Estimation of Optimum Transformer Capacity based on Load Curve

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Abstract: *This paper presents the development of a software package that can be used to select a transformer of optimum capacity for given loading condition and also to check the thermal parameters of an existing transformer.*

The application of a load in excess of nameplate ratings and/or an ambient temperature higher than designed, involves a degree of risk and accelerated ageing. This software package identifies such risks and indicates how, within limitations, transformers may be loaded in excess of the nameplate rating without adverse effects.

The basis of this software package is the standard equations given in the IEC 354 Loading guide for oil immersed power transformers. The program is coded in Turbo/Borland C++.

The results of the software package are shown to be accurate for any complex shape of load curve. This gives a solution to the tedious manual calculations involved with complex load profiles found in reality. The load curves analysed on several industries also give an indication of a lack of knowledge of users on the possibilities of loading a transformer beyond its name plate rating.

List of Symbols

θ_a = Ambient temperature
θ_h = Ultimate (steady state) hot spot temperature
$\Delta\theta_{oi}$ = Initial top oil temperature rise
$\Delta\theta_{on}$ = 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
$\Delta\theta_{or}$ = 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
$\Delta\theta_{oun}$ = Ultimate top oil temp. rise in n^{th} interval
$\Delta\theta_{td}$ = Temperature difference between hot spot and top oil
Hg_r = Temperature difference between hot spot and top oil at rated current
K = Load factor during t = $\frac{\text{Load}}{\text{Transformer capacity}}$
L = Loss of Life in per unit days
R = Loss ratio = $\frac{\text{Load loss at rated current}}{\text{No load loss}}$
t = time interval of application of specific load
t_1, t_2 = period under consideration; $t_2 - t_1 = T$
T = total time interval of application
T_p = Peak duration
τ_o = Oil time constant
V = Relative ageing rate
x = Oil exponent
y = Winding exponent

1. INTRODUCTION

1.1 Effects of loading beyond name plate rating

The life duration of a transformer depends to a high degree on extraordinary events, such as over-voltages, short-circuits in the system and emergency loading.
The consequences of loading[1,2] a transformer beyond its nameplate rating are as follows.

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

Due to these reasons, there will be a risk of premature failure associated with the increased currents and temperatures. This risk may be of an immediate short term nature or long term failure due to cumulative deterioration of the transformer over many years.

1.1.1 Short term risks

The reduction in dielectric strength due to the possible presence of gas bubbles in the region of high electrical stress, (i.e. the windings and leads) is the main risk for short time failures. These bubbles may develop in the paper insulation when the hot spot temperature rises suddenly above a critical temperature of about 140^0C.

The pressure build up in the bushings may result in a failure due to oil leakage & gassing in the bushings may also occur if the temperature of the insulation exceeds about 140^0C.

1.1.2 Long term risks

Cumulative thermal deterioration of the mechanical properties of the conductor insulation will accelerate at higher temperatures. This deterioration process may ultimately reduce the effective life of the transformer.
The short term risks normally disappear after the load is reduced to normal level but that will affect the reliability.

The long term risk is the reduction in the effective life of the transformer.

1.2 Scope

This software package identifies the risks involved with over-loading and indicates how, within limitations transformers may be loaded in excess of their nameplate rating. This is applicable to ONAN type distribution 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 with normal cyclic loading of duration one day. This software package provides guidance for loading of distribution transformers from the point of view of operating temperature and thermal ageing. It can be used to achieve two objectives.

- To select a transformer of optimum capacity for a given loading condition.
- To check whether an existing transformer is operating safely. i.e.

  If over-loaded how the load cycle should be reduced.

  If under-loaded how the load cycle can be changed in order to achieve the maximum usage of the transformer.

2. SELECTING A TRANSFORMER BASED ON THERMAL PARAMETERS

The method of selecting a transformer using the Tables and Graphs given in the guide[3] IEC 354 as well as using the software package developed are described in the following section.

2.1 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.

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

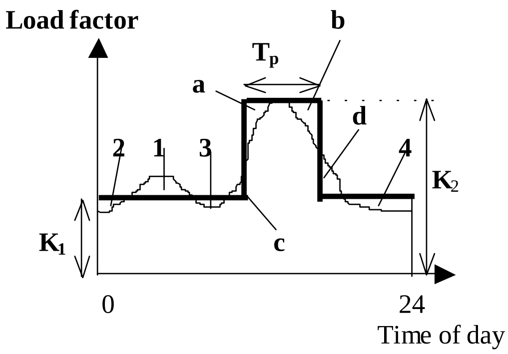

Figure 2.1.1- Approximation method

To oad cycle has to be represented by a simplified load cycle as shown in figure 2.1.1.

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

2.2 Software method

In this method the standard equations given in IEC 354 loading guide for oil immersed power transformers have been used. This method uses the actual load curve and the approximation to two steps is not necessary.

2.2.1 Top Oil Temperature Rise

Any change in load conditions is treated as a small step function. 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.

The oil temperature rise (eg: for top oil) after time interval t is given by equation (1),

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

and the Ultimate top oil temperature rise $\Delta\theta_{ou}$ is given by equation (2).

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

2.2.2 Hot Spot Temperature

For ON cooling, the ultimate hot spot temperature (θ_h) under any load K can be stated as in equation (3).

$$\theta_h = \theta_a + \Delta\theta_{ot} + \Delta\theta_{td} \qquad (3)$$

Since during one cycle of the load there are variations in the load, the simple method of using equation (2) cannot be applied to obtain top oil temperature rise and hence it cannot be substituted in equation (3) . To obtain the top oil temperature rise in each time interval of the load cycle, taking into consideration the different loads before that particular time interval, some adjustments have to be made to equation (1).

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

Then the equation (1) can be modified as equation (4).

$$\Delta\theta_{on} = \Delta\theta_{o(n-1)} + (\Delta\theta_{oun} - \Delta\theta_{o(n-1)})(1 - e^{-t/\tau o}) \qquad (4)$$

The temperature difference between hot spot & top oil is given by equation (5).

$$\Delta\theta_{td} = Hg_r K^y \qquad (5)$$

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

2.2.3 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 (6).

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

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 (7).

$$L = \frac{1}{T}\int_{t1}^{t2} V \, dt \qquad (7)$$

3. SOFTWARE DEVELOPMENT

3.1 Flow chart

The flow chart for implementing the thermal equations (1) to (7), suitably modified[4], is shown in figure 3.1.

In **Module A** of the program, the data is assigned.

In the **Module B** the optimum value of the transformer capacity is selected for a given load profile.

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

3.2 Modified calculations

<u>Calculating Top Oil</u>

Rearranging Equation (4)

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

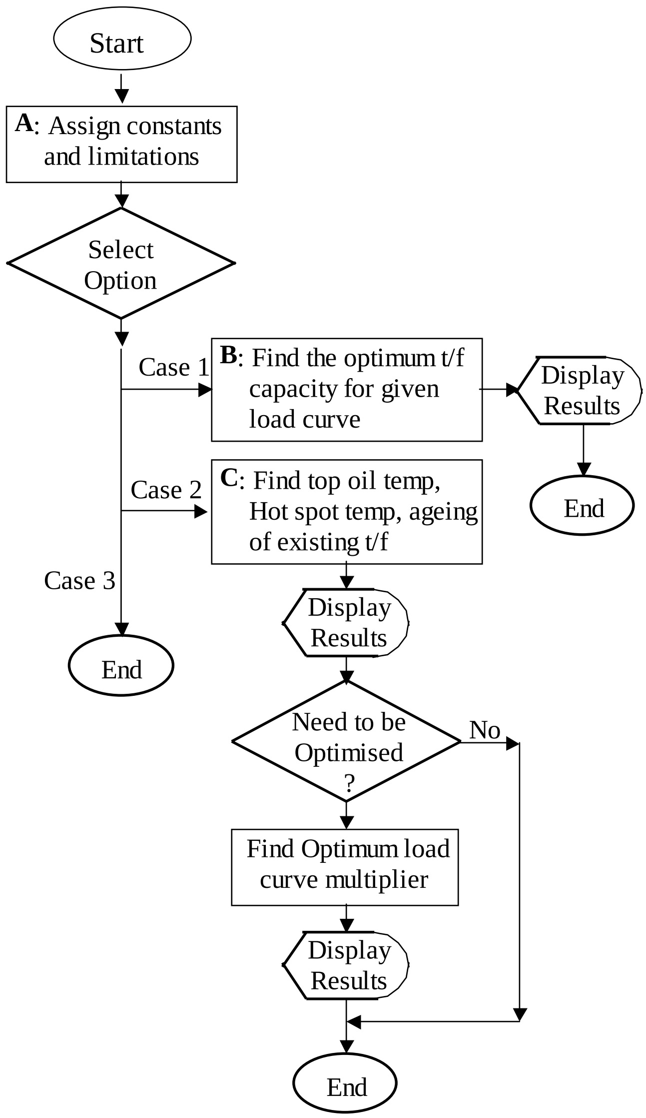

Figure 3.1 - Flow Chart

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

This gives

$$\Delta\theta_{on} = \Delta\theta_{o(n-1)}\,(1 - C) + \Delta\theta_{oun} * C \qquad (8)$$

Equation (8) can be extended to represent the total duration of the load cycle by a series of equations, which will form a matrix equation (9).

$$\begin{bmatrix} \Delta\theta_{o1} \\ \Delta\theta_{o2} \\ \\ \Delta\theta_{on} \end{bmatrix} = \begin{bmatrix} \Delta\theta_{on}^{*} \\ \Delta\theta_{o1} \\ \\ \Delta\theta_{o(n-1)} \end{bmatrix} (1 - C) + C \begin{bmatrix} \Delta\theta_{ou1} \\ \Delta\theta_{ou2} \\ \\ \Delta\theta_{oun} \end{bmatrix} \qquad (9)$$

***** *Since the load curve is of cyclic nature for the first time duration '1', the initial top oil temperature rise is equal to the final top oil temperature rise.*

Rearranging equation (9) gives equation (10).

$$[A]\begin{bmatrix}\Delta\theta_{o1}\\ \Delta\theta_{o2}\\ \\ \Delta\theta_{on}\end{bmatrix} = C\ [B] \qquad (10)$$

where

$$[A]=\begin{bmatrix}1 & 0 & 0 & \text{--------} & (C-1)\\ (C-1) & 1 & 0 & \text{--------} & 0\\ 0 & (C-1) & 1 & \text{--------} & 0\\ \\ 0 & \text{------------} & 0 & (C-1) & 1\end{bmatrix},[B] = \begin{bmatrix}\Delta\theta_{ou1}\\ \Delta\theta_{ou2}\\ \\ \Delta\theta_{oun}\end{bmatrix}$$

Equation (10) is solved using LU Decomposition method, to obtain the top oil temperature rise ($\Delta\theta_{on}$) for each time interval. 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

With reference to equation (3)

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

Hot spot temperature has to be found for each time interval in the load cycle and stored in an array [θ_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 are stored in an array [$\Delta\theta_{on}$], described earlier.

Temperature difference between hot spot and top oil is calculated by equation (5).

Thus the equation (3) becomes modified as equation (11).

$$[\theta_h] = [\theta_a] + [\Delta\theta_{on}] + [Hg_r K^y] \qquad (11)$$

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 (6) and (7). To obtain this the function 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,

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

4. CASE STUDIES & JUSTIFICATION

Program testing plays an important role in the software development life cycle. Hence, in order to justify the results of this software package, the following cases were studied.

For case 1 and case 2, the transformer capacity is taken as 1.0 p.u. These analyses are valid for any kVA rating.

Case 1

This is a two step load with load steps of 0.8 & 1.1p.u. as illustrated in figure 4.1. In this case the values obtained for hot spot temperature (108^{0}C) & loss of life (0.74 p.u days) from both methods are found to be the same.

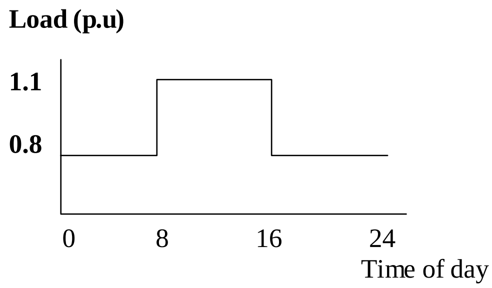

Figure 4.1 – Load curve for Case 1

Case 2

The load curve in Case 2 has several steps as shown in figure 4.2. When approximated to two steps, it is similar to Case 1.

Since the actual load curve is different from the approximated curve, the value for ageing obtained from software is 0.93 p.u.days, compared to the value of 0.74 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 damage..

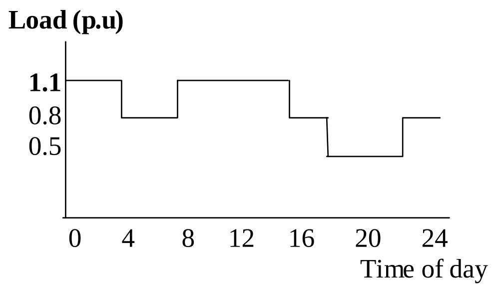

Figure 4.2 – Load curve for Case 2

Case 3

Several industrial loads were also analysed with the software developed. Two of them are discussed here.

The load curve of Lanka Transformers Limited (LTL) was obtained using demand readings at 15min intervals as shown in figure 4.3. The load curve thus obtained is of a complex shape and difficult to approximate to a two-step curve. The results of the load curve analysis using the software package is given in Display 4.1.

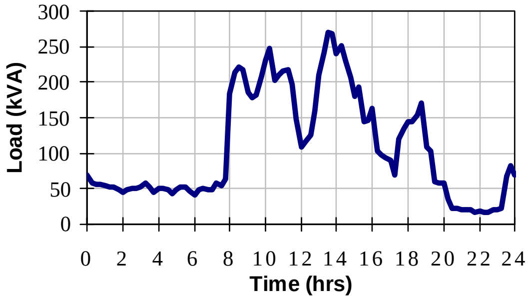

Figure 4.3 - Daily Load Profile of LTL

OPTIMIZED PARAMETERS		
Top Oil Temperature (celcius)	: 86.0691	(105)
Hotspot Temperature (celcius)	: 125.581	(140)
Loss of life (p.u.days)	: 0.979328	(1)

OPTIMIZED TRANSFORMER CAPACITY **180 kVA**

Display 4.1 - Optimum Transformer parameters for LTL

The results in Display 4.1 shows that the required transformer capacity which satisfy all thermal parameters is of 180kVA.

The actual supply transformer in operation at Lanka Transformers is however of capacity 400kVA. It is seen to be much more than required. The data were then analysed with option 2 of software package, and the results obtained are given in displays 4.2 and 4.3.

T/F THERMAL PARAMETERS		
Top Oil Temperature (celcius)	: 53.8316	(105)
Hotspot Temperature (celcius)	: 106.662	(140)
Loss of life (p.u. days)	: 0.323399	(1)

Optimise (Y/N)? :

Display 4.2 – Thermal parameters of existing transformer at LTL

OPTIMIZED PARAMETERS		
Top Oil Temperature (celcius)	: 86.1468	(105)
Hotspot Temperature (celcius)	: 125.725	(140)
Loss of life (p.u.days)	: 0.993953	(1)
Load Curve Multiplier	: 2.237	

Display 4.3 - Load curve multiplication possibility to existing load profile at LTL

The results indicate that the existing transformer is under utilised and the load curve multiplier is 2.23 for optimum utilisation.

Case 4

The load curve of another industry and its data analysis is illustrated in figure 4.4 and display 4.4

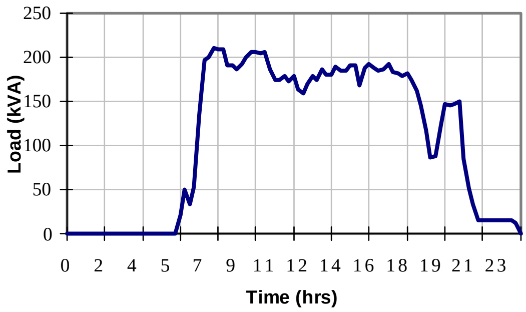

Figure 4.4 - Load Profile of an Industry

OPTIMIZED PARAMETERS		
Top Oil Temperature (celcius)	: 84.1615	(105)
Hotspot Temperature (celcius)	: 113.39	(140)
Loss of life (p.u.days)	: 0.96342	(1)

OPTIMIZED TRANSFORMER CAPACITY **165 kVA**

Display 4.4 - Optimum Transformer parameters

The results are similar in this case too. The required transformer capacity is 165kVA, where as installed capacity is 400kVA, which is much more than required.

It is to be noted that this does not however take into account the increased capacity usually installed to cater for unforeseen loads and future expansion.

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5. CONCLUSION

From the study carried out (Case 1), it is evident that the results obtained from both software & tables are the same when the load curve is of two-step nature. However, as can be seen (Case 2) with a load curve of several steps the table and graph method cannot give sufficiently accurate results for loss of life as from the package.

This is because of the change in hot spot temperature is not linearly proportional to change in load factor, which is considered equal in the two step method. As the software package is developed based on the standard equations given in IEC 354 guide, the results of the software package are accurate for 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.

Finally Case studies 3 and 4, give an indication of under utilisation of transformers by users due to the lack of knowledge on the possibilities of loading a transformer beyond its name plate rating.

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