Spring 2015

A study into improving transformer loading capability beyond nameplate rating

Aakanksha Pasricha

A STUDY INTO IMPROVING TRANSFORMER LOADING CAPABILITY BEYOND NAMEPLATE RATING

by

AAKANKSHA PASRICHA

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

2015

Approved by

Mariesa Crow, Advisor

Mehdi Ferdowsi

Jonathan Kimball

ABSTRACT

Utilities are becoming increasingly interested in the prospect of overloading the transformers beyond the nameplate rating to meet the increased demand for power as it may be more economically viable than installing a new transformer. The safety of the transformer has to be ensured while overloading it and hence there is a maximum loading beyond which the transformer should not be overloaded. A study has been performed on 38 transformer units and the factors that limit their overloading capability have been analyzed. Ancillary equipment ratings were found to be the most prominent limiting factor. Several case studies and evaluation results have been provided to establish this. A new practice for selecting ancillary equipment has been proposed that will improve the transformer overloading capability significantly. Analytical results have been provided to demonstrate the effect the proposed solution will have on transformer overloading capability.

ACKNOWLEDGEMENT

I would like to express my deepest appreciation and gratitude for my Committee Chair, Dr. Mariesa L. Crow, for giving me the motivation, persistent guidance and encouragement in conducting my research work and presenting it in the form of a thesis.

I would like to thank my Committee members, Dr. Mehdi Ferdowsi and Dr. Jonathan Kimball, for their valuable suggestions about improving my thesis and for being very supportive.

I would also like to thank my advisors at Ameren, Mr. Randall L. Schlake and Mr. Gregory B. Palmer, who provided me with the data required for conducting the research and who have patiently trained me in the subject of transformer loading capability.

Finally, I would like to thank my family from whom I derive all the inspiration to work hard and strength to carry on in difficult times. This thesis would not have been possible without their encouragement and support.

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

Page

LIST OF TABLES

NOMENCLATURE

Symbol	Description
θ_H	Winding hottest-spot temperature, $^\circ C$
θ_A	Average ambient temperature during the load cycle to be studied, $^\circ C$
$\Delta\theta_{TO}$	Top-oil rise over ambient temperature, $^\circ C$
$\Delta\theta_H$	Winding hottest-spot rise over top-oil temperature, $^\circ C$
θ_{TO}	Top-oil temperature, $^\circ C$
$\Delta\theta_{TO,U}$	Ultimate top-oil rise over ambient temperature, $^\circ C$
$\Delta\theta_{TO,i}$	Initial top-oil rise over ambient temperature for t=0, $^\circ C$
τ_{TO}	Oil time constant of transformer for any load L and for any specific temperature differential between the ultimate top-oil rise and the initial top-oil rise
$\Delta\theta_{TO,R}$	Top-oil rise over ambient temperature at the rated load on the tap position to be studied, $^\circ C$
K_i	Ratio of initial load to the rated load, per unit
R	Ratio of load loss at rated load to no-load loss on the tap position to be studied, $^\circ C$
K_u	Ratio of ultimate load to the rated load, per unit
$\Delta\theta_{H,U}$	Ultimate winding hottest-spot rise over top-oil temperature, $^\circ C$
$\Delta\theta_{H,i}$	Initial winding hottest-spot rise over top-oil temperature, $^\circ C$
τ_w	Winding time constant at hot spot location, hours

$\Delta\theta_{TO,R}$ Winding hottest-spot rise over top-oil rise temperature at the rated load on the tap position to be studied, $°C$

m An empirically derived exponent used to calculate the variation of $\Delta\theta_{H}$ with changes in load. The value of m has been selected for each mode of cooling to approximately account for effects of changes in resistance and off viscosity with changes in load.

n An empirically derived exponent used to calculate the variation of $\Delta\theta_{TO}$ with changes in load. The value of n has been selected for each mode of cooling to approximately account for effects of change in resistance with change in load.

F_{AA} Aging acceleration factor

F_{AA_n} Aging acceleration factor for the temperature which exists during the time interval Δt_n

F_{EQA} Equivalent aging factor for the total time period

1. MOTIVATION

Transformer loading above the nameplate rating is a concept that is gaining increasing popularity among utilities. When there is increased demand for power, either due to a short term emergency (like the loss of another transformer in a substation) or on a long term basis, transformers are required to carry a load above their nameplate rating. There is an incentive for the utilities in doing so because the cost of installing a new transformer is normally much higher. Utilities want to extract the most out of the existing transformers and are interested in knowing how much they can achieve this practice within safe limits. This is known as transformer loading capability beyond the nameplate rating.

Utilities typically follow the practice of restricting the peak load below the nameplate rating of the transformers in their system. This ensures normal life expectancy for the transformer. However, since the peak loads are held less than the nameplate ratings, the life expectancy of the transformer is greater than what it would have been if rated load were applied continually. Therefore, transformers are lasting for much longer than their predicted life expectancy.

To meet the increased demand for power, utilities have to install more transformers, leading to a large capital expenditure for the transformer and its accessories. The other option is to overload the existing transformers beyond their nameplate ratings, which means that they can extract more out of the existing transformers instead of installing new ones.

The downside to this approach is that this will lead to reduced transformer working life and thereby increased depreciation costs for the utility and also increased cost of losses by operating the transformers on loads beyond the nameplate rating. If the additional cost of accelerated loss of life does not justify the addition of a new transformer, it is profitable to overload the existing transformer without adding a new one. Sometimes it is also profitable to overload a transformer for generating more revenue if the additional revenue justifies the loss of life.

Apart from the economic considerations, there are also emergency conditions created by the loss of a transformer in a substation due to a fault. In this case, other transformers have to support more load. This may also require overloading the transformers beyond their nameplate ratings.

For the above-mentioned reasons, utilities are becoming increasingly interested in the prospect of overloading existing transformers. By carefully considering each component of the transformer and its accessories, it may be possible to redefine the maximum rating of the transformer to enable increased use. This study has been motivated by a project, sponsored by Ameren Corporation, with the aim of investigating how much they can load their transformers beyond the nameplate rating while ensuring the safety of the transformers.

The factors that determine how much load the transformer can support beyond the nameplate rating are the hot spot temperature, the top oil temperature and the ratings of the ancillary equipment: the bushings and the (under) load tap changers (LTCs). In this study, several transformers have been examined for their loading capability beyond the nameplate rating, with the aim of finding out the factors that limit the transformer loading capability in real life and the means of eliminating those factors so that utilities can extract the most out of their transformers.

A striking observation was that in most cases the limiting factor was the ancillary equipment: the bushings and the LTCs. For example in a transformer that was evaluated, Bailey# 1, the load for which the hot spot temperature limit is reached is 121% (for Long Term Emergency) but the bushing and LTC rating is 106.7%. So the rated loading beyond the nameplate rating is limited to 106.7% and not 121%. If the bushing and LTC ratings were higher than 121%, the rated loading would be 121% which means the utility could have extracted more out of the same transformer.

In this thesis, several such case studies have been presented examining the factors which affect the transformer loading beyond nameplate rating out of which in more than 60% of the cases, the limiting factor has been found to be the bushing and LTC ratings. In the end, the practice utilities follow in selecting the bushings and LTCs has been critiqued and a solution has been proposed which will ensure that the utilities are able to extract the most performance out of their transformers.

2. BACKGROUND THEORY

2.1 LIMITING FACTORS IN TRANSFORMER OVERLOADING

The factors that limit how much load the transformer can support beyond the nameplate rating are

- the hottest-spot temperature,
- the top oil temperature, and
- the ratings of the bushings and LTCs.

In this section each of them are discussed in brief.

Hottest-spot temperature is defined as 'the hottest temperature of the current carrying components of a transformer in contact with insulation or insulating fluid.'[1] Due to losses in a transformer, the temperature of the transformer winding is higher than the ambient temperature. However the increased temperature is not uniform in all spots in the winding. There is a spot where the temperature is the maximum and this temperature is known as the hottest-spot, or simply hot-spot, temperature. For safe operation of the transformer the hot-spot temperature limits are defined in Table 2.1.

Table 2.1. Hot spot temperature limits

Type of loading	55 degree rise	65 degree rise
NR	100	110
LT	130	140
ST	150	160

Top-oil temperature is defined as ‘the temperature of the top layer of the insulating fluid in a transformer, representative of the temperature of the top liquid in the cooling flow stream. Generally measured 50 mm below the surface of the liquid.’[1] The top-oil temperature limits for safe operation are given in Table 2.2.

Table 2.2. Top-oil temperature limits

Type of loading	55 degree rise	65 degree rise
NR	95	110
LT	95	110
ST	95	110

The higher the transformer loading is, the higher the hottest-spot temperature and the top-oil temperature will be. The transformer must not be loaded so that these limits are exceeded or damage to the transformer may occur.

Ancillary equipment mainly includes the bushings and the Load Tap Changers (LTCs) of the transformer. A bushing is ‘an insulating structure including a central conductor, or providing a central passage for a conductor, with provision for mounting on a barrier, conducting or otherwise, for the purpose of insulating the conductor from the barrier and conducting current from one side of the barrier to the other.’[1] An LTC is ‘a selector switch device, which may include current interrupting contactors, used to change transformer taps with the transformer energized and carrying full load.'[1]

Not only is it necessary to ensure that the hottest-spot and top oil temperatures are within limits, it must also be ensured that the transformer loading doesn't exceed the ratings of the bushings and LTC.

2.2 TYPES OF TRANSFORMER LOADING

There are three conditions under which a transformer can be loaded:

- Normal life expectancy loading,
- Long-time emergency loading, and
- Short-time emergency loading

Normal life expectancy loading is defined as the continuous loading which results in a continuous hot-spot temperature of 110°C (or equivalent variable temperature with 120°C maximum in any 24 h period for a 65°C rise design), assuming the average ambient temperature of 30°C . Since loads are never constant in real life and keep varying, it is acceptable if transformers are operated above 110°C hot-spot temperature for short periods and operated for much longer periods at temperatures below 110 °C. Such a loading will also result in normal life expectancy because thermal aging is a cumulative process. Therefore, the normal rating is the peak load in a loading cycle which results in an equivalent hottest spot temperature of 110 °C.

The heat generated due to the losses in the transformer causes temperature rise in the internal structures of the transformer. Average winding temperature rise of a transformer is 'the arithmetic difference between the average winding temperature of the hottest winding and the ambient temperature'.[1] Liquid-filled transformers come in standard rises of 55°C and 65°C above the ambient. The transformers that have thermally upgraded insulation have the average winding temperature rise of 65°C. The hot-spot and top-oil temperature limits are different for the two designs. Hot-spot temperature and top-oil temperature limits for normal life-expectancy loading are given in table 2.3.

Table 2.3. Hot-spot temperature and top-oil temperature limits for normal life-expectancy loading

Normal Rating	**Transformer Rise Design**	
	55 °C	65 °C
Top Oil Temperature	100 °C	110 °C
Hot Spot Temperature	95 °C	110 °C

The variation of the hot-spot temperature as a function of the hour under normal life-expectancy loading is illustrated in Figure 2.1.

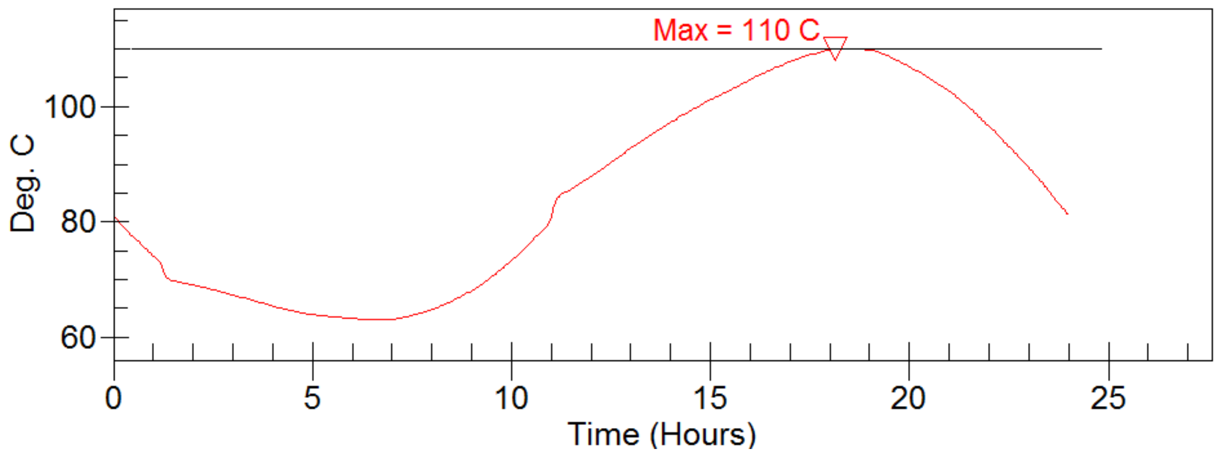

Figure 2.1. Hot-spot temperature profile for Normal Life Expectancy loading

Long-time emergency loading is a condition in which a power transformer is so loaded that its hot-spot temperature is in the range of 120°C–140°C. Long-time emergency loading is due to prolonged outage of some system element. It causes either the conductor hot-spot or the top-oil temperature to exceed those suggested for normal loading. This type of loading is characterized by one long-time outage of a transmission system element which may last several months. Two or three such occurrences may take place over the normal life-time of the transformer. Hot-spot temperature and top-oil temperature limits under long-time emergency loading are given in Table 2.4.

Table 2.4. Hot-spot temperature and top-oil temperature limits for Long-Time Emergency loading

Long-Time Emergency Rating	**Transformer Rise Design**	
	55 °C	65 °C
Top Oil Temperature	100 °C	110 °C
Hot Spot Temperature	130 °C	140 °C

The variation of the hot-spot temperature as a function of the hour under long-time emergency loading is illustrated in Figure 2.2.

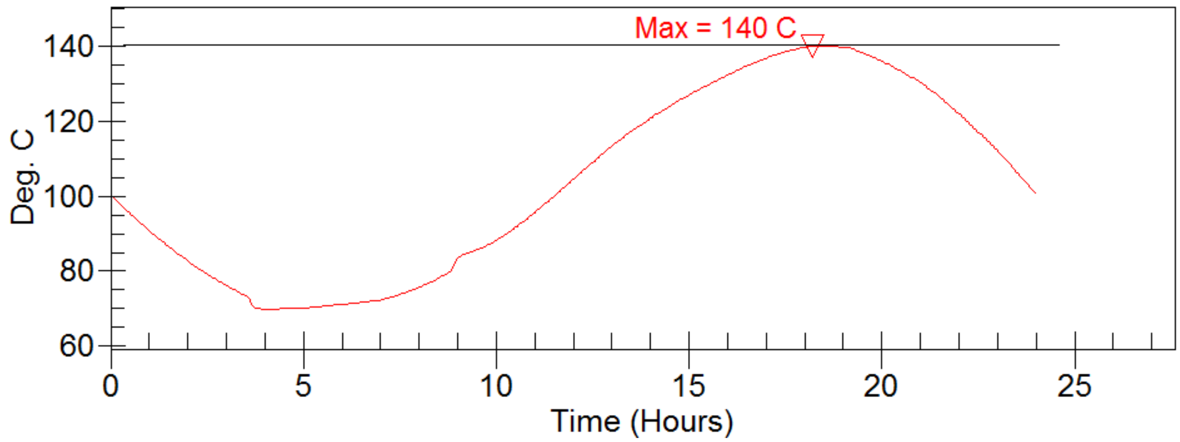

Figure 2.2. Hot-spot temperature profile for Long-Time Emergency loading

Short-time emergency loading is a condition in which a power transformer is so loaded that its hot-spot temperature can be as high as 160°C for a short time. Short-time emergency loading is caused due to one or more unlikely events that seriously disturb normal system loading, such as the loss of another transformer in a substation. For example, in a substation with two transformers, if one of the transformers becomes un-operational due to a fault, the other transformer has to support the entire load. If there is Automatic Load Reduction (ALR), the load that the transformer has to support will be reduced and after a period of approximately 4 hours some of the load is diverted to other substations depending upon the tie capacity. This puts an end to the short-time emergency condition. This type of loading is characterized by an unusually heavy loading but lasts for only few hours.

This type of loading has greater risk and is expected to occur once or twice during the lifetime of the transformer. Hot-spot temperature and top-oil temperature limits under short-time emergency loading are given in Table 2.5.

Table 2.5. Hot-spot temperature and top-oil temperature limits for Short-Time Emergency loading

Short-Time Emergency Rating	**Transformer Rise Design**	
	55 °C	65 °C
Top Oil Temperature	100 °C	110 °C
Hot Spot Temperature	150 °C	160 °C

The variation of the hot-spot temperature as a function of the hour under short-time emergency loading is illustrated in Figure 2.3.

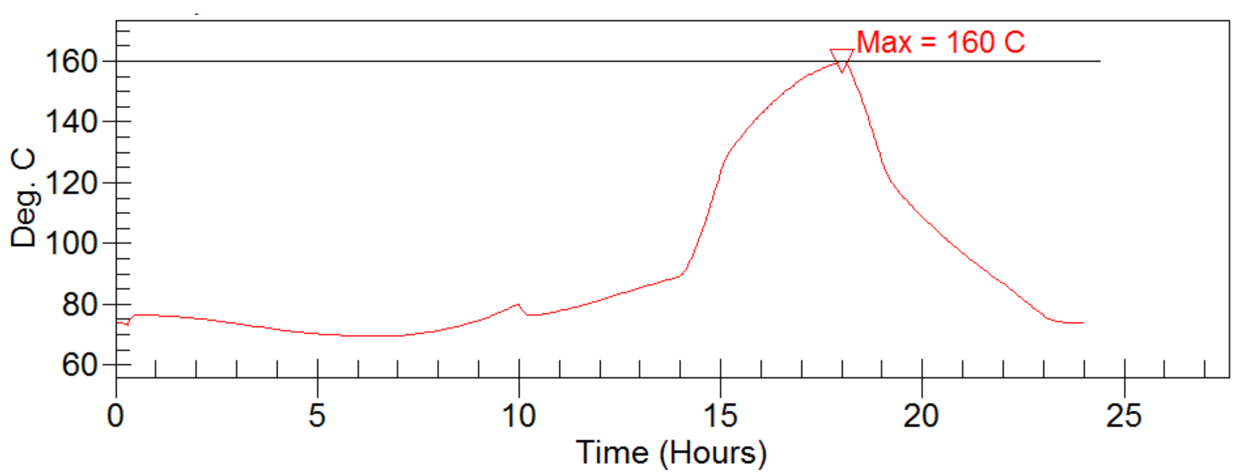

Figure 2.3. Hot-spot temperature profile for Short-Time Emergency loading

2.3 TRANSFORMER LIFETIME

A transformer's lifetime is determined by its insulation lifetime. The aging of insulation is mainly dependent on the hot-spot temperature. The normal life of a transformer, when operated at the hot-spot temperature of 110°C (for a 65 °C average winding rise transformer) is 180,000 hours or 20.55 years. The percent loss of life in 24 hours of such an operation is 0.0133%. The higher the hot-spot temperature is, the greater the deterioration that the insulation undergoes and the greater the percent loss of life in the same 24 hours of operation will be. This means that whenever a transformer is loaded beyond the nameplate rating, there is some additional loss of life resulting from it, reducing the overall life of the transformer. But as stated before, due to economic considerations it may be a prudent decision to load the transformer beyond the nameplate rating regardless of the additional loss of life.

> For a given hot-spot temperature, the rate at which transformer insulation aging is accelerated compared with the aging rate at a reference hot-spot temperature [is known as the aging acceleration factor]. The reference hot-spot temperature is 110 °C for 65 °C average winding rise and 95 °C for 55 °C average winding rise transformers (without thermally upgraded insulation). For hot-spot temperatures in excess of the reference hot-spot temperature the aging acceleration factor is greater than 1. For hot-spot temperatures lower than the reference hottest-spot temperature, the aging acceleration factor is less than 1. [1]

However, the aging, and hence the percent loss of life, increases non-linearly with the hot-spot temperature as shown in Table 2.6. Therefore, particularly during long-time and short-time emergency loading the loss of life is very high, but since such occurrences are very rare during the lifetime of a transformer, this is acceptable.

At the same time the transformer cannot be operated beyond a certain hot-spot temperature because the aging will be drastically accelerated. Hence, limits have to be placed on the hot-spot temperature while evaluating the loading capability beyond nameplate rating.

Table 2.6. Aging acceleration factors and percent loss of life in 24 hours for different values of hot-spot temperatures

Hot-spot temperature	Aging acceleration factor	Percent loss of life in 24 h
110	1.00	0.0133
120	2.71	0.0360
130	6.98	0.0928
140	17.2	0.2288
150	40.6	0.5400
160	92.1	1.2249
170	201.2	2.6760
180	424.9	5.6512
190	868.8	11.5550
200	1723	22.9159

2.4. RISKS ASSOCIATED WITH TRANSFORMER OVERLOADING

Apart from the aging and long-time mechanical deterioration of winding insulation, there are other risks associated with loading the transformers beyond the nameplate rating. The following extract taken from the IEEE Std. C57.91-1995 "Guide for Loading Mineral-Oil-Immersed Transformers" gives an exhaustive list of the risks associated with loading the transformers beyond the nameplate rating.

> a) Evolution of free gas from insulation of winding and lead conductors (insulated conductors) heated by load and eddy currents (circulating currents between or within insulated conductor strands) may jeopardize dielectric integrity…..
> b) Evolution of free gas from insulation adjacent to metallic structural parts linked by electromagnetic flux produced by winding or lead currents may also reduce dielectric strength.
> c)…….. If a percent loss of total life calculation is made based on an arbitrary definition of a "normal life" in hours, one should recognize that the calculated results may not be as conservative for transformers rated above 100 MVA as they are for smaller units since the calculation does

not consider mechanical wear effects that may increase with megavoltampere rating.

d) Operation at high temperature will cause reduced mechanical strength of both conductor and structural insulation. These effects are of major concern during periods of transient overcurrent (through-fault) when mechanical forces reach their highest levels.

e) Thermal expansion of conductors, insulation materials, or structural parts at high temperatures may result in permanent deformations that could contribute to mechanical or dielectric failures.

f) Pressure build-up in bushings for currents above rating could result in leaking gaskets, loss of oil, and ultimate dielectric failure…..

g) Increased resistance in the contacts of tap changers can result from a build-up of oil decomposition products in a very localized high temperature region at the contact point when the tap changer is loaded beyond its rating. In the extreme, this could result in a thermal runaway condition with contact arcing and violent gas evolution……

h) Auxiliary equipment internal to the transformer such as reactors and current transformers, may also be subject to some of the risk identified above…….

i) When the temperature of the top oil exceeds 105 °C……., there is a possibility that oil expansion will be greater than the holding capacity of the tank and also result in a pressure that causes the pressure relief device to operate and expel the oil. The loss of oil may also create problems with the oil preservation system or expose electrical parts upon cooling. [2]

For these reasons, utilities are cautious when loading transformers beyond their nameplate rating. Therefore, it must be ensured that the hot-spot temperatures and the top-oil temperatures are kept within reasonable limits while overloading, as they determine the health and longevity of the transformer.

3. DETERMINING TRANSFORMER LOADING CAPABILITY

The IEEE Std. C57.91-1995 “Guide for Loading Mineral-Oil-Immersed Transformers” details the standard method of calculating the transformer loading capability. Computer programs are commercially available that perform this evaluation. For this study, the EPRI PTLoad v.6.2. Software has been used. The software computes the maximum peak load that can be impressed on a transformer while meeting specified limitations and also identifies the limiting factors.

3.1 INPUTS TO THE COMPUTER PROGRAM

Inputs to the program consist of the following:

- transformer characteristics,
- ambient temperatures,
- repetitive 24 hour load cycle,
- transformer oil analysis data, and
- specified daily percent loss of life.

Transformer characteristics include the load loss and no-load loss, type of cooling, top-oil rise, hottest-spot rise, gallons of oil, and weight of tank and fittings. The load loss, top-oil rise and the hottest-spot rise are all specified at the rated load for the respective cooling stage. The load loss, top-oil rise, and the hottest-spot rise are entered for two cooling stages. This data is available from the transformer test report and the nameplate.

“Ambient temperature is an important factor in determining the load capability of a transformer since the temperature rises for any load must be added to the ambient to determine operating temperatures."[2] A higher ambient temperature leaves less room for temperature rise due to the load since the hot-spot temperature limit is fixed. This means that the higher the ambient temperature is, the lower the transformer loading capability will be, and vice-versa.

> Transformer ratings are based on a 24 h average ambient of 30°C….Whenever the actual ambient can be measured, such ambients should be averaged over 24 h, and then used in determining the transformer's temperature and loading capability. The ambient air temperature seen by a transformer is the air in contact with its radiators or heat exchangers. [2]

Ambient temperatures over a 24 hour period (with an interval of 1 hour), at the place where the transformer is located, need to be input to the software. At this juncture, it is important to note that the loading capability of a transformer is different in summer and winter because of the difference in ambient temperatures and also the loading cycle. The day chosen for entering the temperature data into the software is the peak load day in the season.

The user inputs the 24 hour load cycle so that the program can use it as a multiplicand and set different values of load multipliers to determine the magnified load cycle at which the limiting values of hotspot temperature or top-oil temperature (whichever comes first) are reached. The repetitive 24 hour load cycles for summers and winters are different. This is due to the difference in the power consumption patterns during summers and winters. Figures 3.1 and 3.2 show the typical load cycles for summers and winters respectively. Therefore, if it is desired to calculate the loading capability for summers, a load cycle on a summer day and the ambient temperatures on the same day are used as inputs to the software. The same applies for winters.

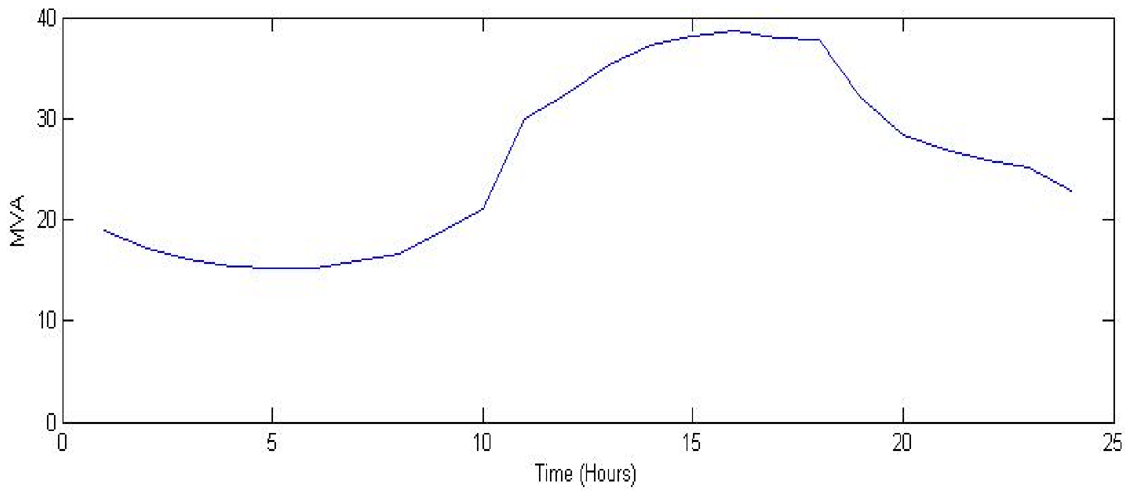

Figure 3.1. A typical load cycle for summers

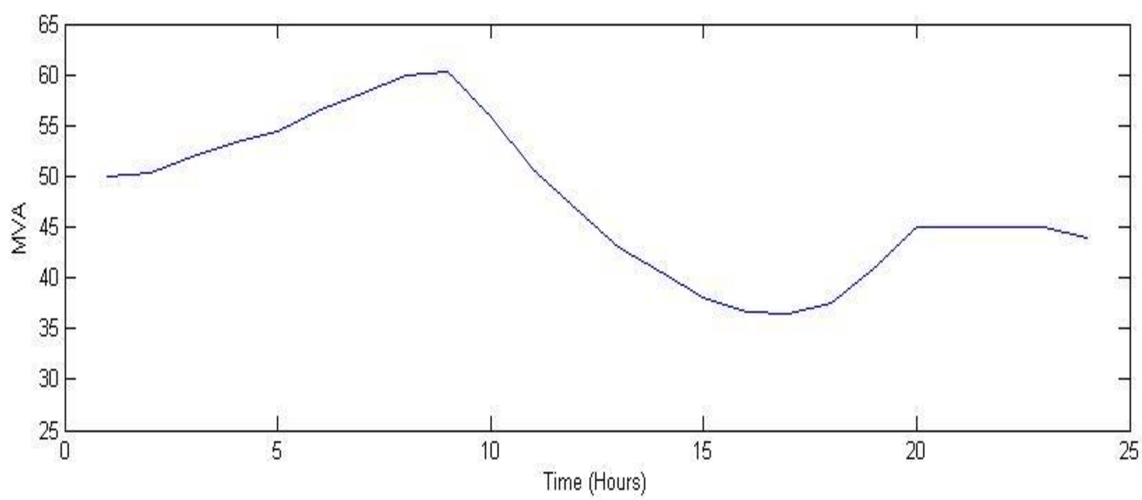

Figure 3.2. A typical load cycle for winters

The transformer oil analysis data is required because aging or deterioration of insulation is also a time function of moisture content and oxygen content, in addition to temperature. With modern oil preservation systems, the moisture and oxygen contributions to insulation deterioration can be minimized, leaving insulation temperature as the controlling parameter. Nevertheless, the transformer oil analysis data also needs to be taken into account for accuracy. This is available from the transformer oil analysis report. Such tests are conducted regularly for the purpose of maintenance.

Apart from the above-mentioned inputs, utilities can also specify the maximum daily percent loss of life they can afford.

3.2 LOGIC FOR COMPUTER PROGRAM

Computer programs use a systematic convergence procedure to obtain the highest allowable peak load which satisfies the limiting criterion (the hottest-spot temperature, top-oil temperature, and daily specified percent loss of life). The user inputs the 24 hour load cycle and the program sets an initial load multiplier such that the peak load is midway between the minimum continuous load and maximum permitted peak load which is 200% of the nameplate rating. For this assumed load cycle, the hottest-spot temperatures, top-oil temperatures and insulation aging are calculated for each interval of 1 hour and the total aging is calculated. The calculated values are then compared with the limiting values. Depending on the results, the load multiplier is changed and the calculations are repeated until the calculated value of the total percent loss of life is close enough to the value specified by the user (within a tolerance of +/- 4%) and the hottest-spot temperature and top-oil temperature limits are not exceeded. Once these criteria are all met, the program prints out the corresponding peak load, the peak hottest-spot temperature, the peak top-oil temperature and the total percent loss of life. Figure 3.3

shows the logic diagram for the computer program used for calculating transformer loading.

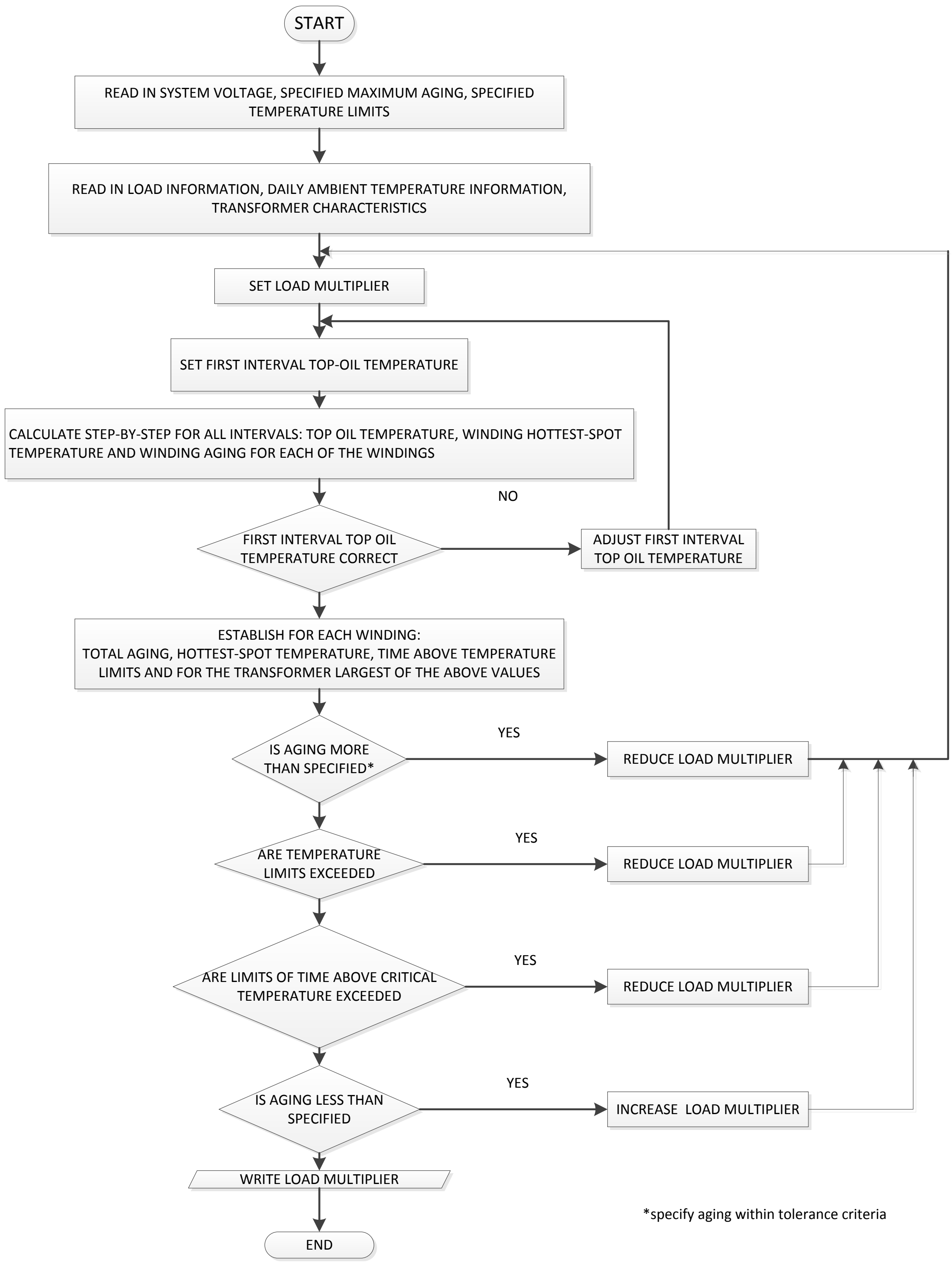

Figure 3.3. Logic diagram for computer program used for calculating transformer loading capability [2]

3.3 CALCULATION OF TEMPERATURES

Although the load varies continually over 24 hours, for the purpose of these calculations, it is assumed constant during each 1 hour interval, which is the equivalent load during that period. This results in 24 steps and for each step the hottest-spot temperature and the top-oil temperature are calculated at the end of 1 hour of application of that load. The top-oil temperature and the hot-spot temperature at rated load are given in the transformer test reports. Using these temperatures, the temperatures for loads other than the rated load are calculated.

The hottest-spot temperature is assumed to consist of three components given by (1).

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H \qquad (1)$$

The top-oil temperature is given by (2).

$$\theta_{TO} = \theta_A + \Delta\theta_{TO} \qquad (2)$$

3.3.1. Top-Oil Rise over Ambient. The top-oil temperature rise at a time after a step load change is given by the exponential expression (3) containing an oil time constant.

$$\Delta\theta_{TO} = (\Delta\theta_{TO,U} - \Delta\theta_{TO,i})\left(1 - \exp^{\frac{1}{\tau_{TO}}}\right) + \Delta\theta_{TO,i}\tau_{TO} \qquad (3)$$

For the two-step overload cycle with a constant equivalent prior load the initial top-oil rise is given by (4).

$$\Delta\theta_{TO,i} = \Delta\theta_{TO,R}\left[\frac{(K_i{}^2 R + 1)}{(R+1)}\right]^n \qquad (4)$$

For the multi-step load cycle analysis with a series of short-time intervals, (3) is used for each load step, and the top-oil rise calculated for the end of the previous load step is used as the initial top-oil rise for the next load step calculation. The ultimate top-oil rise is given by (5).

$$\Delta\theta_{TO,U} = \Delta\theta_{TO,R}\left[\frac{(K_U{}^2 R + 1)}{(R+1)}\right]^n \tag{5}$$

The top-oil rise obtained above is added to the ambient temperature at that hour to obtain the top-oil temperature as in (2).

3.3.2. Hot-Spot Rise over Top-Oil. Transient winding hottest-spot temperature rise over top-oil temperature is given by (6).

$$\Delta\theta_H = (\Delta\theta_{H,U} - \Delta\theta_{H,i})\left(1 - \exp^{\frac{1}{\tau_w}}\right) + \Delta\theta_{H,i} \tag{6}$$

The initial hot-spot rise over top oil is given by (7).

$$\Delta\theta_{H,i} = \Delta\theta_{H,R} K_i^{2m} \tag{7}$$

The ultimate hot-spot rise over top oil is given by (8).

$$\Delta\theta_{H,U} = \Delta\theta_{H,R} K_U{}^{2m} \tag{8}$$

The hot-spot rise obtained above is added to the ambient temperature at that hour and the top-oil rise at that hour to get the hottest-spot temperature as in (1).

Using these equations the program systematically calculates the hottest-spot and the top-oil temperatures for each load step and checks whether the temperatures go beyond the specified limits.

3.3.3. Oil Time Constant. The top-oil time constant used in the equations for calculating the top-oil rise and the hot-spot rise is a function of the thermal capacity, top-oil rise at rated load, the initial top-oil rise , the ultimate top-oil rise and the total loss at rated load. The thermal capacity is obtained from the weight of core and coil assembly, weight of tank and fittings and the volume of oil in the transformer tank. This data is available on the nameplate of the transformer.

3.4. CALCULATION OF TOTAL LOSS OF LIFE IN 24 H CYCLE

Once the hot-spot temperature for each interval has been calculated, the aging acceleration factor during that interval will be given by (9).

$$F_{AA} = EXP^{\left[\frac{1500}{383} - \frac{1500}{\theta_H + 273}\right]} \tag{9}$$

The equivalent life (in hours or days) at the reference temperature that will be consumed in a given time period for the given temperature cycle is given by (10).

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA_n} \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \tag{10}$$

As each interval is 1 hour and the total period is 24 hours, the above relation reduces to (11).

$$F_{EQA} = \frac{\sum_{n=1}^{24} F_{AA_n}}{24} \tag{11}$$

And Equivalent loss of life (in hours) = $F_{EQA} \times 24$ (12)

Percent loss of life in 24 hours = $\frac{F_{EQA} \times 24}{\text{Normal insulation life}} \times 100$ (13)

4. AN OVERVIEW OF THE STUDY

As described in the previous sections, transformer loading beyond nameplate rating is a very important consideration for utilities, both from the economic point of view as well as from the point of the constraints posed due to the emergency conditions. However, to maintain the safety of the transformer and to not over-accelerate its aging, transformers can be overloaded only within certain limits. Due to these reasons, the utilities set a maximum permitted peak load limit beyond which the transformers should not be loaded. This limit is typically 150% of the nameplate rating.

Therefore, the ideal situation for utilities is if they can operate the transformers at 150% loading, which would mean that they are making the best use of the transformers. However, this situation seldom happens. In many cases, either the hot-spot or the top-oil temperature limits are reached at a load less than 150% of the nameplate rating and in other cases, the bushing and LTC ratings put a limit on the transformer loading even though the hot-spot and top-oil temperature limits have not been reached.

In this study several transformers have been examined for their loading capability beyond the nameplate rating, with the aim of finding out the most prominent factors that limit the transformer loading capability in real life and eliminating those factors so that utilities can extract the most out of the transformers.

In this study, the loading capability of 38 transformers was calculated using the EPRI PTLoad v.6.2. software, which implements the methodology described in the previous sections. The following steps give in brief the procedure followed in conducting the study:

1. The transformer data, ambient temperature data, repetitive 24 hour load cycle and transformer oil data were provided to the software as inputs and the limits for hot-spot temperature and top-oil temperature were specified.
2. The software calculated the peak load (the maximum load to which the transformer can be overloaded without exceeding the hot-spot or the top-oil temperature limits) along with the multiplied 24 hour load cycle, the percent loss of life, the limiting factor (hot-spot temperature or top-oil temperature) and the values of the hot-spot and the top-oil temperatures as a function of hour.
3. The LTC and bushing ratings were available from the nameplate. The peak load obtained as the output from the software was compared to the bushing rating and the LTC rating. If the calculated peak load exceeded either the bushing rating or the LTC rating, the peak load was considered to be the same as the rating of the ancillary equipment with the lowest rating and that ancillary equipment (bushing or LTC) was considered as the limiting factor.
4. If the peak load as obtained from the previous step exceeded 150% of the nameplate rating, the final peak load was set at 150% the nameplate rating. In other words, peak load was never allowed to exceed 150% of the nameplate rating.
5. Depending on steps 2, 3 and 4, there could be up to five different factors that limited the loading capability of the transformer beyond the nameplate rating.
   - The hot-spot temperature (HS)
   - The top-oil temperature (TO)
   - The bushing rating (B)

- The LTC rating (LTC)
- The nameplate rating (NP)

6. The peak loads along with limiting factors were recorded for each transformer.

5. FINDINGS

5.1. CASE STUDIES

In this section, some of the cases out of the 50 evaluations that were performed on different transformers, have been discussed in detail.

5.1.1. Eldon#1Winter. This is a transformer with a 55 degree insulation system and a top nameplate rating of 33.33MVA. The bushing and LTC ratings are 53.78 MVA and 71.7 MVA respectively which are 161.36% and 215.12% of the nameplate rating.

From the evaluation it was obtained that the Normal Rating of this transformer is 148.3% of the nameplate rating. The limiting factor is hot-spot temperature, which means that at the peak load of 148.3%, the hot-spot temperature limit of 110 ℃ is reached, while the top-oil temperature is still below the limit.

The long-time emergency and short-time emergency ratings are both set to 150% although they came out to be higher than 150% in the evaluation. But since the maximum allowed peak load is 150%, the rating has to be 150%. This is why the limiting factor is top percent of the nameplate rating (NP).

This is one of the best cases that have been evaluated in this study as the ratings are either 150% or very close to it, which means that the utilities will be able to extract the most out of this transformer.

Here it is observed that the bushing and LTC ratings are quite a bit higher than the nameplate rating, which is not the norm. Sometimes such anomalies are found in the industry which may be due to ready availability of equipment with ratings other than the most preferred one or due to human error. Nevertheless, the result of this anomaly is good, as if the bushing and LTC ratings were low, they would have restricted the loading capability of the transformer.

5.1.2. Bailey#1Winter. This is a transformer with a 65 degree insulation system and a top nameplate rating of 112 MVA. The bushing and LTC ratings are 119.5 MVA each which is 106.7% of the nameplate rating.

From the evaluation, it was obtained that all of the three ratings, the Normal, the Long-Time Emergency and the Short-Time Emergency, are restricted to 106.7% due to the bushing and LTC ratings. Had the ratings of bushing and LTC been higher than 150%, the ratings would have been 139.67% (NR), 150% (LT) and 150% (ST). But due to the evaluation, they are restricted to 106.7%. This implies that the utilities are getting much less than the transformer is capable of delivering.

5.1.3. Huster#2Summer. This is a transformer with a 55 degrees insulation system and a top nameplate rating of 100MVA. The bushing and LTC ratings are 119.5MVA and 99.97MVA respectively which are 119.5% and 99.97% of the nameplate rating.

The Normal Rating for this transformer is 93.25% with the limiting factor of hot-spot temperature. But the Long-Time and Short-Time ratings are both 99.97% with the limiting factor of the LTC rating. Had the LTC and bushing ratings been high enough, the Long-Time Emergency rating would have been 127.37% and the Short-Time Emergency rating would have been 147.95% which are significantly greater compared to what they are with the given bushing and LTC ratings.

5.1.4. Esther#1Summer. This is a transformer with a 65 degrees insulation system and a top nameplate rating of 84MVA. The bushing and LTC ratings are

179.27MVA and 119.5MVA respectively which are 213.42% and 142.26% of the nameplate rating.

From the evaluation it was obtained that the Normal Rating is 104.8% of the nameplate rating with the limiting factor of hot-spot temperature. The Long-Time Emergency Rating is 126.64% with the limiting factor of hot-spot temperature. The Short-Time Emergency Rating is 137.83% top-oil temperature which means that the top-oil temperature limit of 110 degrees is reached at a loading of 137.83%.

This is also one of the very few cases in which the bushing and LTC ratings are significantly higher than the nameplate ratings and hence they are not limiting the extent to which the transformer can be loaded.

5.2 ANALYSIS OF RESULTS

Table 5.1 shows the results obtained from the study - the peak loads (in percentage of the nameplate rating) along with the limiting factor for each case.

Table 5.1. Peak loads (in percentage of the nameplate rating) and limiting factors

S. no.	Unit	Season	Normal rating, Limiting factor	Short Term Emergency rating, Limiting factor	Long Term Emergency Rating, Limiting factor
1	Adair#1	Summer	110.64% HS	150% NP	135.6% HS
2	Adair#1	Winter	150% NP	150% NP	150% NP
3	Adair#2	Summer	103.07% HS	128.03% LTC	127.14% HS

Table 5.1. Peak loads (in percentage of the nameplate rating) and limiting factors (cont.)

4	Adair#2	Winter	128.03% LTC	128.03% LTC	128.03% LTC
5	Arnold# 2	Summer	94.59% HS	106.7% B,LTC	106.7% B,LTC
6	Arnold# 2	Winter	106.7% B,LTC	106.7% B,LTC	106.7% B,LTC
7	Arnold#3	Summer	94.87% HS	106.7% B,LTC	106.7% B,LTC
8	Arnold#3	Winter	106.7% B,LTC	106.7% B,LTC	106.7% B,LTC
9	Bailey# 1	Summer	96.91% HS	106.7% B,LTC	106.7% B,LTC
10	Bailey#1	Winter	106.7% B,LTC	106.7% B,LTC	106.7% B,LTC
11	Bailey#2	Summer	106.7% B,LTC	106.7% B,LTC	106.7% B,LTC
12	Bailey#2	Winter	106.7% B,LTC	106.7% B,LTC	106.7% B,LTC
13	Bailey#3	Summer	97.54% HS	143.4% B,LTC	133.12% B,LTC
14	Bailey#3	Winter	143.4% B,LTC	143.4% B,LTC	143.4% B,LTC
15	Berkeley #1	Summer	91.48% HS	99.97% LTC	99.97% LTC
16	Berkeley #2	Summer	95.87% HS	99.97% LTC	99.97% LTC
17	Berkeley#3	Summer	103.93% HS	106.7% B,LTC	106.7% B,LTC

Table 5.1. Peak loads (in percentage of the nameplate rating) and limiting factors (cont.)

18	Berkeley#4	Summer	93.1% HS	99.97% LTC	99.97% LTC
19	Conway#1	Summer	94.76% HS	106.7% B,LTC	106.7% B,LTC
20	Conway#2	Summer	103.7% HS	106.7% B,LTC	106.7% B,LTC
21	Conway#3	Summer	94.77% HS	106.7% B,LTC	106.7% B,LTC
22	Conway#4	Summer	94.43% HS	106.7% B,LTC	106.7% B,LTC
23	Delbridge	Summer	110% HS	N/A	134.5% TO
24	Delbridge	Winter	150% NP	N/A	150% NP
25	Eldon#1	Summer	93.48% HS	150% NP	130.47% HS
26	Eldon#1	Winter	148.3% HS	150% NP	150% NP
27	Eldon#2	Summer	106.43% HS	150% NP	132.7% HS
28	Eldon#2	Winter	148.33% HS	150% NP	150% NP
29	Esther#1	Summer	104.8% HS	137.83% TO	126.64% HS
30	Esther#2	Summer	108.89% HS	142.2% B,LTC	131.73% HS
31	Huster#1	Summer	89.26% LTC	89.26% LTC	89.26% LTC

Table 5.1. Peak loads (in percentage of the nameplate rating) and limiting factors (cont.)

32	Huster#2	Summer	93.25% HS	99.97% LTC	99.97% LTC
33	Huster#3	Summer	93.09% HS	99.97% LTC	99.97% LTC
34	Lakeside#1	Summer	100% LTC	100% LTC	100% LTC
35	Lakeside#1	Winter	100% LTC	100% LTC	100% LTC
36	Lakeside#2	Summer	100% LTC	100% LTC	100% LTC
37	Lakeside#2	Winter	100% LTC	100% LTC	100% LTC
38	Marshall#1	Summer	106.5% HS	106.7% B,LTC	106.7% B,LTC
39	Marshall#2	Summer	106.29% HS	106.7% B,LTC	106.7% B,LTC
40	Marshall#3	Summer	106.2% HS	106.7% B,LTC	106.7% B,LTC
41	Marshall#4	Summer	101.5% HS	106.7% B,LTC	106.7% B,LTC
42	MaurerLake#1	Summer	99.93% HS	150% NP	134.13% TO
43	MaurerLake#2	Summer	96.03% HS	135.52% TO	119.17% HS
44	MaurerLake#3	Summer	115.35% HS	N/A	119.5% B
45	O’Fallon#2	Summer	95.69% HS	106.7% B,LTC	106.7% B,LTC

Table 5.1. Peak loads (in percentage of the nameplate rating) and limiting factors (cont.)

46	PointPrairie#1	Summer	96.87% HS	106.7% B,LTC	106.7% B,LTC
47	PointPrairie#2	Summer	100.46% HS	106.7% B,LTC	106.7% B,LTC
48	Warson#1	Summer	71.71% B,LTC	71.71% B,LTC	71.71% B,LTC
49	Warson#2	Summer	64.03% B,LTC	64.03% B,LTC	64.03% B,LTC
50	Warson#3	Summer	71.71% B,LTC	71.71% B,LTC	71.71% B,LTC

By carefully observing this table it can be immediately deduced that the limiting factor in most cases is the bushing or the LTC. Figure 5.1 shows the exact distribution of the limiting factors in the form of a pie-chart.

From the pie-chart it can be seen that in 61% of cases, the limiting factor is either the bushing rating, the LTC rating, or both. Thus it can be concluded that in practice, the most prominent factor that restricts a transformer from delivering what it is capable of is the ancillary equipment ratings.

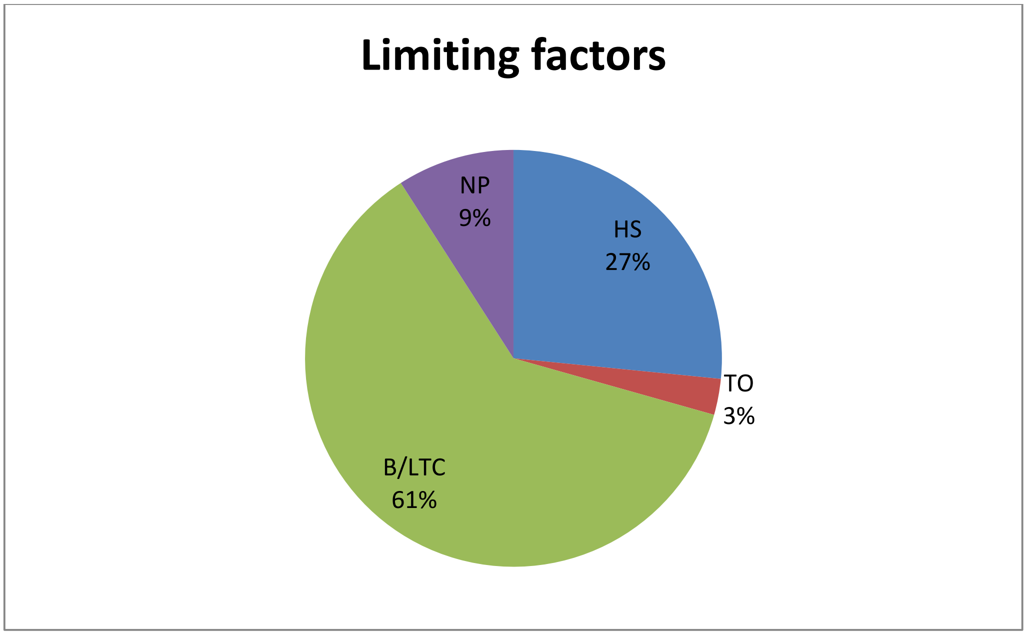

Figure 5.1. Distribution of limiting factors in transformer overloading capability

6. PROPOSED SOLUTION

Through the study it was found out that the practice that utilities follow at present for selecting bushings and LTCs needs to be changed. In most cases, bushing and LTC ratings are just a little above the nameplate rating which rules out any possibility for loading the transformer beyond the nameplate rating. Table 6.1 shows a comparison between the nameplate ratings and the bushing and LTC ratings to establish this.

Table 6.1. Bushing and LTC ratings as percentage of nameplate rating of transformer

S. No.	Unit	Bushing rating as a percentage of nameplate rating (%)	LTC rating as a percentage of nameplate rating (%)
1	Adair#1	256.07	N/A
2	Adair#2	256.07	128.03
3	Arnold# 2	106.7	106.7
4	Arnold#3	106.7	106.7
5	Bailey# 1	106.7	106.7
6	Bailey#2	106.7	106.7
7	Bailey#3	143.4	143.4
8	Berkeley #1	119.5	99.97
9	Berkeley #2	119.5	99.97
10	Berkeley#3	106.7	106.7
11	Berkeley#4	119.5	99.97
12	Conway#1	106.7	106.7

Table 6.1. Bushing and LTC ratings as percentage of transformer nameplate rating (cont.)

13	Conway#2	106.7	106.7
14	Conway#3	106.7	106.7
15	Conway#4	106.7	106.7
16	Delbridge	192.23	N/A
17	Eldon#1	161.36	215.12
18	Eldon#2	192.23	211.47
19	Esther#1	213.42	142.26
20	Esther#2	142.26	142.26
21	Huster#1	106.7	89.26
22	Huster#2	119.5	99.97
23	Huster#3	119.5	99.97
24	Lakeside#1	142.27	100
25	Lakeside#2	142.27	100
26	Marshall#1	106.7	106.7
27	Marshall#2	106.7	106.7
28	Marshall#3	106.7	106.7
29	Marshall#4	106.7	106.7
30	MaurerLake#1	430.24	N/A
31	MaurerLake#2	384.45	N/A
32	MaurerLake#3	119.5	179.27
33	O’Fallon#2	106.7	106.7
34	PointPrairie#1	106.7	106.7
35	PointPrairie#2	106.7	106.7

Table 6.1. Bushing and LTC ratings as percentage of transformer nameplate rating (cont.)

36	Warson#1	71.71	71.71
37	Warson#2	64.03	64.03
38	Warson#3	71.71	71.71

Figure 6.1 shows the distribution of the bushing and LTC ratings. A detailed analysis of bushing and LTC ratings indicates that 74% of the bushing and LTC ratings are less than 120% of nameplate rating. For example, in 10 transformer units out of the 38 transformer units examined, both the LTC and bushing ratings are 106.7% of the nameplate rating, which allows only little room for overloading the transformer.

This practice is justified as long as the utilities do not routinely load the transformer beyond nameplate rating because installing bushings and LTCs with higher ratings can be costlier. But as they start exploring the prospects of loading the transformer beyond nameplate rating, this practice is also found to be the biggest constraining factor.

As mentioned earlier, the most desirable thing for the utilities is if they can operate the transformer at 150% of the nameplate rating, as it allows them to extract the maximum out of their transformers. However, due to the limitations posed by the hot-spot temperature limit, top-oil temperature limit and the ratings of bushings and LTCs, in most cases utilities have to settle at less than 150%.

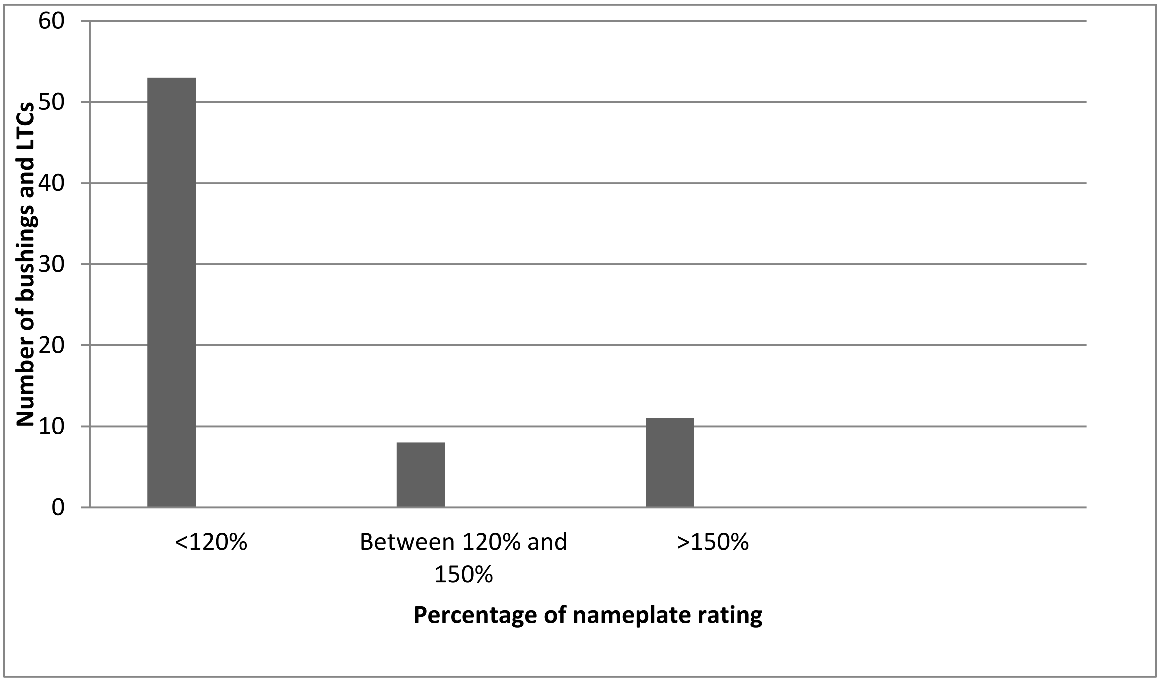

Figure 6.1.Distribution of bushing and LTC ratings

It is proposed that while selecting the bushings and LTCs it should be ensured that their ratings are at least 150% of the nameplate rating. Doing this will completely eliminate the limiting factor of ancillary equipment from the picture and utilities can extract much more out of the transformers. Bushings and LTCs are much cheaper than a transformer. Therefore, the additional cost of overrated bushings and LTCs is negligible compared to the cost of installing a new transformer for the want of more loading capability.

Figures 6.2 to 6.5 illustrate the effect it will have on the transformer loading capability, once the limiting factor of ancillary equipment has been removed. It is observed that by having bushings and LTCs of ratings greater than 150% of the nameplate rating of transformer, the overloading capability of the transformer improves significantly.

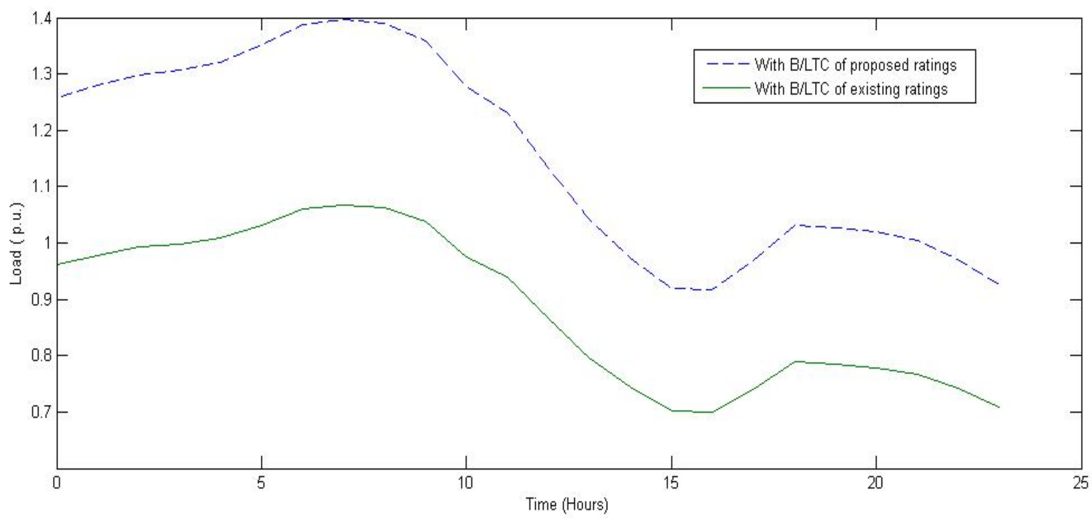

Figure 6.2. A comparison of the loads Bailey#1 transformer can support under normal conditions during winters with B/ LTC of proposed ratings and with B/LTC of given ratings

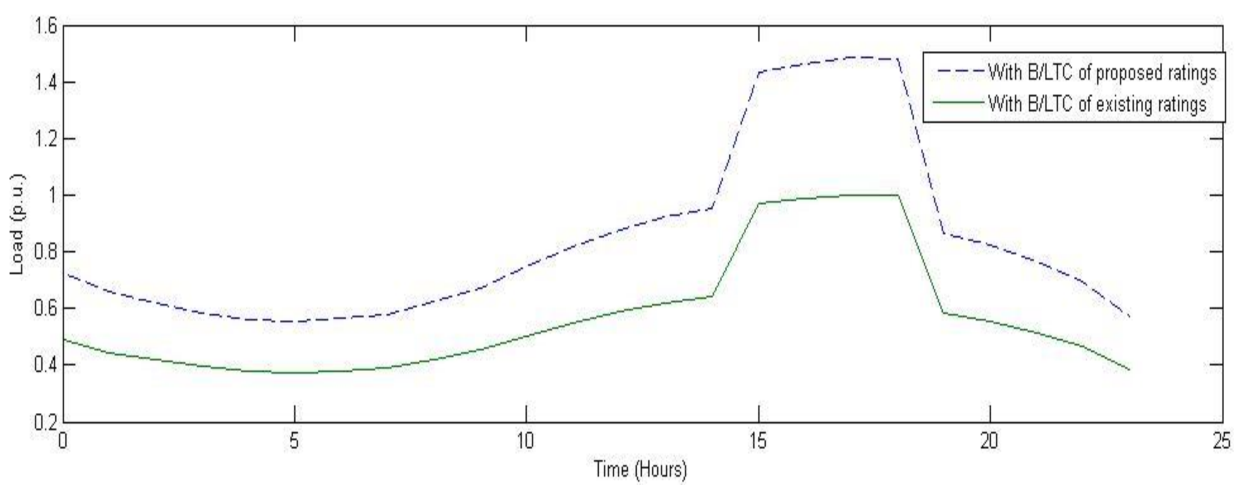

Figure 6.3. A comparison of the loads Huster#2 can support under Short-Time Emergency during summers with B/ LTC of proposed ratings and with B/LTC of given ratings

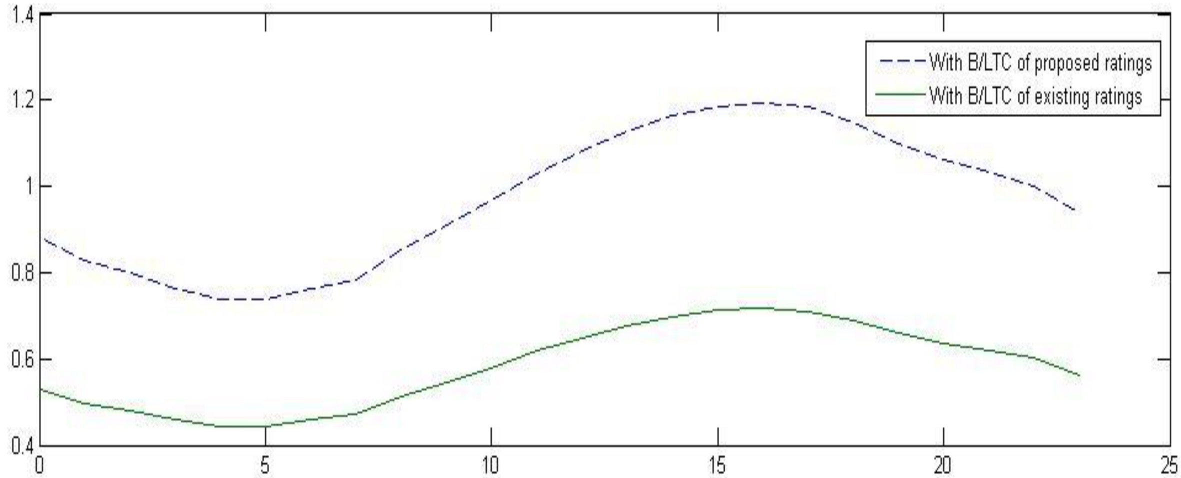

Figure 6.4. A comparison of the loads Warson#2 can support under Long-Time Emergency during summers with B/ LTC of proposed ratings and with B/LTC of given ratings

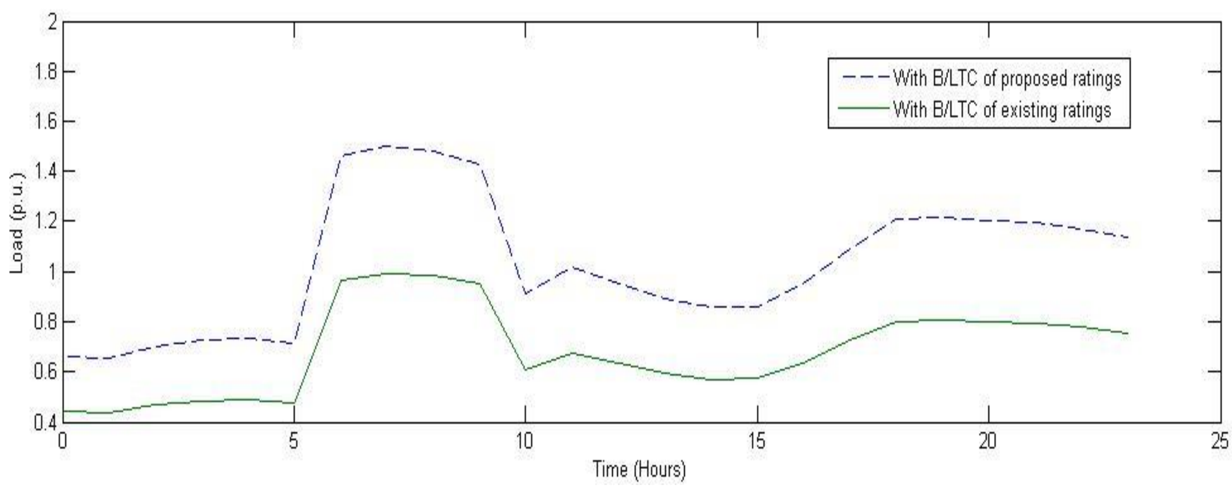

Figure 6.5. A comparison of the loads Lakeside#1 can support under Short-Time Emergency during winters with B/ LTC of proposed ratings and with B/LTC of given ratings

7. CONCLUSION

In this study, 38 transformers have been examined, their loading capability above the nameplate rating has been evaluated and the factors that limit it have been analyzed. The aim was to find out the most prominent limiting factors and come up with a solution for eliminating some of the limiting factors in order to maximize the transformers' loading capability.

It was observed that the most prominent limiting factors are the ancillary equipment ratings which includes the bushing and the LTC ratings. A detailed analysis showed that more than 60% of the time, transformers are not delivering what they are capable of because of improper bushing and LTC ratings.

It was found out that the problem lies in the practice that utilities follow in selecting the bushings and LTCs. Their ratings are little above the nameplate rating of the transformer, which does not allow the transformer to be overloaded to a significant degree. It has been proposed that the bushings and LTCs should be selected such that their ratings are at least 150% of the nameplate rating of the transformer. This will completely eliminate the limiting factor of ancillary equipment ratings, there by greatly improving the loading capability of transformers.

BIBLIOGRAPHY

[1] IEEE Std. C.57.12.80-2010, "IEEE Standard Terminology for Power and Distribution Transformers"

[2] IEEE Std. C.57.91-1995, "IEEE Guide for Loading Mineral-Oil Immersed Transformers"

VITA

The author, Aakanksha Pasricha, was born in Yamunanagar, India. In 2010, she received her B.Tech (Bachelor of Technology) in Electrical Engineering from Indian Institute of Technology (IIT) Roorkee, India. She worked as a Physics instructor for 2 years and as a lecturer in the Department of Electrical Engineering for 1 semester at RKDF Institute of Science and Technology, Bhopal. In May, 2015, she received her MS in Electrical Engineering from Missouri University of Science and Technology.