VI.B
Power Transformers

GUIDE FOR DETERMINATION OF POWER TRANSFORMER LOAD CAPABILITY RATINGS

PJM INTERCONNECTION

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SCOPE AND PURPOSE

This guide documents the procedures to be used in establishing PJM normal, emergency (four hour), and load dump thermal ratings for power transformers designed, built and tested under IEEE/ANSI standards. This guide is based on the latest revision of IEEE Guide for Loading Mineral Oil Immersed Transformers [IEEE C57.91- 2011(R1995)], Reference 1. It is intended for use on all transformers subject to PJM operating guidelines and controls, except generator step-up transformers. The principles used in establishing the various parameters and limits are discussed in the body of the guide. Although this rating method is intended to be all inclusive, it is recognized that exceptions may be necessary for special conditions.

REVISION HISTORY AND BACKGROUND

September 1969:	Rev. 0 – Original Document.
February 1999:	Rev. 1 - Format changes and general revision.
June 2011:	Rev. 2 - General revision and document standardization with clarification of emergency and load dump ratings, and revision of associated equations.
May 2024”	Rev. 3 - General revision.

The original PJM Power Transformer Rating Procedures were developed by a task force of the Transmission and Substation Design Subcommittee (TSDS) in 1969. Those procedures were developed to form a common transformer rating method to coordinate planning, engineering, and operating practices within the PJM Interconnection. The procedures were based on then current industry guidelines which were USAS C57.92-1962 and NEMA TR98-1964.

TSDS formed a task force in 1987 to review transformer rating practices within PJM due to significant changes taking place in the industry guidelines. At that time, the procedures were not revised, but many variations in rating procedures were noted among the member companies.

Further changes in industry loading guidelines led to formation of another task force in 1995 to revise the procedures to incorporate up-to-date industry guidelines and to provide appropriate default parameters for operation of transformers on the PJM Interconnection System. The revised guide incorporating these changes was published in 1999.

In 2010 Transmission and Substation Subcommittee (TSS) convened a Working Group to update and revise the guide for consistency with PJM Operating procedures and industry rating practice. The revisions included the definition of load dump rating, development of ambient adjusted ratings, and discussion of the need to review ancillary equipment capability in the determination of transformer ratings.

DISCUSSION OF RATING METHOD

This document provides guidance for the calculation of transformer loading capability under prescribed conditions. The calculations are to be performed following the method identified in Reference 1, Clause 7. The Working Group (WG) believes that this IEEE guide represents the most up to date reference on loading. Employees of five of the Heritage MAAC Group PJM companies served on the IEEE Transformers Committee Working Group which produced the 1995 revision.

The equations produce values for temperatures of the hottest spot and top oil, and a value for the loss of insulation life which results from a given loading cycle. The results can then be compared to limiting criteria, to determine if that load level produces acceptable internal temperatures. By iteration, the load can be increased to identify the maximum peak load acceptable for that load cycle, emergency condition, and ambient temperature combination.

This guide addresses the loading capability of transformers built in the past 45+ years which have 65°C (or 55/65°C) average winding rise insulation systems. Reference 1 contains an Annex titled "Philosophy of Guide Applicable to Transformers with 55°C Average Winding Rise Insulation Systems". If a transformer built with a 55°C rise insulation system must be evaluated, refer to that Annex for the required modifications to the calculations.

PJM operating philosophy strives to restore loads to below the Normal Rating in four hours or less. The intent of this guide is that transformer loading will not be above the Normal Rating for greater than four hours. Unlike other equipment, it is imperative for transformers that the four hour period not be exceeded due to accelerated loss of life and increased risk of failure. This is due to the four hour time constant in the transformer rating calculation.

DEFINITIONS

Following are definitions of terms used in this Guide.

Ambient Temperature

Actual, or expected, air temperature surrounding the transformer under study.

Daily Load Cycle

The variation in load applied to a given transformer throughout a 24 hour day. The typical cycle is assumed to be repeated each day. A cycle with an emergency event would match the typical cycle up to the point in time when the emergency condition occurs. At the end of the emergency event, the typical cycle resumes.

Loading Capability

Loading that can be carried for a specified period of time, at the selected ambient temperature, which will result in an acceptable loss of insulation life while not exceeding the acceptable maximum operating temperatures or percent of nameplate rating.

Normal Rating (Normal Loading Capability)

The peak load value calculated for a specified load cycle and ambient temperature that will result in a percent loss of life equivalent to that produced by operation at a hottest spot temperature of 110ºC for 24 hours. The transformer may be operated continuously under this set of conditions without experiencing any accelerated loss of insulation life.

Emergency Rating (Emergency Loading Capability)

The Loading Capability allowable for a maximum operating period of 4 hours duration, as defined by PJM. Other emergency rating durations may be calculated for operating company Planning and Operating purposes.

Load Dump Rating

The PJM emergency Loading Capability allowable for a maximum operating period of 15 minutes duration, as defined by PJM.

Nameplate Rating

The transformer rating, in MVA, established by the manufacturer in accordance with the applicable ANSI/IEEE, IEC, etc. standards.

The rating is established as confirmation of the performance of the equipment under specified conditions without exceeding prescribed temperatures or other limiting criteria.

Percent Loss of Life

The calculated equivalent aging (in hours at the reference hottest-spot temperature) over a time period (usually 24 hours) times 100 divided by the total defined insulation life in hours at the reference hottest-spot temperature. Loss of life calculations are based on the reference hottest-spot temperature of 110°C. For further discussion see Reference 1.

Thermal Time Constant

In general, the time required for approximately 63% of an ultimate temperature change to occur when a step change in load occurs and is maintained. Top oil thermal time constant refers to the change in transformer top oil temperature in relation to ambient temperature (measured in hours).

Winding hottest spot thermal time constant refers to the change between the winding hottest spot temperature and the top oil temperature (measured in minutes).

Top Oil Temperature

The temperature of the top layer of the insulating oil in a transformer. It is representative of the temperature of the top oil in the cooling flow stream and is typically measured by a thermal probe in the tank slightly below the surface of the oil.

Winding Hottest Spot Temperature (Hottest Spot Conductor Temperature)

The maximum or hottest temperature of the current carrying components of a transformer winding and the leads that are in contact with insulation or insulating oil.

LOADING THEORY AND APPLICATION

LOADING CAPABILITY

The equations in the PJM and IEEE Loading Guides are used to determine the operating temperatures (oil and winding hottest spot) of a transformer based on the load cycle and ambient temperature. The equations are also used to determine percent loss of insulation life referenced to a benchmark value such as those discussed in Reference 1. The allowable loading capability for any defined load cycle and ambient temperature profile is determined by iterating the calculations until any one of the temperature, loss of life, or maximum percentage of nameplate rating limits is reached.

Load cycle is a critically important factor for transformers, more so than for other system components, because the bulk oil thermal performance is subject to much longer time constants (generally several hours), and the ultimate winding temperature is a combined calculation of oil rise over ambient and winding temperature rise over oil. Therefore, defining both the load cycle and ambient temperature profile is necessary for determination of transformer loading capability.

Top oil temperature and winding hottest spot temperature are the primary factors in determining allowable normal and emergency ratings. Calculated hottest spot temperature is a direct factor in calculation of loss of insulation life. The higher hottest spot temperatures experienced during emergency loading result in increased risk factors as discussed in Reference 1. Allowable limits for hottest spot temperature and loss of life under emergency loading conditions are determined by each Owner based on their assessment of these risk factors. Top oil temperature is important both because the oil is the ambient reference to which a calculated winding temperature gradient is applied – resulting in the calculated hottest spot temperature – and because transformer tanks have to be designed to accommodate thermal expansion of the oil within reasonable bounds.

AMBIENT TEMPERATURE

Since maximum transformer temperatures are a function of ambient temperature and loading, the value of ambient temperature is important for the determination of ratings. The transformer nameplate rating per C57.12.00, Reference 5, is based upon a 30°C average ambient over a 24 hour period where the maximum temperature will not exceed 40°C.

For short-time (less than 24 hours) intervals the maximum expected ambient temperature is of prime importance. For normal ratings the average temperature over the 24 hour load cycle is of prime importance since these ratings are based on the cumulative loss of insulation life over a 24 hour cycle. In the same manner, loss of insulation life calculated for normal or long term emergency ratings can be based upon an average ambient temperature over a 24 hour period as described in, C57.91 Clause 6, Reference 1. Calculations based on the average ambient temperature will give approximately the same loss of insulation life as calculations done with all the various temperatures during the 24 hour period.

Planning Criteria

Studies in conjunction with historic temperature data and past practice have suggested that 30°C and 10°C are appropriate ambient temperature default values to use for summer and winter normal ratings studies (see IEEE Paper 69TP49-PWR, Reference 6,). Similarly, for PJM emergency ratings the suggested ambient temperatures are 35°C for the summer period and 15°C for the winter period.

For planning purposes, PJM companies utilize both long term emergencies for conditions where equipment must be replaced, and short term where the emergency condition is relieved by switching load to other sources, or by restoration of the initiating event. These studies are traditionally done at peak ambient and peak load for the time period of the study.

While actual (expected) values of ambient temperature will be most accurate, default values are provided for consistent application and for use where actual values are not available. For transformers it is recommended that the following default values of ambient temperatures be utilized for planning purposes:

Rating	Ambient (˚C)		Ambient (˚F)	
	Winter	Summer	Winter	Summer
Normal	10	30	50	86
Emergency	15	35	59	95

<u>Operations Criteria</u>

PJM Operations utilizes normal and emergency ambient adjusted ratings in 5°F increments. Transformer ratings at these 5°F increments can be developed in either of the following two ways –

1. Calculate just 2 sets of ratings to be used across all the seasonal temperature increments. The first to be associated with the summer (20°C/68˚F to 35°C/95˚F ambients) and the second associated with the winter (0°C/32˚F to 15°C/59˚F) utilizing the default values for average temperatures identified in the table above.

2. Calculate individual ratings at each 5°F temperature increment utilizing a constant value for that ambient temperature throughout the loading cycle.

LOSS OF LIFE

Loss of life calculations require a defined end of life point. The previous (1999) revision of this PJM guide specified the 200 Retained Degree of Polymerization (DP 200) criteria as the end of life point. This results in a normal life expectancy of 150,000 hours, for operation at 110°C/230˚F as described in Reference 1, Clause 5. PJM normal loss of life was therefore defined as 0.016% per day as derived from the aging curve based on the DP 200 criteria (150,000 hours at 110°C/230˚F).

Current standards (Reference 5) redefine thermally upgraded paper or equivalent insulation systems as having a minimum life expectancy of 180,000 hours when tested per C57.100. The resulting PJM normal loss of life will then be defined as 0.0133% per day as derived from the aging curve in Figure 1 of Reference 5, C57.12.00 (180,000 hours at 110°C/230˚F).

This PJM Guide suggests 180,000 hours be used for consistency with industry standards. However, as published in the previous revision, a suitable alternative minimum life expectancy of 150,000 hours may still be used.

In the previous revisions, the default values for acceptable loss of life percentages for emergencies have been defined as follows –

Duration	Typical Emergency Event	Loss of Life (%)
1 day or less	First or second contingency loss	5
1 month	Replacement of ancillary components	10
3 months	Replacement with spare	10
6 months	Major field repair	10

The 5% loss of life limit is recommended for calculation of PJM emergency and load dump ratings. The historical values above may still be used for planning purposes for longer duration emergency events.

NORMAL RATINGS

Transformer paper insulation systems are designed and manufactured to operate at 110°C/230˚F maximum winding temperature on essentially a continuous basis. Normal ratings are therefore determined by calculating the peak load value for a specified load cycle and ambient temperature that will result in percent loss of life equivalent to that produced by operation at hottest spot temperature of 110ºC/230˚F for 24 hours. The transformer may be operated continuously under this set of conditions. See the Loss of Life section for suggested limits.

The normal rating will typically be greater than the transformer nameplate rating. Design and manufacturing margins cause the temperature rise test results at the transformer nameplate rating to be less than the defined temperature limit values. As a result, the calculated loss of life for continuous operation at the nameplate rating will always be less than that calculated for continuous operation at the hottest spot temperature limit of 110°C/230˚F.

The calculated normal rating is inversely proportional to changes in either ambient temperature or load profile.

EMERGENCY & LOAD DUMP RATINGS

EMERGENCY RATING

The emergency ratings determined using this guide are based on the assumption that actual loads at these levels will be rare events. Emergency ratings calculated for these conditions are based on allowable temperature and loss of life limits that exceed those used for normal ratings. Operating at these higher temperatures subjects the transformer to higher relative risk. Reference 1 provides some suggested guidelines for emergency temperature and loss of life limits. This PJM Guide accepts the maximum limits for emergency ratings as provided in Reference 1:

Top Oil Temperature	110°C/230˚F
Hottest Spot Conductor Temperature	180°C/356˚F
Maximum Loading	200%
Loss of Insulation Life (per event)	5%

LOAD DUMP RATING

There are inherent difficulties in using the equations in Reference 1 to calculate temperatures or ratings for a very short time period with reasonably accurate results. The equations were developed to determine temperatures at thermal equilibrium conditions. The 15 minute load duration is a very short time in relation to the time constants for the bulk oil rise in power transformers. As a result, there are difficulties in calculating 15 minute ratings, as required by the definition of Load Dump Rating.

The WG suggests that a reasonable alternative to modeling this scenario would be to calculate a short term rating of about 1 hour or less. That short term value may be used as the 15 minute ”Load Dump‟ rating.

ANCILLARY DEVICES

The overload capability calculation has traditionally been accepted as highly accurate and definitive, even though the temperature calculations for the bulk oil and the windings were the only criteria considered. However, there are other factors that must be reviewed for loading transformers beyond nameplate, particularly for large units. Ancillary devices such as bushings, current transformers, tap changers, or internal components such as the core and flux shields, may not be designed to tolerate loading at the emergency levels. It is generally advisable to review the capability of these devices at the anticipated emergency loading conditions with the manufacturer and also to include analysis of the capability of these components as a requirement in the purchase specification.

Reference 1 provides tutorial information on this topic in section 4.1.

CURRENT TRANSFORMERS (CTs)

Transformer specifications and subsequent Engineering review should be used to assure that the CTs are sized to adequately carry the overload currents defined for the transformer application. The CTs should not limit the loading capability of the transformer.

Further information on understanding and developing CT ratings is available in the PJM documents VI.F Current Transformers, and VI.C Circuit Breakers.

BUSHINGS & CONNECTIONS

The following information is excerpted from Reference 1, C57.91 Annex B.

> The following discussion applies to oil-impregnated, paper-insulated, capacitance-graded bushings only. For other bushing types, consult with the manufacturer for loading guidelines. Bushings are normally designed with a hottest spot total temperature limit of 105°C/221˚F at rated bushing current with a transformer top-oil temperature of 95°C/203˚F averaged over a 24 h time period. Operating a transformer beyond nameplate current can result in bushing temperatures above this limit which cause bushing loss-of-life depending on the actual time-temperature profile the bushing sees.
>
> A number of factors that reduce the severity of bushing overloads compared to transformer winding insulation overloads include the following:
>
> a) Transformer top-oil temperature may be well below 95°C/203˚F at rated transformer output.
> b) Bushings are sealed units preserving insulation and thermal integrity.
> c) Bushing insulation is usually drier than transformer insulation.
> d) Bushing insulation is not significantly stressed by fault-current forces.
> e) The use of bushings with higher current ratings than the connected transformer windings.
>
> Possible bushing overload effects include the following:
>
> a) Internal pressure build-ups
> b) Aging of gasket materials
> c) Unusual increases in power factor from thermal deterioration
> d) Gassing caused by hottest-spots in excess of 140°C/284˚F
> e) Thermal runaway from increased dielectric losses at high temperatures
> f) Heating in metallic flanges due to stray magnetic flux
>
> The following overload limits are established for coordination of bushings with transformers:

Ambient air	40°C/104˚F maximum
Transformer top-oil temperature	110°C/230˚F maximum
Maximum current	2 times rated bushing current
Bushing insulation hottest-spot temperature	150°C/302˚F maximum

The bushing stud terminal connector provided by the substation design engineer shall match the physical size of the bushing terminal, and the ampere rating shall be equal to or greater than the bushing rating.

DETERMINATION OF RATINGS

The 1999 Task force reviewed the data inputs, and the default values that were set up for the computer program written in 1969 by a previous PJM loading study group. The WG continues to recommend the option to establish default values to be used if the individual company does not have actual (or historical) data. However, the use of more appropriate, actual, data for the case being studied is encouraged. The defaults are listed in the Default Parameters section of the guide.

COMPUTER PROGRAM

At this time, the PJM TSS committee does not have a common computer program for member companies to use as they implement the procedures documented in this guide. Several member companies are using the EPRI PTLOAD program.

INPUT DATA REQUIRED

The inputs required to perform the calculations are contained in Clause 7.2 of Reference 1. The specific transformer data requirements are:

- Top oil temperature rise over ambient temperature at rated load
- Average conductor temperature rise over ambient temperature at rated load.
- Winding/lead hottest spot conductor temperature rise over ambient temperature at rated load
- Load loss at rated load
- No-load (core) loss
- Total loss at rated load
- Confirmation of oil flow design (directed or non-directed)
- Weight of core and coil assembly
- Weight of tank and fittings
- Volume of oil in the tank and cooling equipment

Ambient profile and load cycle for the study case are required.

As part of the analysis, ambient temperatures are a critical factor in determining the loading capability, since insulation temperature determines the degree of insulation aging, and it is dependent on the ambient. The ambient temperature value required for use in these equations is the 24 hour average ambient, during the load cycle being studied. Each company should determine the appropriate value of average ambient to use for the particular study required. There can be significant difference in the average ambient during a summer emergency loading condition across the geographical area covered by this guide.

While a 30°C/86˚F summer average may be appropriate for transformers in the northern areas, a similar emergency in southern areas may require analysis in an average summer ambient of 30-38°C/86˚F-100.4˚F. Similarly, winter emergencies may require analysis using ambients of -10°C/14˚F to 5°C/41˚F across the systems.

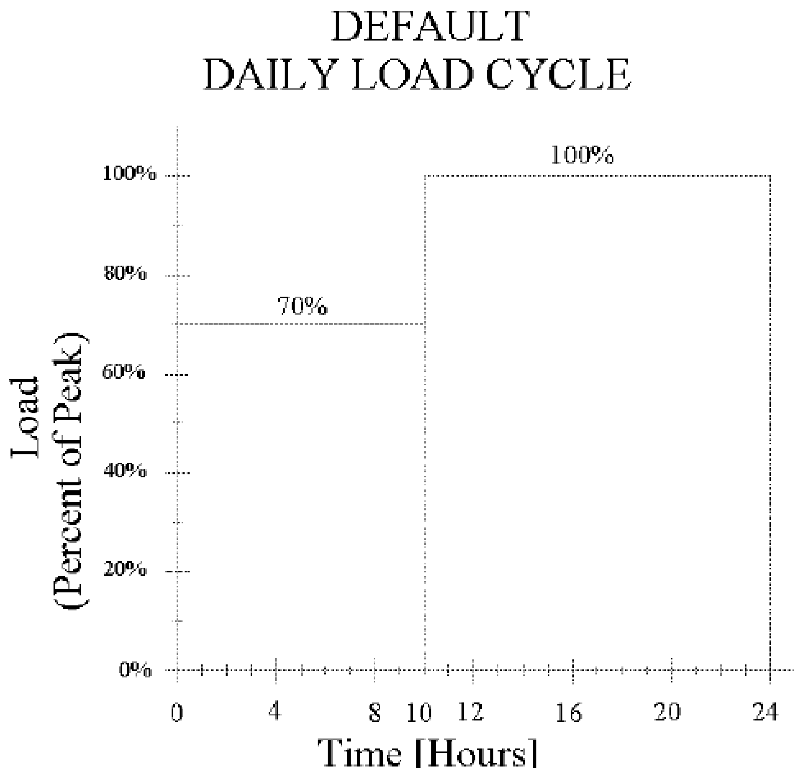
DEFAULT PARAMETERS

LOAD CYCLES

NORMAL RATINGS

The method of calculating transformer ratings for normal conditions, and for planning studies covering contingency conditions with durations greater than or equal to 24 hours (i.e. 24 hour, 6 month), requires the use of a daily load cycle for the specific transformer. In the event that a daily load cycle for a specific transformer is known or can be predicted, its ratings can be calculated using the known load cycle. Otherwise, the recommended default daily load cycle is shown in Figure 1.

FIGURE 1
Default Load Curve for Normal or Long Time Ratings



A third more conservative alternative is used by some PJM TOs. They have set the load cycle to remain at a constant value for all 24 hours. Therefore, when they calculate a normal rating, it is based on operation at the normal value for all 24 hours.

EMERGENCY RATINGS

Emergency overload events are assumed to occur coincident with the peak of the transformer specific 24 hour load cycle, or at the point in the cycle that will result in the maximum hot spot temperatures during the overload period. In the case of the default load cycle (Figure 1); this point of maximum hot spot temperatures would be at the end of the 24 hour period. Therefore, emergency rating calculations use a typical daily load cycle which has been modified to include the overload event. The default load curve for short time (emergency or load dump) ratings is shown in Figure 2. If the load curve for the specific transformer is known for the period prior to the overload (i.e. T_P, see Figure 2), it may be substituted in place of the default values shown in Figure 2. The calculations are based on the assumption that at the end of the emergency duration the pre-emergency load cycle of Figure1 resumes. Refer to Annex A.

FIGURE 2
Default Load Curve for Emergency Ratings

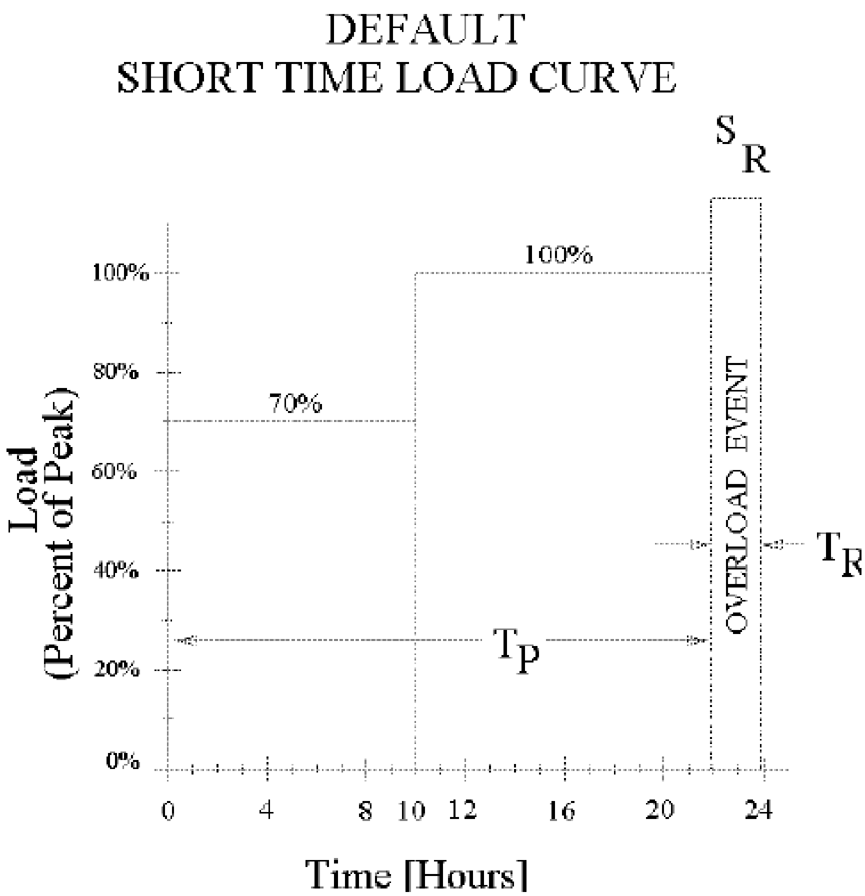


Figure 2 Notes:

1) At some PJM TOs, the loading prior to the emergency or the load dump event is assumed to be 100% of the normal rating for the ambient temperature condition. (This provides the most conservative ratings.)

2) Load curve of Fig 2 is shown for a 2 hour short term emergency rating; adjust T_R & T_P accordingly for other overload durations (i.e., standard 4 hour emergency and 15 minute load dump).

3) T_R is the duration of the overload.

4) S_R is the loading/rating during the overload.

5) T_P designates the portion of the day (prior to the overload) when the transformer is loaded at a typical loading per Figure 1. (See also Note 1)

TEMPERATURE & LOAD LIMITATIONS

Absolute temperature limits of 180°C/356˚F for the hot spot and 110°C/230˚F for top oil have been selected for use in the calculations. In addition, a limit of 200% of maximum nameplate rating has been imposed. These values are established as upper limits, but lower values may be selected based on engineering judgment. Present practice varies between the PJM companies.

Note: When hot spot temperature exceeds 140°C/284˚F, and the moisture content of the paper insulation is high, it is possible for free gas bubbles to form in an operating transformer. Some companies, to be cautious, will insist that the hot spot should not be allowed to exceed the 140°C/284˚F value.

OIL AND HOTSPOT EXPONENTS

The default values for the exponents for use in all calculations are provided in tables in Reference 1. Actual exponents determined from additional temperature rise tests per Reference 3 would provide more accurate results and should be used, when available.

REFERENCES

1. IEEE C57.91-IEEE Guide for Loading Mineral-Oil-Immersed Transformers

2. PJM Power Transformer Rating Procedures-1999, Determination of Power Transformer Ratings

3. IEEE C57.119, IEEE Recommended Practice for Performing Temperature Rise Tests on Oil-Immersed Power Transformers at Loads Beyond Nameplate Ratings

4. IEEE 1538, IEEE Guide for Determination of Maximum Winding Temperature Rise in Liquid-Filled Transformers

5. IEEE C57.12.00, IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers

6. IEEE Paper 69TP49-PWR, Oil Immersed Power Transformer Overload Calculations By Computer; Blake, Kelly

ANNEX A

PJM Operating Guidelines provide for the following consecutive or overlapping loading scenarios:

- If the emergency limit is exceeded the TO has 15 minutes “time to correct” to reduce loading back to under the emergency limit, and then must also take all further actions within another 15 minutes to return to within normal rating if possible, without shedding load.

- If load dump rating limit is exceeded, the TO has 5 minutes “time to correct” to reduce loading back under the load dump limit, and then must continue actions within the next 15 minutes to return to the emergency rating limit, and then must continue actions within the next 15 minutes to return to within normal rating.

TSS member companies calculate emergency ratings based on more of a “single contingency” type of scenario, a scenario in which the rating must return to within the “normal” rating limit after the single emergency period. The WG discussed whether the overlapping PJM Operating scenarios rendered the “single contingency” type of ratings calculations less valid.

The PJM emergency rating is a four hour rating that cannot be carried for more than four hours in a twenty four hour period. However, PJM Operating Guidelines require action within 15 minutes of exceeding that rating to return to within that rating, and then further action within another 15 minutes to get back to within the normal rating. The result should be that for most operating cases, loading at the emergency rating will not be expected to be prolonged for four hours.

PJM post-contingency planning criteria dictates that actions be taken to avoid the potential for exceeding emergency limits if a contingency event occurs. This results in even less likelihood that actual operating conditions will result in exceeding normal load limits or emergency limits.

The WG concluded that based on both the degree of conservatism felt to be inherent in the calculations of emergency ratings (due to such factors as use of single daily ambient profile, relatively conservative load cycles, and possibly conservative exponents, etc.) and the actions required by PJM in short times to return to normal ratings, that the present “single contingency” type of ratings calculations used by members can be considered applicable even for cases where the PJM Operations Guides allow for the overlapping emergency scenarios discussed above. As a result, the WG suggests it is not necessary in ratings calculations to simulate the consecutive, or overlapping, scenarios outlined in PJM operating criteria. Four hour ratings calculated in the "single contingency" manner are considered acceptable for use under PJM‟s operating criteria.