LOADING OF TRANSFORMERS BEYOND NAMEPLATE RATING

by

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Abstract

The application of a load in excess of nameplate ratings, and/or an ambient temperature higher than designed of a transformer, involves a degree of risk and accelerated ageing. A software package has been developed, based on the standard thermal equations given in IEC 354: *Loading guide for oil immersed power transformers*, to identify the risks involved and indicate how transformers may be loaded in excess of the nameplate rating without adverse effects.

The software package eliminates the tedious manual calculations otherwise involved with the practical complex load profiles. It is also shown that accurate results are obtained with the package not obtained with the limited step approximations required by the manual method. This ensures that unexpected damages to the transformer are avoided. The study also shows that there is no significant change in the voltage regulation and on the efficiencies of motor loads due to the loading provided they are kept within the specified limits.

1. Introduction

1.1 Scope

A software package has been developed to provide guidance for loading of ONAN type distribution transformers from the point of view of operating temperature and thermal ageing. This package identifies the risks involved with over-loading and indicates how, within limitations transformers may be loaded in excess of their nameplate rating. The package is applicable to transformers with a maximum rating of 2500 kVA three phase or 833 kVA per limb single phase. The high voltage rating is limited to 33 kV and without on-load tap-changing, complying with IEC 76: *Power Transformers* with normal cyclic loading of duration one day.

The package can be used to achieve two objectives, namely to select a transformer of optimum capacity for a given loading condition and to check the utilisation of an existing transformer.

1.2 Loading effects on transformer life

The rating of a distribution transformer is usually assigned for continuous operation at that value. However, extraordinary events, such as over-voltages, short-circuits in the system and emergency loading can affect the life of a transformer to a high degree.

Consequences[1,2] of loading a transformer beyond name-plate rating can be as follows.

1. The temperatures of windings, insulation, oil etc. increase and can reach unacceptable levels.
2. The leakage flux density outside the core increases, causing additional eddy current heating in metallic parts linked by the flux.
3. The moisture and gas content in the insulation and in the oil increase with the temperature increase.
4. Bushings, tap-changers, cable-end connections and current transformers are exposed to higher stresses.

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These increase the risk of premature failure, which may be of an immediate short term nature or may lead to long term failure due to cumulative deterioration of the transformer over many years.

1.2.1 Consequential Risks

The main risk for short time failures is the reduction in dielectric strength due to the presence of gas bubbles in the region of high electrical stress. These bubbles may develop in the paper insulation when the hot spot temperature rises suddenly above a critical temperature of about 140^0C. This affects the reliability of the transformer.

The short-term risks normally disappear, if failure has not been initiated, after the load is reduced to normal level.

The pressure build up in the bushings may also result in a failure due to oil leakage and gassing in the bushings, if the temperature of the insulation exceeds the said critical temperature.

Cumulative thermal deterioration of the mechanical properties of the conductor insulation will accelerate at higher temperatures. This deterioration process will ultimately reduce the effective life of the transformer.

2.0 Transformer Selection Based On Thermal Parameters

The IEC 354 - Loading guide for oil immersed power transformers[3] gives the standard method of selecting a transformer using Tables and Graphs. It also gives the standard equations for the same purpose. These latter equations are used in the software package developed[4] (see Appendix-A for details).

2.1 Software Development

The main flow chart for implementing equations A1 to A6 of the appendix, suitably modified[5], is shown in figure 2.1.

In **Module A** of the program, the data is assigned together with any limitations imposed.

In the **Module B** the optimum value of the transformer capacity is selected for a given load profile. This is described more fully in the flow chart of figure 2.2. Each important block of the flow chart is described in the following sections B1 to B5.

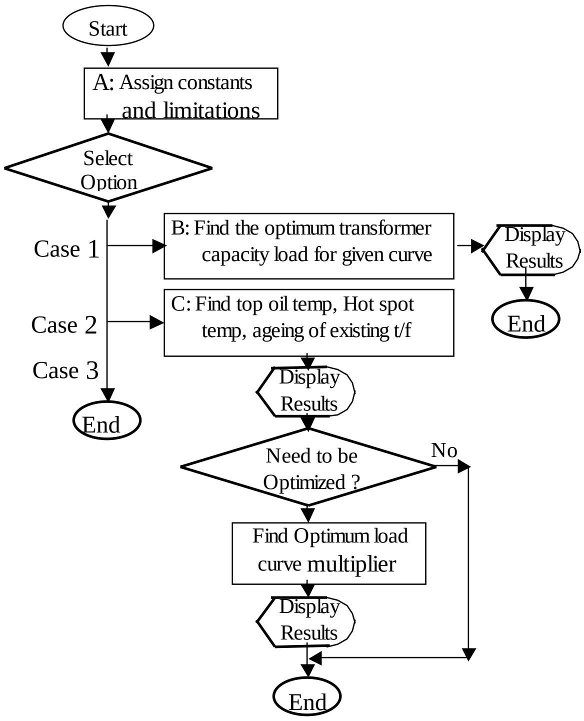

Figure 2.1 - Main Flow Chart

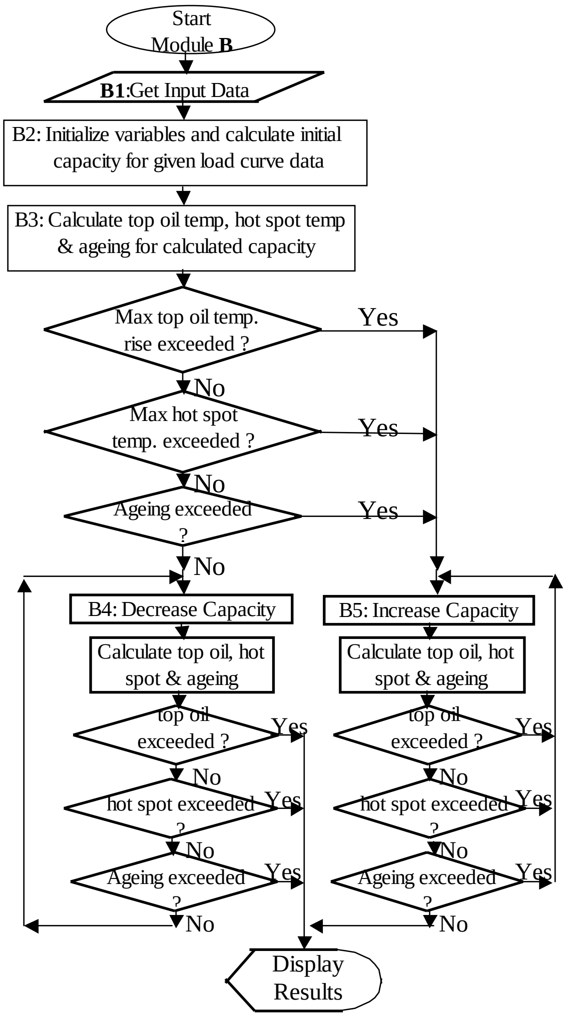

Figure 2.2 - Flow Chart for finding Optimum Transformer Capacity

B1: Get Input Data

The weighted ambient temperature; the Mean monthly maximum temperature; the period for which load data is available; and the load data for each period are input to the program in this section

B2: Initialize Variables

This is used to initialize the capacity for thermal parameter calculations in case 1.

Low - assigned to the minimum load in the cycle

High - assigned to the maximum load in the cycle

The initial required capacity is selected as the mean of the Low and High values.

Req_capacity = (Low + High) / 2

B3: Calculate Top Oil, Hot Spot & Ageing

In the program, any change in the load conditions is treated as a small step change. Therefore for a continually varying load, the step function has to be applied over small time intervals, throughout the load cycle.

Calculation of the top oil temperature rise as well as hot spot temperature throughout the load cycle thus requires the use of a computer program.

Calculating Top Oil

To obtain the top oil temperature rise in each time interval of the load cycle, some adjustments have to be made to the equation A1, taking into consideration the different loads before that particular time interval,

Consider a load cycle with 'n' number of equal time intervals, each of duration 't'.

The equation A1 can be modified as equation (1).

$$\Delta\theta_{on} = \Delta\theta_{o(n-1)} + (\Delta\theta_{oun} - \Delta\theta_{o(n-1)})(1 - e^{-t/\tau o}) \quad (1)$$

Rearranging Equation (1)

$$\Delta\theta_{on} = \Delta\theta_{o(n-1)} (e^{-t/\tau o}) + \Delta\theta_{oun}(1 - e^{-t/\tau o})$$

where

$\Delta\theta_{on}$ = Top oil temp. rise at end of n^{th} interval

$\Delta\theta_{o(n-1)}$ = Top oil temp. rise at end of $(n-1)^{th}$ interval

$\Delta\theta_{oun}$ = Ultimate top oil temp. rise in n^{th} interval

t = time interval of application of specific load

τ_o = Oil time constant

Let $(1 - e^{-t/\tau o}) = C$. This gives

$$\Delta\theta_{on} = (1 - C)\, \Delta\theta_{o(n-1)} + C\, \Delta\theta_{oun} \quad (2)$$

Equation (2) can be extended to represent the total duration of the load cycle by a series of equations, which will form the matrix equation (3).

$$\begin{pmatrix} \Delta\theta_{o1} \\ \Delta\theta_{o2} \\ \\ \Delta\theta_{on} \end{pmatrix} = (1 - C) \begin{pmatrix} \Delta\theta_{on}^{*} \\ \Delta\theta_{o1} \\ \\ \Delta\theta_{o(n-1)} \end{pmatrix} + C \begin{pmatrix} \Delta\theta_{on1} \\ \Delta\theta_{on2} \\ \\ \Delta\theta_{onn} \end{pmatrix} \quad (3)$$

** Since the load curve is assumed to be of cyclic nature, for the first time duration, the initial top oil temperature rise is equal to the final top oil temperature rise.*

Rearranging equation (3) gives equation (4).

$$[A] \begin{pmatrix} \Delta\theta_{o1} \\ \Delta\theta_{o2} \\ \\ \Delta\theta_{on} \end{pmatrix} = C \begin{pmatrix} \Delta\theta_{ou1} \\ \Delta\theta_{ou2} \\ \\ \Delta\theta_{oun} \end{pmatrix} \quad (4)$$

where

$$[A] = \begin{bmatrix} 1 & 0 & 0 & --- & 0 & (C-1) \\ (C-1) & 1 & 0 & --- & 0 & 0 \\ 0 & (C-1) & 1 & --- & 0 & 0 \\ : & : & : & : \;:: & : & : \\ 0 & 0 & 0 & --- & (C-1) & 1 \end{bmatrix}$$

Equation (4) is solved, to obtain the top oil temperature rise ($\Delta\theta_{on}$) for each time interval, using the standard LU decomposition method. From the array of $\Delta\theta_{on}$ values, the maximum is selected ($\Delta\theta_{omax}$) and the maximum top oil temperature (θ_{omax}) is calculated as follows:

$$\theta_{omax} = \theta_a + \Delta\theta_{omax}$$

Calculating Hot Spot

Using equation A3 of the appendix,

$\theta_h = \theta_a + \Delta\theta_{on} + \Delta\theta_{td}$

where

θ_a = Ambient temperature
θ_h = Ultimate (steady state) hot spot temperature
$\Delta\theta_{td}$ = Temperature difference between hot spot and top oil

Hot spot temperature has to be found for each time interval in the load cycle and stored in an array $[\theta_h]$. Mean monthly maximum temperature is used as ambient temperature for hot spot calculations.

Top oil temperature rise for each time interval has been calculated and is stored in an array $[\Delta\theta_{on}]$.

Temperature difference between hot spot and top oil is calculated by equation A4.

Thus the equation A3 becomes modified as equation (5).

$$[\theta_h] = [\theta_a] + [\Delta\theta_{on}] + [Hg_r K^y] \qquad (5)$$

where

Hg_r = Temperature difference between hot spot and top oil at rated current
K = Load factor during t

$$= \frac{\text{Load}}{\text{Transformer capacity}}$$

y = Winding exponent

With these calculations the maximum value of θ_h from the time intervals is found and stored as the maximum hot spot temperature for calculations (θ_{hmax}).

Calculating Ageing

Relative loss of life is calculated with reference to equations A5 and A6. To obtain this, the relative ageing rate V was integrated using the Simpson's rule.

$$\int_{t1}^{t2} V \ dt = \frac{h}{3}\{V_0 + V_n + 4(V_{odd}) + 2(V_{even})\}$$

$$= \frac{h}{3}\{2V_n + 4(V_{odd}) + 2(V_{even})\}$$

since by the characteristics of the curve of V,

$V_0 = V_n$

If the number n is taken as even, then

$$\int_{t1}^{t2} V \ dt = \frac{h}{3}\{4(V_{odd}) + 2(V_{even})\}$$

Hence,

$$\text{relative ageing } L = \frac{h}{3T}\left\{\sum 4V_{odd} + \sum 2V_{even}\right\}$$

where

L = Loss of Life in per unit days
t_1, t_2 = period under consideration; $t_2 - t_1 = T$
T = total time interval of application
V = Relative ageing rate

B4: Decrease Capacity

If all the limitations are not exceeded, the initial value of the variable 'high' is re-assigned a value

high = capacity - 1

The range of capacities that is being considered is reduced to a new range. This loop will continue till the optimum capacity is found.

B5: Increase Capacity

When any one of the limitations is exceeded, the initial value of the variable 'low' is re-assigned a value

low = capacity + 1

The range of capacities is again reduced to a new range. This loop too will continue till the optimum capacity is found.

The **Module C** in figure 2.1 finds the optimum load curve multiplier, which is described using the flow chart in figure 2.3. Important blocks of the flow chart are described in sections C1 to C3.

C1: Load Curve Multiplier (F)

The Load curve multiplier is a factor used to increase or decrease the magnitude of the load profile. To calculate the thermal parameters for the load profile, this factor is made equal to unity initially. Afterwards it is varied in order to find the set of thermal parameters, which would yield the most optimum load profile.

C2: Increase F

This is performed when all the thermal parameters are within limits. Increase of F is done in two ways.

1. If the program operation has entered this stage without performing the decrease of F, F is increased by a significant value (say 10%).
2. If the program operation has entered this stage after performing the 'decrease' of F initially, F is increased by a much smaller value (say 1%).

C3: Decrease F

Decreasing of F is performed when any of the thermal parameters have exceeded the limitations. Decrease of F is also two folds.

1. If the program operation has entered this stage without performing an increase of F, F is decreased by a significant value (say 10%) .
2. If the program operation has entered this stage after performing the 'increase' of F initially, F is decreased by a much smaller value (say 1%).

3.0 Inaccuracies In The Manual Two Step Approximation

The IEC guide requires a two step approximation with the manual method. When the profile of the load curve changes, such that a two step approximation does not follow the actual shape, the results obtained from the software become more accurate. Table 3.1 shows its excess over rated value with change in load factor of,

1. The Ultimate top oil temp. rise ($\Delta\theta_{ou}-\Delta\theta_{our}$)
2. Temperature difference between hot spot and top oil ($\Delta\theta_{td}-\Delta\theta_{tdr}$)
3. Hot spot temperature ($\theta_{h}-\theta_{hr}$)

From the table 3.1 and the corresponding graphs shown in figure 3.1 it is seen that the increase in hot spot temperature due to increase in load factor beyond 1 p.u. is considerably higher than decrease in hot spot temperature due to an equal decrease in load factor. This effect is taken into account in the software method and result in accurate results.

K	$\Delta\theta_{ou}-\Delta\theta_{our}$	$\Delta\theta_{td}-\Delta\theta_{tdr}$	$\theta_{h}-\theta_{hr}$
0.5	-24.5	-15.4	-39.9
0.6	-20.5	-12.8	-33.3
0.7	-16.1	-10.0	-26.1
0.8	-11.2	-6.9	-18.1
0.9	-5.8	-3.6	-9.4
1.0	0.0	0.0	0.0
1.1	6.2	3.8	10.0
1.2	12.8	7.8	20.6
1.3	19.7	12.0	31.7
1.4	27	16.4	43.4
1.5	34.7	21.0	55.7

Table 3.1 – Excess in Temp.rises & Hotspot temp. with load factor

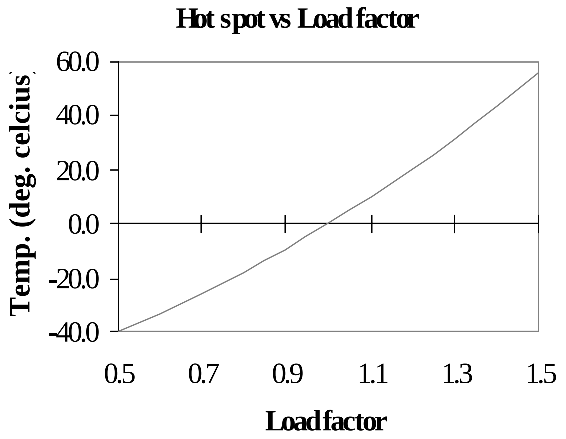

Figure 3.1 – Excess in Hotspot temperature with load factor

In the two step approximation method, the effect caused by change in load factor is linearised for changes in hot spot temperature and can thus lead to significant errors.

This inaccuracy caused by the two step approximation is further illustrated in the case studies 1 and 2.

Case Study 1

The load curve in Case Study 1 has several steps as shown in figure 3.2. Two step approximation is also shown.

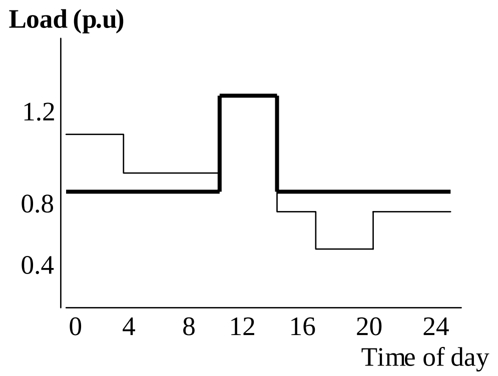

Figure 3.2 – Load curve for case study 1

Since the actual load curve is different from the approximated curve, the value for ageing obtained from software is 0.94 p.u.days, compared to the value of 0.62 p.u.days obtained from the two step curve. This inaccurate lower value of ageing from the two step curve can lead to an unexpected early damage of the transformer. If the actual load curve follows the two step curve, the software method also gives the same result of 0.62 p.u. days for ageing. This proves that the results from the software are correct.

Case Study 2

An industrial load with an installed transformer capacity of 175kVA, analysed using demand readings at 15min intervals, is shown in figure 3.3. The load curve is of a complex shape and difficult to approximate to a two-step curve. The two step approximation drawn in accordance to the guideline is also superimposed on the diagram. The results of the load curve analysis using the software package are given in Display 3.1.

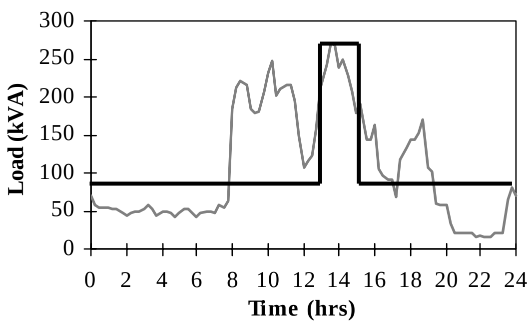

Figure 3.3 - Daily Load Profile of Industrial Load

The results with two step approximation gives 0.91 p.u days for ageing against 1.35 p.u. obtained from the software method.

T/F THERMAL PARAMETERS

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Top Oil Temperature (celcius)	: 87.75	(105)
Hotspot Temperature (celcius)	: 128.71	(140)
Loss of life (p.u. days)	: 1.35	(1)

Optimise (Y/N)? :

Display 3.1 -Thermal parameters of existing transformer at the Industrial Load

4. Effects on Performance

Some practising engineers may get the feeling that the loading of a transformer beyond its nameplate rating could give rise to problems in the distribution network, such as an unacceptable voltage regulation or a marked reduction in the efficiency of industrial loads such as induction motors. This is discussed in the following sections.

4.1 Voltage Regulation on Transformer

Analysis is made on the change in percentage voltage regulation due to loading above nameplate rating. Two transformers of 100kVA, 33kV/415V and 400kVA, 11kV/415V were considered with typical data. The standard equation[6] (6) was used for the calculation of percentage voltage regulation at a current loading of a times the rated full load current.

$$R(a) = a(V_r \cos\theta 2 + V_x \sin\theta 2) + \frac{a^2}{200}(V_x \cos\theta 2 - V_r \sin\theta 2)^2 \qquad (6)$$

where

$\theta 2$ = Power factor angle
R(a) = % voltage regulation
V_r = % resistance voltage at full load
V_x = % leakage reactance voltage at full load

The percentage voltage regulations of both transformers, at a power factor of 0.8 lagging, are plotted in figure 4.1.

The calculations show that in the 100kVA and 400kVA transformers the percentage regulation is 6.62% and 4.88% respectively even at 150% loading.

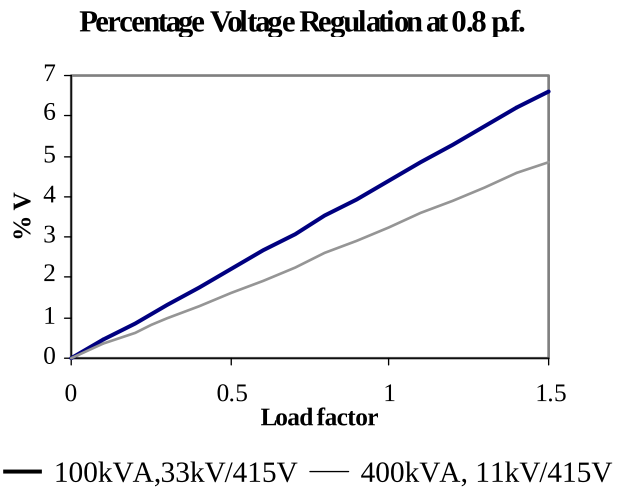

Figure 4.1 – Percentage Voltage Regulation at 0.8 p.f.

4.2 Effects on Motor Efficiency

The efficiency variation due to the reduction in terminal voltage is analysed using a 55kW Induction motor. The efficiency equation (7) used for the calculation is,

$$Efficiency = \frac{1}{\left(1 + \frac{losses}{outputpower}\right)} \tag{7}$$

The losses include the stator copper and core losses, rotor copper loss and rotational losses.

For the determination of these losses no-load and block rotor tests were carried out.

The results obtained for motor efficiency with variable terminal voltage are illustrated in table 4.2.

This indicates that even with 10% reduction in terminal voltage, the effect on the motor performance is of no significance.

Voltage, V	360	380	400
Efficiency	86.20	87.23	87.93

Table 4.2 – Variation of efficiency with reduction in terminal voltage

5. Conclusions

The software package is developed based on the standard equations given in IEC 354 guide. The software package can be applied to any complex shape of load curve. Hence this package gives a solution to the tedious manual calculations involved with complex load profiles found in reality.

The studies made shows that the results obtained for loss of life is more precise with the software package, than with manual two step approximation. This will help to reduce unexpected damage to the transformer in the future.

The practical results obtained for transformer voltage regulation shows that it has no significant effect on the distribution network at acceptable loading conditions above nameplate rating.

With regard to industrial loads such as induction motors, again the test results show that the voltage drops caused by loading transformers above nameplate rating has no major effect on its performance.

Thus it is recommended that maximum utilisation of the transformer be made allowing loading beyond nameplate rating within specified limits.

6.0 References

1. Brown P.M., and White J.P., *"Determination of the maximum cyclic rating of high-voltage power transformers"*, Power Engineering Journal, Feb 1998, pp 17-20.
2. Heathcote, M.J., *"Transformer Ratings"*, Letters to the Editor, Power Engineering Journal, Jun 1998, pp 142.
3. *"IEC 354: Loading Guide for Oil Immersed Power Transformers"* , 2nd Edition, 1991.
4. Perera KBMI, Lucas JR, Kumarasinghe KKASD, Dias RLIK, Athukorala UADR, Gunawardana PGA., "Optimisation of Transformer Design based on Load Curve", IEE Sri Lanka Annual session, September 1998.

5. Press W.H., Flannery B.P., Teukolsky S.A., Vetterling .T., *"Numerical Recipes in C"*, Cambridge University Press, 1988.

6. Heathcote Martin J., "*J & P Transformer Book*", Twelfth edition, Johnson & Phillips Ltd, 1998.

Appendix A

A.1 Loading Tables & Graphs method

In the loading tables & graphs method the load curve is approximated to a two step curve. With complex load curves the accuracy of the results depends highly on personal skills of the user.

A1.1 Method of representing an actual load cycle by an equivalent two-step cycle

To use the Tables and Graphs of the guide the daily load cycle has to be represented by a simplified load cycle as shown in figure A.1.1.

The load steps K_1 is selected as the average value of the off-peak portion of the curve while the load

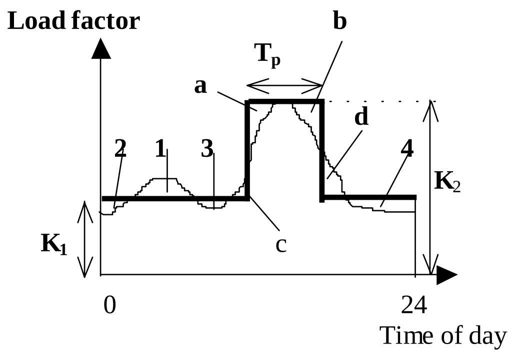

Figure A.1.1- Approximation method

where T_p = Peak duration

step K_2 is selected equal to the peak load of the curve.

i.e. Area **1** = Area **2** + Area **3** + Area **4**

The peak load duration T_p should also be selected on an area basis.

Area **a** + Area **b** = Area **c** + Area **d**

The value T_p is however restricted to a few standard values in the Table and Graph method.

A.2 Software method

The standard equations given in IEC 354 loading guide for oil immersed power transformers have been used in the software method.

A.2.1 Top Oil Temperature Rise

The oil temperature rise (e.g.: for top oil) after time interval t is given by equation A1.

$$\Delta\theta_{ot} = \Delta\theta_{oi} + (\Delta\theta_{ou} - \Delta\theta_{oi})(1 - e^{-t/\tau o}) \qquad A1$$

and the Ultimate top oil temperature rise $\Delta\theta_{ou}$ is given by equation A2.

$$\Delta\theta_{ou} = \Delta\theta_{or}\left[\frac{1 + RK^2}{1+R}\right]^X \qquad A2$$

where

R = Loss ratio = $\frac{\text{Load loss at rated current}}{\text{No load loss}}$

x = Oil exponent

$\Delta\theta_{oi}$ = Initial top oil temperature rise

$\Delta\theta_{or}$ = Top oil rise at rated current

$\Delta\theta_{ot}$ = Top oil temp. rise after time t

$\Delta\theta_{ou}$ = Ultimate top oil temp. rise corresponding to load during time t

A.2.2 Hot Spot Temperature

For ON cooling, the ultimate hot spot temperature (θ_h) under any load K can be stated as in equation A3

$$\theta_h = \theta_a + \Delta\theta_{ot} + \Delta\theta_{td} \qquad A3$$

The temperature difference between hot spot & top oil is given by equation A4

$$\Delta\theta_{td} = Hg_r K^y \qquad A4$$

It is seen that with changes in load this component of hot spot temperature also changes.

A.2.3 Thermal ageing

Relative thermal ageing rate

The relative rate of thermal ageing for transformers designed in accordance with IEC 76 is taken to be equal to unity for a hot spot temperature of 98°C.

This corresponds to operation at an ambient temperature of 20°C and a hot spot temperature rise of 78°C. The relative ageing rate is given by equation A5.

$$V = \frac{\text{ageing rate at } \theta_h}{\text{ageing rate at } 98^\circ \text{C}} = 2^{(\theta_h - 98)/6} \qquad \text{A5}$$

Hot spot rise(78°C) = Hot spot to top oil gradient (23°C) + Top oil temperature rise (55°C)

Hence for a design ambient temperature other than 20°C, the hot spot temperature rise has to be modified accordingly. For example when the design ambient is 30°C , the allowable hot spot rise is 68°C.

Loss of life calculation

The relative ageing (or relative loss of life) over a certain period of time is given by equation A6.

$$L = \frac{1}{T} \int_{t_1}^{t_2} V \, dt \qquad \text{A6}$$

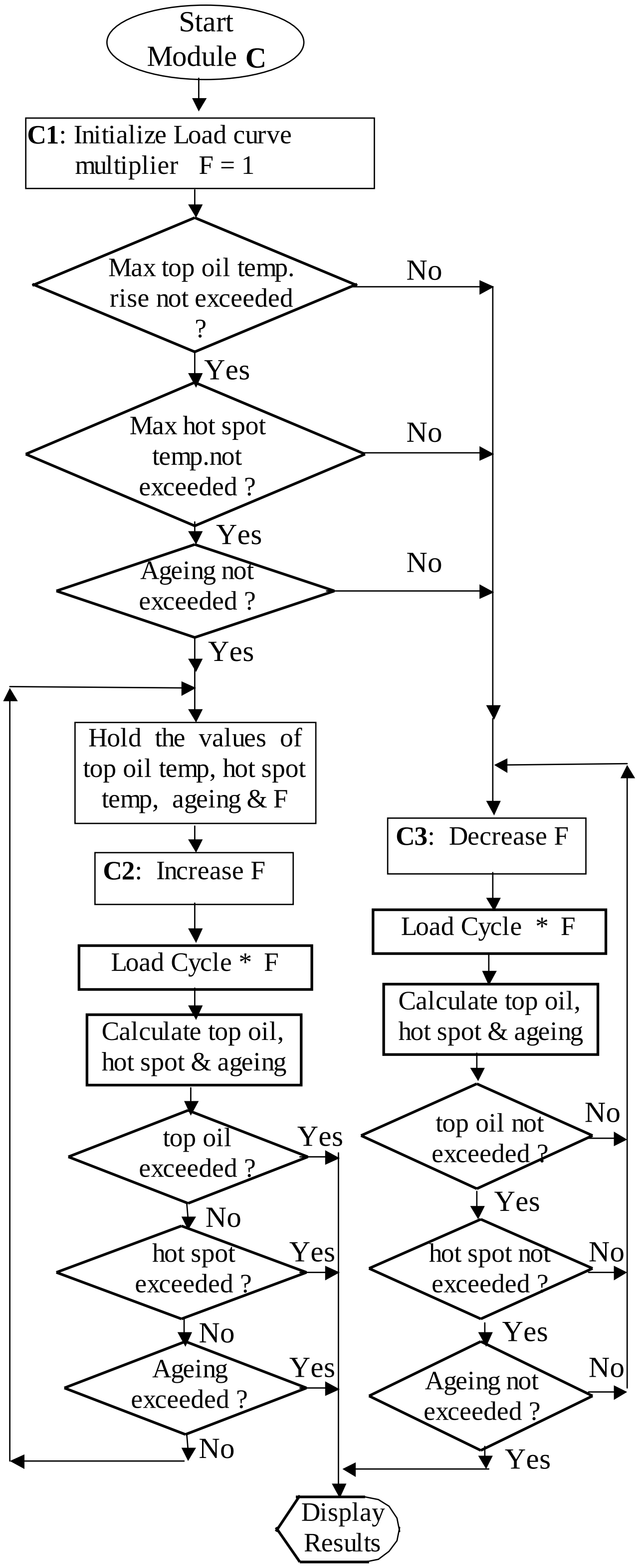

Figure 2.3 - Flow Chart for finding Optimum Load Curve Multiplier