Hours or Less θmax_{e4} (Note 1) (°C)
1	Top Oil	45	85	110
2A	Average Winding Temperatures with 55°C Insulation	55	95	115
2B	Winding Hottest Spot Temperatures with 55°C Insulation	65	105	125
3A	Average Winding Temperatures with 65°C Insulation	65	105	125
3B	Winding Hottest Spot Temperatures with 65°C Insulation	80	120	140
4	Average Winding Temperatures with 80°C Insulation	80	120	140

Note 1: Per IEEE C57.13-2008, Section 4.1.1.1: The values in this column are the maximum temperatures allowed at a 30 °C ambient with a maximum 24 hour average temperature of 30 °C. Per the convention used in the IEEE standards on Instrument Transformers (C57.13) the maximum allowable temperatures for insulation materials are given at an ambient temperature of 30 °C, with the stated assumption that the ambient "…not exceed 40 °C and average temperature of the cooling air for any 24-h period does not exceed 30 °C"

TABLE II
CURRENT TRANSFORMER RATING
(% of Adjusted Rated Continuous Current)
(NOTE: these are the values to be used when evaluating a stand alone current transformer's overload capability- these values are developed with an "n" of 2)

CT Material Class	Top Oil	55 °C Insulation (average winding)	65 °C Insulation (average winding) or 55 °C Insulation (hot spot)	80 °C Insulation (average winding) or 65 °C Insulation (hot spot)	Minimum Rating of Various Insulations
Normal Allowable Maximum Temperatures.[5]	85 °C	95 °C	105 °C	120 °C	

Rating Duration	W	S	W	S	W	S	W	S	W	S
Normal	120	94	117	95	114	96	112	97	112	94
4 Hours	149	129	138	121	133	118	127	115	127	115
15 Min.	176	159	157	142	150	137	142	131	142	131

Notes:

1. These ratings do not include limitations of current transformers connected on reduced taps or limitations of equipment connected to current transformers.

2. Winter (W) ambient temperature is 10 °C for all rating durations.

3. Summer (S) ambient temperatures are 35 °C for all rating durations.

4. These emergency rating factors are based on current transformer half-hour thermal time constants. The fifteen-minute emergency rating factors for current transformers with thermal time constants greater than thirty minutes will be greater than the value given here.

5. Per IEEE C57.13, section 4.1.1.1: The values in this row are the maximum temperatures allowed at a 30 °C ambient with a maximum 24 hour average temperature of 30 °C. Per the convention used in the IEEE standards on Instrument Transformers (C57.13) the maximum allowable temperatures for insulation materials are given at an ambient temperature of 30 °C, with the stated assumption that the ambient "…not exceed 40 °C and average temperature of the cooling air for any 24-h period does not exceed 30 °C".

REFERENCES

1. ANSI Standard	C57.13-2008 Requirements for Instrument Transformers
2. ANSI Standard	C37.010-1999 (R 2005) Application Guide for AC High Voltage Breakers
3. IEC Recommendation	Publication 185 1966 Current Transformers
4. PJM Report	Determination of Power Transformer Ratings, September, 2011, by Transformer Rating Task Force
5. PJM Report	Determination of Circuit Breaker Load Current Capability Ratings, December, 2009, by Station Equipment Rating Task Force

APPENDIX: FORMULAE AND SAMPLE CALCULATIONS

PART A - RATING FORMULAE

Correction of Rated Continuous Current for Operation on Any Tap

The adjusted rated continuous current of a tap may be determined by one of three methods, depending upon the data available.

If temperature rise data from a heat run test is not available, the adjusted rated continuous current may be determined from the formula:

$$\text{Itap} = \text{Itap}_r \times \left(\frac{I_r}{\text{Itap}_r} \right)^{\frac{1}{n}} \times \text{RF} \qquad \text{Eq. 1}$$

If temperature rise data from a heat test run is available and was made at the rated continuous current, the adjusted rated continuous current may be determined from the formula:

$$\text{Itap} = \text{Itap}_r \times \left(\frac{I_r}{\text{Itap}_r} \right)^{\frac{1}{n}} \left(\frac{\theta_r}{\theta} \right)^{\frac{1}{n}} \qquad \text{Eq. 2}$$

If temperature rise data from a heat run test is available and was made at the rated continuous current times the continuous thermal current rating factor, the adjusted rated continuous current may be determined from the formula:

$$\text{Itap} = \text{Itap}_r \times \left(\frac{I_r}{\text{Itap}_r} \right)^{\frac{1}{n}} \left(\frac{\theta_r}{\theta} \right)^{\frac{1}{n}} \times \text{RF} \qquad \text{Eq. 3}$$

Itap = Adjusted rated continuous current of specific current transformer tap under consideration

I_r = Rated continuous current (Full ratio rating)

Itap_r = Rated continuous current of specific current transformer tap under consideration

θ = Test observable temperature rise

θ_r = Limit of observable temperature rise at rated continuous current

RF = Continuous thermal current rating factor (Manufacturer should be consulted for value of the continuous thermal current rating factor. Assume 1.0 if not available) (Note: The primary current path's rating may limit the full use of the rating factor on the secondary windings.)

n = 2

tap under consideration should be used.

Calculation of Normal (Continuous) Current Rating

For operation at average temperatures of other than 30 °C ambient (24 hour average) use the following equation:

$$I_a = I_{tap} \times \left(\frac{30 + \theta_r - \theta_a}{\theta_r} \right)^{\frac{1}{n}} \qquad \text{Eq. 4}$$

I_a = Normal current rating

θ_a = Ambient temperature

Calculation of Emergency Ratings

Winter and summer emergency ratings can be determined as follows:

$$I_{e4} = I_{tap} \times \left(\frac{\theta_{max_{e4}} - \theta_a}{\theta_r} \right)^{\frac{1}{n}} \qquad \text{Eq. 5}$$

$$I_{et} = I_{tap} \times \left[\frac{1}{\theta_r} \left(\frac{\theta_{max_{e4}} - \theta_{max_n}}{1 - e^{\frac{-t}{\tau}}} + \theta_{max_n} - \theta_a \right) \right]^{\frac{1}{n}} \qquad \text{Eq. 6}$$

I_{e4} = Emergency rating for durations of 4 time constants through a maximum of 4 hours.

θmax_{e4} = Emergency (4 hours and less) allowable maximum temperature.

I_{et} = Emergency rating of four time constants (4τ) duration or less.

t = Rating duration (minutes- 15 minutes for load dump ratings).

τ = Thermal time constant of current transformer (minutes).

PART B - SAMPLE CALCULATIONS

Since current transformers may contain more than one material class, it will be necessary to determine ratings for each material class and select the limiting rating for the appropriate conditions.

Per the convention used in the IEEE standards on Instrument Transformers (C57.13) the maximum allowable temperatures for insulation materials are given at an ambient temperature of 30 °C, with the stated assumption that the ambient "…not exceed 40 °C and average temperature of the cooling air for any 24-h period does not exceed 30 °C" (C57.13, section 4.1.1.1). This assumption is reasonable since normal daily temperature cycles may well have 40 °C peak periods and still have daily averages of 30 °C.

Assume a 2000/5 ampere multi-ratio oil-filled wound-type current transformer with 55 °C insulation, a continuous thermal current rating factor (RF) 1.5 and connected on the 1500/5 tap.

Adjusted Rated Continuous Current

$$\mathrm{Itap} = \mathrm{Itap}_r \times \left(\frac{I_r}{\mathrm{Itap}_r} \right)^{\frac{1}{2}} \times \mathrm{RF}$$

RF = 1.5

I_r	Itap_r	Itap
2000 A	1500 A	2598 A

With:
(for 55 °C insulation, θ_r = 55 °C)

$$I_a = I_{tap} \times \left(\frac{30 + \theta_r - \theta_a}{\theta_r} \right)^{\frac{1}{n}}$$

I_{tap}	I_a (Summer) θa = 35 °C	I_a (Winter) θa = 10 °C
2598 A	2477 A	3034 A

If temperature rise data were provided, the example would proceed as follows.

Component	Observable Temperature Rise. θ
Top Oil	35 °C

CT Windings, Average	44 °C
Hottest Spot	49 °C

Adjusted Rated Continuous Current

$$\text{Itap} = \text{Itap}_r \times \left(\frac{I_r}{\text{Itap}_r} \right)^{\frac{1}{2}} \left(\frac{\theta_r}{\theta} \right)^{\frac{1}{2}} \times \text{RF}$$

RF = 1.5

	I_r	Itap_r	θ	θr	Itap
Top Oil	2000 A	1500 A	35 °C	45 °C	2945 A
CT Winding	2000 A	1500 A	44 °C	55 °C	2905 A
Hottest Spot	2000 A	1500 A	49 °C	65 °C	2992 A

NOTE: These adjusted current ratings (I_{tap}) are used in all subsequent calculations.

Normal Ratings

$$I_a = I_{tap} \times \left(\frac{30 + \theta_r - \theta_a}{\theta_r} \right)^{\frac{1}{n}}$$

	Itap	θ_r	I_a (Summer) θa = 35 °C	I_a (Winter) θa = 10 °C
Top Oil	2945 A	45 °C	2776 A	3539 A
CT Winding	2905 A	55 °C	2770 A	3392 A
Hottest Spot	2992 A	65 °C	2874 A	3421 A

The CT's Average Winding temperature is limiting for summer normal ratings.
The CT's Average Winding temperature is limiting for winter normal ratings.

If maximum emergency temperature limits were provided by the manufacture, the emergency ratings would be calculated as follows:

Emergency Ratings of 2 hours (4 Time Constants) to 4 Hours Duration

$$I_{e4} = I_{tap} \times \left(\frac{\theta_{max\,e4} - \theta_a}{\theta_r} \right)^{\frac{1}{n}}$$

	I_{tap}	θ_r	θ_{maxe4}	I_a (Summer) $\theta a = 35\ ^oC$	I_a (Winter) $\theta a = 10\ ^oC$
Top Oil	2945 A	45 ^oC	110 ^oC	3802 A	4390 A
CT Winding	2905 A	55 ^oC	115 ^oC	3504 A	4014 A
Hottest Spot	2992 A	65 ^oC	125 ^oC	3520 A	3980 A

The CT's Average Winding temperature is limiting for emergency summer ratings of two hours (4 time constants) to 4 hours.
The CT's Winding Hot Spot temperature is limiting for emergency winter ratings of two hours (4 time constants) to 4 hours.

Emergency Rating for 15 Minute Duration (1/2 of a Time Constant)

$$I_{et} = I_{tap} \times \left[\frac{1}{\theta_r} \left(\frac{\theta_{max\,e4} - \theta_{max\,n}}{1 - e^{\frac{-t}{\tau}}} + \theta_{max\,n} - \theta_a \right) \right]^{\frac{1}{n}}$$

For this example:
t = 15 minutes (load dump duration)
τ = 30 minutes (time constant of current transformer to be rated)

	I_{tap}	θ_r	θ_{maxe4}	θ_{maxn}	I_a (Summer) $\theta a = 35\ ^oC$	I_a (Winter) $\theta a = 10\ ^oC$
Top Oil	2945 A	45 ^oC	110 ^oC	85 ^oC	4682 A	5183 A
CT Winding	2905 A	55 ^oC	115 ^oC	95 ^oC	4125 A	4560 A
Hottest Spot	2992 A	65 ^oC	125 ^oC	105 ^oC	4099 A	4488 A

The CT's Winding Hot Spot temperature is limiting for emergency summer ratings of 15 minutes (load dump period).
The CT's Winding Hot Spot temperature is limiting for emergency winter ratings of 15 minutes (load dump period).