Comparison of Loading Guide Standards – IEEE and IEC

	IEEE		IEC	
		IEEE Std C57.91-2011		IEC 60076-7-2018
IEEE Clause Title	**Clause**	**IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators**	**Matching Clause**	**POWER TRANSFORMERS – Part 7: Loading guide[1] for mineral-oil-immersed power transformers**
Scope	1.1	This guide provides recommendations for loading mineral-oil-immersed transformers and step-voltage regulators with insulation systems rated for a 65 °C average winding temperature rise at rated load. Because a substantial population of transformers and step-voltage regulators with insulation systems rated for 55 °C average winding temperature rise at rated load are still in service, recommendations that are specific to this equipment are also included.	1	This part of IEC 60076 is applicable to mineral-oil-immersed transformers. It describes the effect of operation under various ambient temperatures and load conditions on transformer life.
Purpose	1.2	Applications of loads in excess of nameplate rating involve some degree of risk. It is the purpose of this guide to identify these risks and to establish limitations and guidelines, the application of which will minimize the risks to an acceptable level.		*None Listed*
Normative References	2	IEEE Std C57.12.00™ IEEE Std C57.12.90™ IEEE Std C57.15™, IEEE Standard Requirements, Terminology, and Test Code for Step-Voltage Regulators IEEE Std C57.100™, Standard Test Procedure for Thermal Evaluation of Insulation Systems for Liquid-Immersed Distribution and Power Transformers	2	IEC 60076-1, Power transformers – Part 2: Temperature rise for liquid-immersed transformers – Part 5: Ability to withstand short-circuit – Part 14: Liquid-immersed power transformers using high-temperature insulation materials
Definitions	3		3	
		aging acceleration factor: For a given hottest-spot temperature, the rate at which transformer insulation aging is accelerated compared with the aging rate at a reference hottest-spot temperature.	3.9	**relative thermal ageing rate** for a given hot-spot temperature, rate at which transformer insulation ageing is reduced or accelerated compared with the ageing rate at a reference hot-spot temperature
		directed flow (oil-immersed forced-oil-cooled transformers): The principal part of the pumped insulating fluid from heat exchangers or radiators is forced, or directed, to flow through specific paths in the winding.		*Not specifically defined*

		non-directed flow (oil-immersed forced-oil-cooled transformers): Indicates that the pumped oil from heat exchangers or radiators flows freely inside the tank, and is not forced to flow through the windings.		*Not specifically defined*
		percent loss of life: The equivalent aging in hours at the reference hottest-spot temperature over a time period (usually 24 h) times 100 divided by the total normal insulation life in hours at the reference hottest-spot temperature.	3.11	**per cent loss of life** equivalent ageing in hours over a time period (usually 24 h) times 100 divided by the expected transformer insulation life
		transformer insulation life: For a given temperature of the transformer insulation, the total time between the initial state for which the insulation is considered new and the final state for which dielectric stress, short circuit stress, or mechanical movement, which could occur in normal service, and could cause an electrical failure.	3.10	**transformer insulation life** total time between the initial state for which the insulation is considered new and the final state…
		Not specifically defined	3.1	**small power transformer** power transformer without attached radiators, coolers or tubes including corrugated tank irrespective of rating
		Not specifically defined	3.2	**medium power transformer** power transformer with a maximum rating of 100 MVA three-phase or 33,3 MVA single-phase
		Not specifically defined	3.3	**large power transformer** power transformer exceeding the limits specified in 3.2
		Known as hottest-spot in IEEE, but not specifically defined	3.8	**hot-spot** if not specially defined, hottest spot of the windings
		Addressed in Annex D	3.12	**non-thermally upgraded paper**[2] kraft paper produced from unbleached softwood pulp under the sulphate process without addition of stabilizers
			3.13	**thermally upgraded paper** cellulose-based paper which has been chemically modified to reduce the rate at which the paper decomposes… *Definition is the same as IEEE C57.12.80*
		Not specifically defined	3.17	**design ambient temperature** temperature at which the permissible average winding and top-oil and hot-spot temperature over ambient temperature are defined
Effect of loading beyond	4	**Effect of loading beyond nameplate rating**	5	**Effect of loading beyond nameplate rating**
	4.1	**General**	5.1	**general**

		Applications of loads in excess of nameplate rating involve some degree of risk.		The normal life expectancy is a conventional reference basis for continuous duty under design ambient temperature and rated operating conditions.
			5.2	**general consequences** The consequences of loading a transformer beyond its nameplate rating are as follows…
	4.2	**Voltage and frequency considerations** Voltage and frequency influences should be recognized when determining limitations for loading a transformer beyond its nameplate rating.	7.4.4	**Voltage limitations** Unless other limitations for variable flux voltage variations are known, the applied voltage should not exceed 1,05 times either the rated voltage or the tapping voltage on any winding of the transformer.
	4.3	**Supplemental cooling of existing self-cooled transformers** The load that can be carried on existing self-cooled transformers can usually be increased by adding auxiliary cooling equipment such as fans, external forced-oil coolers, or water spray equipment…		
	4.4	**Information for user calculations** If the user intends to perform calculations to determine the loading capability of a transformer using Clause 7 or Annex G, the user should request the following minimum information in the specification or final test report: More precise calculations of loading capability may be performed if desired using Clause 7 or Annex G if the following additional information is provided:		
Transformer insulation life	5	**Transformer insulation life**	6	**Relative ageing rate and transformer insulation life**
			6.1	**General** For the manufacture of paper and pressboard for electrical insulation, mainly unbleached softwood kraft pulp is used.
	5.1	**General** The subject of loss of transformer insulation life has had a rich but controversial history of development, with distribution and power transformers taking independent research paths (refer to I.1 in Annex I). As a result of recent study and testing, the approach to determination of insulation loss of life in this guide has been significantly modified (refer to I.2 in Annex I.) Aging or deterioration of insulation is a time function of temperature, moisture content, and oxygen content. With modern oil preservation	6.2	**Insulation life** In recent years, extensive work on paper degradation has been carried out and published in references [9] to [15], indicating that cellulose ageing may be described by combination of the three processes, i.e. oxidation, hydrolysis and pyrolysis. **Figure 2 - Correlation between tensile strength and DP value** **Figure 3 - Accelerated ageing in mineral oil at 140 °C, oxygen and moisture contents**

		systems, the moisture and oxygen contributions to insulation deterioration can be minimized, leaving insulation temperature as the controlling parameter. Since, in most apparatus, the temperature distribution is not uniform, the part that is operating at the highest temperature will ordinarily undergo the greatest deterioration. Therefore, in aging studies it is usual to consider the aging effects produced by the highest (hottest-spot) temperature. Because many factors influence the cumulative effect of temperature over time in causing deterioration of transformer insulation, it is not possible to predict with any great degree of accuracy the useful life of the insulation in a transformer, even under constant or closely controlled conditions, much less under widely varying service conditions. Wherever the word "life" is used in this guide, it means calculated insulation life, not actual transformer life.		**maintained at < 6 000 ppm and 0,5 % respectively** **Figure 4 - Expected life for non-thermally upgraded paper and its dependence upon moisture, oxygen and temperature** **Figure 5 - Expected life for thermally upgraded paper and its dependence upon moisture, oxygen and temperature**
	5.2	**Aging equations** Experimental evidence indicates that the relation of insulation deterioration to time and temperature follows an adaptation of the Arrhenius reaction rate theory that has the following form: $\text{Per Unit Life} = A\,e^{\left[\frac{B}{\Theta H+273}\right]}$ $\text{Per Unit Life} = 9.8\times10^{-18}\,e^{\left[\frac{15000}{\Theta H+273}\right]}$ $F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\Theta H+273}\right]}$ F_{AA} is the aging acceleration factor Θ_H is the winding hottest-spot temperature, °C	6.3	**Relative ageing rate** Although ageing or deterioration of insulation is a time function of temperature, moisture content, oxygen content and acid content, the model presented in this document is based only on the insulation temperature as the controlling parameter. **Table 1 - Relative ageing rates due to hot-spot temperature**
	5.3	**Percent loss of life** The insulation per unit life curve (see **Error! Reference source not found.**) can also be used to calculate percent loss of total life, as has been the practice in earlier editions of the referenced transformer loading guides. To do so, it is necessary to arbitrarily define the normal insulation life at the reference temperature in hours or years. Benchmark values of normal insulation life for a	6.4	**Loss-of-life calculation** The loss of life L over a certain period of time is equal to

		well-dried, oxygen-free system can be selected from Table I.2. Then the hours of life lost in the total time period is determined by multiplying the equivalent aging determined in Equation (3) by the time period (*t*) in hours. This gives equivalent hours of life at the reference temperature that are consumed in the time period. Percent loss of insulation life in the time period is equivalent hours life consumed divided by the definition of total normal insulation life (h) and multiplied by 100. Usually the total time period used is 24 h. The equation is given as follows: $$\% \text{ Loss of life} = \frac{F_{EQA} \times t \times 100}{\text{Normal insulation life}}$$ F_{EQA} is equivalent aging factor for the total time period a minimum normal insulation life expectancy of 180 000 hours is required. Other values for the end of life criteria have been used historically for developing transformer loading capability studies. The equations provided in this clause include a variable for the end of life criteria, so those users who have used alternative values may continue to do so. The end of life criteria are described in Table I.2 of **Error! Reference source not found.**…		
			Annex A (inform-ative)	**Insulation life expectancy and relative ageing rate considering oxygen and water effect**
			A.1	**Insulation life expectancy** Ageing or change of polymerization of paper insulation is often described as a 1st order process that can be described by an Arrhenius equation which is derived for various moisture and air conditions. **Table A.1 – Activation energy (EA) and environment factor (A) for oxidation, hydrolysis** **Table A.2 – Expected life of paper under various conditions** - Non-thermally upgraded and thermally upgraded paper - With and without air

				- With varying % moisture content
			A.2	**Relative ageing rate considering oxygen and water effect** **Table A.3 – Relative ageing rates due to hot-spot temperature, oxygen and moisture** Non-upgraded paper insulation **Table A.4 – Relative ageing rates due to hot-spot temperature, oxygen and moisture** Upgraded paper insulation
Ambient temperature and its influence on loading	6	**Ambient temperature and its influence on loading**	8.3	**Ambient temperature**
	6.1	**General** Transformer ratings are based on a 24 h average ambient of 30 °C. This is the standard ambient used in this guide. *Maximum ambient temperature is 40 °C*		*Taken from IEC 60076-1* *The temperature of cooling air at the inlet to the cooling equipment not exceeding:* *40 °C at any time* *30 °C monthly average of the hottest month* *20 °C yearly average (life ambient temperature)*
	6.2	**Approximating ambient temperature for air-cooled transformers** a) Average temperature. Use average daily temperature for the month involved, averaged over several years. b) Maximum daily temperature. Use average of the maximum daily temperatures for month involved averaged over several years. These ambients should be used as follows: - For loads with normal life expectancy, use a), the average temperature as the ambient for the month involved. - For short-time loads with moderate sacrifice of life expectancy, use b), the maximum daily temperature for the month involved.	8.3.1	**Outdoor air-cooled transformers** For dynamic considerations, such as monitoring or short-time emergency loading, the actual temperature profile should be used directly.
			8.3.2	**Correction of ambient temperature for transformer enclosure** A transformer operating in an enclosure experiences an extra temperature rise which is about half the temperature rise of the air in that enclosure… **Table 5 - Correction for increase in ambient temperature due to enclosure**
	6.3	**Approximating ambient temperature for**	8.3.3	**Water-cooled transformers** For water-cooled transformers, the ambient

		water-cooled transformers The ambient temperature to be used for water-cooled transformers is the cooling water temperature plus an added 5 °C to allow for possible loss of cooling efficiency due to deposits on cooling coil surfaces of water-cooled transformers in service.		temperature is the temperature of the incoming water, which shows less variation in time than air.
			7.3.4	**Outdoor ambient conditions** Wind, sunshine and rain may affect the loading capacity of distribution transformers, but their unpredictable nature makes it impracticable to take these factors into account.
	6.4	**Influence of ambient on loading for normal life expectancy** Average ambient temperatures should cover 24 h time periods. The associated maximum temperatures should not be more than 10 °C above the average temperatures for air-cooled, and 5 °C for water-cooled transformers. **Table 3 - Loading on basis of temperatures (average ambient other than 30 °C and average winding rise less than limiting values) (for quick approximation) (ambient temperature range –30 °C to 50 °C)**		
Calculation of temperatures	7	**Calculation of temperatures**		
	7.1.1	**Load Cycles, general** Transformers usually operate on a load cycle that repeats every 24 h. For normal loading or planned overloading above nameplate, a multi-step load cycle calculation method is usually used.	3.4	**cyclic loading** loading with cyclic variations (the duration of the cycle usually being 24 h) which is regarded in terms of the accumulated amount of ageing that occurs during the cycle
	7.1.2	**Method of converting actual to equivalent load cycle**		
	7.1.3	**Equivalent peak load**		
	7.1.4	**Equivalent continuous prior load**		
	7.2	**Calculation of temperatures** The equivalent continuous prior load is the rms load obtained by Equation (5) over a chosen period of the day.	Annex F (informative)	**Thermal model parameters**
	7.2.1	**General** The method given here for calculation of oil and winding temperatures for changes in load requires no iterative procedures.	F.1	The model in this document represents the traditional way of modelling based on many years of experience, and it has been verified under different operational conditions, providing satisfactory hot-spot temperature estimates.

<table>
<tr><td></td><td></td><td>An alternate method, which requires computer calculation procedures, is given in Annex G. This method is more exact in accounting for changes in load loss and oil viscosity caused by changes in resistance and oil temperature, respectively. The effect of a variable ambient temperature is also considered.</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td>F.2</td><td>Thermal constant estimation: experimental approach</td></tr>
<tr><td></td><td></td><td></td><td>F.3</td><td>Dynamic thermal modelling: further development</td></tr>
<tr><td></td><td>7.2.2</td><td>Components of temperature
Hottest-spot temperature and top-oil temperature are defined.</td><td></td><td></td></tr>
<tr><td></td><td>7.2.3</td><td>Top-oil rise over ambient
The top-oil temperature rise at a time after a one-step and two-step load change, as well as the ultimate top-oil rise are defined.</td><td></td><td></td></tr>
<tr><td></td><td>7.2.4</td><td>Oil time constant
The thermal capacity C, used to calculate the top-oil time constant is defined for ONAN, ONAF and forced-oil cooling modes, either directed or non-directed.</td><td>Annex E (inform-ative)</td><td>Calculation of winding and oil time constant</td></tr>
<tr><td></td><td>7.2.5</td><td>Winding hot-spot rise
Equations are provided to calculate the transient winding hottest-spot temperature rise over top-oil temperature.</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td>Annex G (inform-ative)</td><td>Oil and winding exponents</td></tr>
<tr><td></td><td>7.2.6</td><td>Exponents for temperature rise equations
Table 4—Exponents used in temperature determination equations [a]
<table>
<tr><th>Type of cooling</th><th>m</th><th>n</th></tr>
<tr><td>ONAN</td><td>0.8</td><td>0.8</td></tr>
<tr><td>ONAF</td><td>0.8</td><td>0.9</td></tr>
<tr><td>Non-directed OFAF or OFWF</td><td>0.8</td><td>0.9</td></tr>
<tr><td>Directed ODAF or ODWF</td><td>1.0</td><td>1.0</td></tr>
</table>
[a] Other values of exponents may be used if substantiated by design and test data.</td><td>G.1</td><td>General
The traditional oil exponent, x = 0,8, and winding exponent, y = 1,6, have been used since 1916 in the transformer loading calculus.</td></tr>
<tr><td></td><td></td><td></td><td>G.2</td><td>Historical background</td></tr>
<tr><td></td><td></td><td></td><td>G.3</td><td>Theoretical approach</td></tr>
<tr><td></td><td></td><td></td><td>G.4</td><td>Extended temperature rise test approach
The extended test consists of the three successive thermal runs:
- Regular heat run</td></tr>
</table>

				- Under-load test - Over-load test
	7.3	**Computer calculation of loading capability** Due to the wide variations in transformer characteristics typical loading capability tables are not published in this guide. The equations given in Clause 5 and Clause 7 may be used to develop a computer program that calculates the loading capability for a specific transformer design	Annex H (Inform-ative)	**Practical example of the exponential equations method**
			H.1	**General** The curves in Figure 14 are taken from an example in real life.
			H.8	**Comparison with measured values** **Figure H.1 – Hot-spot temperature response to step changes in the load current** **Figure H.2 – Top-oil temperature response to step changes in the load current**
	7.4	**Bibliography for Clause 7**		
Loading of distribution transformers and step-voltage regulators	8	**Loading of distribution transformers and step-voltage regulators**		
	8.1	**Life expectancy**		
	8.1.1	**General** Distribution transformer and voltage regulator life expectancy at any operating temperature is not accurately known. The information given regarding loss of insulation life at elevated temperatures is considered to be conservative and the best that can be produced from present knowledge of the subject...		
	8.1.2	**Normal life expectancy** …continuous loading at rated output when operated under usual service conditions… It is assumed that operation under these conditions is equivalent to operation in a constant 30 °C ambient temperature. The hottest-spot conductor temperature is the principal factor in determining life due to loading… Normal life expectancy will result from operating continuously with hottest-spot conductor temperature of 110 °C or an equivalent daily transient cycle… Distribution and power transformer model tests		

		indicate that the normal life expectancy at a continuous hottest-spot temperature of 110 °C is 20.55 years.		
	8.2	**Limitations**	7.3	**Specific limitations for small transformers**
	8.2.1	**General** Among these limitations are oil expansion, pressure in sealed units, and the thermal capability of bushings; leads, tap changers, or associated equipment such as cables, reactors, circuit breakers, fuses, disconnecting switches, and current transformers… Operation at hottest-spot temperatures above 140 °C may cause gassing in the solid insulation and the oil. Subsurface and vault locations can increase the ambient temperature and should be accounted for. The combination of heating due to loading and solar radiation can present a hazard to anyone making contact with the tank.	7.3.1	**Current and temperature limitations**
			7.3.2	**Accessory and other considerations**
			7.3.3	**Indoor transformers**
	8.3	**Types of loading**		
	8.3.1	**Loading for normal life expectancy under specific conditions** Distribution transformers and voltage regulators may be operated above 110 °C average continuous hottest-spot temperature for short periods provided they are operated for much longer periods at temperatures below 110 °C…		
	8.3.2	**Loading by top-oil temperature** Top-oil temperature alone should not be used as a guide for loading transformers and voltage regulators… It should be recognized that, due to the thermal lag in the oil temperature rise, time is required for a transformer or voltage regulator to reach a stable temperature for any change in load…		
	8.3.3	**Continuous loading based on average winding test temperature rise** For each degree Celsius in excess of 5 °C that the average winding test temperature rise is below 65 °C, the transformer or voltage regulator load may		

		be increased above rated kVA by 1.0%... The above is not applicable to all distribution transformers and voltage regulators…		
	8.3.4	**Short-time loading with moderate sacrifice of life expectancy (operation above 110 °C hottest-spot temperature)** this information is not intended to furnish the sole basis for calculating the normal life expectancy of transformer and voltage regulator insulation. As a guide, many users consider an average loss of life of 4% per day in any one emergency operation to be reasonable.		
	8.4	**Loading specific to voltage regulators**		
	8.4.1	**General** Most voltage regulators are 55 °C rise products and of sealed construction, using thermally upgraded paper insulation. Some voltage regulator nameplates show both 55 °C and 65 °C ratings with a 1.12 factor in the kVA rating for the higher rise units. The tap changer is integral to the regulator and usually is the critical factor in establishing the loading limits…		
	9	**Loading of power transformers**		
	9.1	**Types of loading and their interrelationship** Power transformer life expectancy at various operating temperatures is not accurately known… To provide guidance on risk associated with higher operating temperature, four different loading conditions beyond nameplate have been developed as examples, and are used throughout this guide… Normal life expectancy a) Normal life expectancy loading Sacrifice of life expectancy b) Planned loading beyond nameplate c) Long time emergency loading Short time emergency loading	3.5	**normal cyclic loading** higher ambient temperature or a higher-than-rated load current is applied during part of the cycle, but, from the point of view of relative thermal ageing rate (according to the mathematical model), this loading is equivalent to the rated load at normal ambient temperature
			3.6	**long-time emergency loading** loading resulting from the prolonged outage of some system elements that will not be reconnected before the transformer reaches a new and higher steady-state temperature
			3.7	**short-time emergency loading** unusually heavy loading of a transient nature (less

				than 30 min) due to the occurrence of one or more unlikely events which seriously disturb normal system loading
	9.2	**Limitations**	7	**Limitations**
	9.2.1	**Temperature or load limitations** **Table 8 - Suggested limits of temperature or load for loading above nameplate power transformers with 65 °C rise** **Table 9 - Maximum temperature limits used in the examples in this guide**	7.1	**Temperature limitations** **Table 2 – Maximum permissible temperature limits applicable to loading beyond nameplate rating** **-** Normal cyclic loading - Long-time emergency loading - Short-time emergency loading
			7.2	**Current limitations** It is recommended that the current limits given in Table 3 are not exceeded even if the circumstances of the overload mean that the temperatures in Table 2 are not exceeded **Table 3 – Recommended current limits applicable to loading beyond nameplate rating**
			7.4.1	**Current and temperature limitations**
			7.5.2	**Current and temperature limitations**
			7.4	**Specific limitations for medium-power transformers**
			7.4.3	**Short-circuit withstand requirements**
			7.5	**Specific limitations for large power transformers**
			7.5.1	**General** For large power transformers, additional limitations, mainly associated with the leakage flux, should be taken into consideration.
			7.5.4	**Short-circuit withstand requirements (7.4.3)**
			7.5.5	**Voltage limitations (7.4.4)**
	9.2.2	**Ancillary components** Tap changers bushings, leads, and other ancillary equipment may restrict loading to levels below those calculated by the equations in Clause 7 or Annex G… Additional information on loading of ancillary components is given in Annex B	7.4.2	**Accessory, associated equipment and other considerations**
			7.5.3	**Accessory, equipment and other considerations (7.4.2)**
			9	**Influence of tap-changers**
			9.1	**General**

				All quantities used in Equations have to be appropriate for the tap at which the transformer is operating. The rated oil temperature rise, losses and winding gradients have to be measured or calculated for that tap.
			9.2	**Load loss** **Figure 15 – Principle of losses as a function of the tap position**
			9.3	**Ratio of losses**
			9.4	**Load factor** The winding-to-oil temperature rise mainly depends on the load factor.
	9.2.3	**Risk considerations** Normal life expectancy loading is considered to be risk free; however, the remaining three types of loading have associated with them some indeterminate level of risk. Specifically, the level of risk is based on the quantity of free gas, moisture content of oil and insulation, and voltage. The presence of free gas as discussed in Annex A may cause dielectric failure during an overvoltage condition and possibly at rated power frequency voltage.		
	9.3	**Normal life expectancy loading**		
	9.3.1	**General** The basic loading of a power transformer for normal life expectancy is continuous loading at rated output when operated under usual conditions as indicated in 4.1 of IEEE Std C57.12.00-2010. It is assumed that the operation under these conditions is equivalent to operation in an average ambient temperature of 30 °C for cooling air or 25 °C for cooling water. Normal life expectancy will result from operating with a continuous hottest-spot conductor temperature of 110 °C (or equivalent variable temperature with 120 °C maximum in any 24 h period). The 110 °C hottest-spot temperature is based on the hottest-spot rise of 80 °C plus the standard average ambient temperature of 30 °C…		
	9.3.3	**Normal life expectancy loading by top-oil temperature** **a)** Top-oil temperature alone should not be used as a guide for loading power transformers. It should be recognized that,		

		due to thermal lag in oil rise, time is required for a transformer to reach a stable temperature following any change in load.		
	9.3.4	**Normal life expectancy loading by average winding test temperature rise** **Figure 7 - Typical load cycles for the examples** **b) Normal life expectancy loading** **c) Planned loading beyond nameplate rating** **d) Long-time emergency loading** **Short-term emergency loading**		
	9.4	**Planned loading beyond nameplate rating** Planned loading beyond nameplate rating results in either the conductor hottest-spot or top-oil temperature exceeding those suggested in Table 9 for normal life expectancy loading, and is accepted by the user as a normal, planned repetitive load…	5.5	**Transformer size** The sensitivity of transformers to loading beyond nameplate rating usually depends on their size.
	9.5	**Long-time emergency loading** Long-time emergency loading results from the prolonged outage of some system element and causes either the conductor hottest-spot or the top-oil temperature to exceed those suggested for planned loading beyond nameplate rating. This is not a normal operating condition, but may persist for some time. It is expected that such occurrences will be rare…	5.4	**Effects of long-time emergency loading** This is not a normal operating condition and its occurrence is expected to be rare but it may persist for weeks or even months and can lead to considerable ageing
	9.6	**Short-time emergency loading** Short-time emergency loading is an unusually heavy loading brought about by the occurrence of one or more unlikely events that seriously disturb normal system loading and cause either the conductor hottest-spot or top-oil temperature to exceed the temperature limits suggested for planned loading beyond name-plate rating. Acceptance of these conditions for a short time may be preferable to other alternatives. Suggested conductor hottest-spot temperatures are presented in Table 9. Top-oil temperature should not exceed 110 °C at any time. This type of loading, with its greater risk, is expected to occur rarely…	5.3	**Effects and hazards of short-time emergency loading** The main risk for short-time failures is the reduction in dielectric strength due to the possible presence of gas bubbles in a region of high electrical stress…
	9.7	**Loading information for specifications** If the maximum load capacity that a transformer user plans to utilize on a planned or emergency basis is included in the specifications at the time of	Annex C (inform-ative)	**Specification of loading beyond rated power** This document gives advice on calculation of the capability of an existing transformer to be loaded beyond rated power.

		purchase, the following information should be given: …		
	9.8	**Operation with part or all of the cooling out of service** When auxiliary equipment, such as pumps or fans, or both, is used to increase the cooling efficiency, the transformer may be required to operate for some time without this equipment functioning. The permissible loading under such conditions is given in Annex H.		
Thermal evolution of gas from transformer insulation	Annex A (norm-ative)	**Thermal evolution of gas from transformer insulation**		
	A.1	A new bubble generation model was developed by Oommen. This is the basis of Equation (7) in Clause 7. The new model used realistic coil segments to produce bubbles under overload conditions. An earlier model (Fessler, McNutt, Rouse, and Kaufman) was developed purely from physical and chemical considerations regarding bubble generation based on vapor pressure computations and the gas content of oil.		
	A.2	**Experimental verification**		
	A.3	**Determination of equation parameters**		
	A.4	**Example**		
	A.5	**Bibliography for Annex A**		
Effect of loading transformers above nameplate rating on bushings, tap changers, and auxiliary components	Annex B (norm-ative)	**Effect of loading transformers above nameplate rating on bushings, tap changers, and auxiliary components**		
	B.1	**Bushings** applies to oil-impregnated, paper-insulated, capacitance-graded bushings only. Bushings are normally designed with a hottest- spot total temperature limit of 105 °C at rated bushing current with a transformer top-oil temperature of 95 °C averaged over a 24 h time period.		
	B.2	**Tap-changers**		
	B.2.1	**Tap-changers for de-energized operation (TCDO)** ANSI standards do not specify the temperature rise of the contacts for TCDOs. The thin film build-up can be effectively		

		controlled if the TCDO is operated a minimum of once a year. The TCDO should be operated across its full range approximately 10 times to ensure that all the contacts have been wiped clean.		
	B.2.2	**Load tap-changers** IEEE Std C57.131™ and IEC 60214 provide the basis for the rating of a load tap-changer.		
	B.3	**Bushing-type current transformers** Bushing-type current transformers have the transformer top-oil as their ambient, which is limited to 105 °C total temperature at rated output for 65 °C rise transformers.		
	B.5	**Bibliography for Annex B**		
Calculation methods for determining ratings and selecting transformer size	Annex C (inform-ative)	**Calculation methods for determining ratings and selecting transformer size**		
	C.1	**General** This annex will illustrate calculation procedures used for the determination of loading limits and the selection of a transformer rating.		
	C.2	**Calculation determining loading beyond nameplate rating of an existing transformer**		
	C.3	**Planned loading beyond nameplate (PLBN)**		
	C.4	**Long-time emergency loading (LTE)**		
	C.5	**Short-time emergency (STE) loading**		
Philosophy of guide applicable to transformers with 55 °C average winding rise (65 °C hottest-spot rise) insulation systems	Annex D (norm-ative)	**Philosophy of guide applicable to transformers with 55 °C average winding rise (65 °C hottest-spot rise) insulation systems**		
	D.1	**General** Some users have considerable experience in loading power transformers above nameplate using computer programs in conjunction with IEEE Std C57.92-1981 and NEMA TR98-1978. The loading of transformers without thermally upgraded insulation can be considered to be similar to transformers with thermally upgraded insulation. The calculation of temperatures included in Clause 7 and Annex G may be applied equally well for transformers without thermally upgraded insulation. The normal loss of life ratings are loadings that		

		result in a daily loss of life equal to that of a continuous winding hottest-spot temperature of 95 °C for 55 °C rise transformers.		
	D.2	**Aging equations** $$\text{Per unit life} = 2.00 \times 10^{-10}\, e^{\left[\frac{15000}{\Theta_H + 273}\right]}$$ $$F_{AA} = e^{\left[\frac{15000}{368} - \frac{15000}{\Theta_H + 273}\right]}$$ F_{AA} is the aging acceleration factor Θ_H is the winding hottest-spot temperature, °C		
Unusual temperature and altitude conditions	Annex E (norm-ative)	**Unusual temperature and altitude conditions**		
	E.3	**Operation at rated kVA** Transformers may be operated at rated kVA at altitudes greater than 1000 m (3300 ft) without exceeding temperature limits, provided the average temperature of the cooling air does not exceed the values of Table E.1 for the respective altitudes.		
	E.4	**Operation at less than rated kVA** Transformers may be operated at altitudes greater than 1000 m (3300 ft) without exceeding temperature limits, provided the load to be carried is reduced below rating by the percentages given in Table E.2. **Table E.1—Maximum allowable average temperature of cooling air for carrying rated kVA** **Table E.2—Rated kVA correction factors for altitudes greater than 1000 m (3300 ft)**		
	E.5	**Bibliography for Annex E**		
Cold-load pickup (CLPU)	Annex F (norm-ative)	**Cold-load pickup (CLPU)**		
	F.1	**General** Cold-load pickup (CLPU) is the loading imposed on power and distribution transformers upon re-energization following a system outage.		
	F.2	**Duration of loads**		
	F.3	**CLPU ratio**		

		The ratio of the post-interruption load to pre-interruption load varies with the length and time of day of the interruption and the ambient temperature during interruption.		
	F.5	**Bibliography for Annex F**		
Alternate temperature calculation method	Annex G (inform-ative)	**Alternate temperature calculation method**	8	**Determination of temperatures**
	G.1	**General** Clause 7 equations use a very simple estimation of transformer temperatures. Annex G equations take into account the temperature of the oil entering and exiting the winding cooling ducts. The equations presented in this annex consider type of liquid, cooling mode, winding duct oil temperature rise, resistance and viscosity changes, and ambient temperature and load changes during a load cycle. However, the equations may not be equally valid for all distribution and power transformers covered by this guide and for all loading conditions.		
	G.2	**List of symbols**	4	**Symbols and abbreviations**
	G.3	**Equations**	8.2.2	**Exponential equations solution** **Table 4 – Recommended thermal characteristics for exponential equations** Exponents and constants for small, medium and large transformers
			8.2.3	**Difference equations solution**
			8.2	**Top-oil and hot-spot temperatures at varying ambient temperature and load conditions**
	G.3.1	**Introduction** The winding hottest-spot and oil temperatures are obtained from equations for the conservation of energy during a small instant of time, Δt. The system of equations constitutes a transient forward-marching finite difference calculation procedure. The equations were formulated so that temperatures obtained from the calculation at the prior time t_1 are used to compute the temperatures at the next instant of time $t_1 + \Delta t$ or t_2. The time is incremented again by Δt, and the last calculated temperatures are used to calculate the temperatures for the next time step. At each time step, the losses were calculated for the load and corrected for the resistance change with	8.2.1	**General** Two alternative ways of describing the hot-spot temperature as a function of time, for varying load current and ambient temperature: a) exponential equations solution b) difference equations solution

		temperature. Corrections for fluid viscosity changes with temperature were also incorporated into the equations. With this approach, the required accuracy is achieved by selecting a small value for the time increment Δ*t* and the programming approach is very simple. No iteration is required.		
	G.3.2	**Average winding temperature**		
	G.3.3	**Winding duct oil temperature rise over bottom oil**		
	G.3.4	**Winding hottest-spot temperature**	8.1	**Hot-spot temperature rise in steady state**
			8.1.1	**General** The adjacent oil temperature is assumed to be the top-oil temperature inside the winding.
			8.1.2	**Calculation of hot-spot temperature rise from normal heat-run test data** A thermal diagram is assumed, on the understanding that such a diagram is the simplification of a more complex distribution.
			8.1.3	**Direct measurement of hot-spot temperature rise** Fibre optic probes are installed in windings to measure the hot-spot temperature rise.
			8.1.4	**Hot-spot factor** The hot-spot factor H is winding-specific and should be determined on a case-by-case basis when required.
	G.3.5	**Average oil temperature**		
	G.3.6	**Top and bottom oil temperatures**		
	G.3.7	**Stability requirements**		
	G.3.8	**Fluid viscosity and specific heats of materials** Constants are included for three different liquids: mineral oil, silicone and HTHC.		
	G.3.9	**Summary of exponents** Exponents are provided for ONAN, ONAF, OFAF and ODAF cooling modes.		
	G.3.10	**Adjustment of rated test data for a different tap position** If it is desired to adjust the test data for operation on a no-load tap position other than that reported on the test report, Equations in G.3.10.1 through G.3.10.3 may be used.		
	G.3.10.1	**Top-and bottom-oil rise over ambient**		
	G.3.10.2	**Average winding rise over ambient**		
	G.3.10.3	**Hottest-spot rise over ambient**		

	G.3.11	**Load cycles and ambient temperatures**		
	G.4	**Discussion** Sources, application and limitations of the equations and the provided computer program.		
	G.6	**Computer program Input data for computer program** - Listing of the BASIC language program code - Input data requirements and format - Example with input and results	Annex I (inform-ative)	**Application of the difference equation solution method**
			I.1	**General** This annex provides example on the application of difference equation method described in 8.2.3.
			I.2	**Example** 1) Establish the transformer parameters 2) Establish the input data 3) Calculate the initial conditions 4) Solve the differential equations 5) Tabulate the output data 6) Plot the output data
			I.3	**Use of measured top-oil temperature**
			Annex J (inform-ative)	**Flowchart, based on the example in Annex H**
			Annex K (inform-ative)	**Example of calculating and presenting overload data** **Table K.1 – Example characteristics related to the loadability of transformers** **Table K.2 – An example table with the permissible duties and corresponding daily loss of life (in “normal” days), and maximum hot-spot temperature rise during the load cycle** **Figure K.1 – OF large power transformers: permissible duties for normal loss of life**
	G.7	**Bibliography for Annex G**		
Operation with part or all of the cooling out of service	Annex H (norm-ative)	**Operation with part or all of the cooling out of service**		
	H.2	**ONAN/ONAF transformers**		
	H.3	**ONAN/ONAF/ONAF, ONAN/ONAF/OFAF, and ONAN/OFAF/OFAF transformers**		
	H.4	**OFAF and OFWF transformers**		

		In general, the heat exchangers used to cool OFAF and OFWF type transformers will dissipate only an insignificant amount of heat when either the forced-oil circulation or the forced cooling medium (air or water) are inoperative.		
	H.4.2	**Calculations**		
	H.4.2.1	**Equations**		
	H.4.3	**Caution**		
	H.5	**Forced-oil-cooled transformers with part of coolers in operation** **Table H.1—Loading capability for OFAF or OFWF transformers**		
Transformer insulation life	Annex I (inform-ative)	**Transformer insulation life**		
	I.1	**Historical perspectives**		
	I.2	**Thermal aging principles**		
	I.3	**Example calculations**		
	I.4	**Bibliography for Annex I**		
			Annex B (inform-ative)	**Core temperature**
			B.1	**General** There are two different core hot-spots which, if not controlled, can cause insulation material degradation and subsequent gassing
			B.2	**Core hot-spot locations** In almost all cores, the core surface hot-spot is not located in the yoke but is located at the top of the middle core-limb.
			Annex D (inform-ative)	**Description of Q, S and H factors** IEC 60076-2 notes that the hotspot factor H is obtained by the product of the Q and S factors: $H = QS$
			Annex L (inform-ative)	**Geomagnetic induced currents**
			L.1	**Background**
			L.2	**GIC capability of power transformers**
			Annex M (inform-ative)	**Alternative oils** Synthetic esters and natural esters have been used for some years now in power transformers.
				Bibliography

[1] The latest rules now have eliminated the category of "guide" from IEC documents and all documents are "standards". Accordingly, whereas in IEEE the Loading Guide is an informative guide, in IEC the Loading Guide is a normative standard. In the next revision, the term "guide" must also be removed from the title.

[2] In IEC not thermally upgraded kraft paper is the standard with the following comparison:

	IEEE	IEC
Life ambient temperature, °C	30 °C	20 °C
Average winding rise	65 °C	65 K
Hottest spot (hot spot) rise	80 °C	78 K
Absolute temperature, °C	110 °C	98 °C