SOFTWARE GUIDED SAFE LOADING OF TRANSFORMERS

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SYNOPSIS

Accelerated ageing occurs in transformers when loads exceed nameplate ratings or ambient temperature exceeds the design value. A software package has been developed by the authors based on IEC 354: *Loading guide for oil immersed power transformers*. It identifies the risks involved and indicates how transformers may be loaded in excess of the nameplate rating (abnormal loading) without adverse effects for specific load curves.

A matrix formulation of top oil temperature allows a near continuous load curve simulation. The relative ageing rate is calculated using Simpson's rule. Results of the package agree exactly with the two step approach specified in the Loading guide for two step load curves. However, it is shown that the two step approximation gives somewhat inaccurate results for certain practical complex load curves. Thus use of the package could minimise unexpected future damages to transformers.

Calculations have been done based on practically obtained data to determine the excess voltage regulation introduced by the abnormal loading and the variation of efficiency of a practical induction motor within this range of voltages. These show that there is no adverse effect on motor efficiency. In addition other general effects of voltage regulation on induction motor characteristics were also considered with the guidance of IEEE standard 141:1993. This shows that while there is no significant change in the full load speed and efficiency the starting and running torque varies as the square of the voltage and can drop to about 81% at a maximum possible voltage drop of 10%.

1. INTRODUCTION

It is well known that accelerated ageing occurs when a transformer is overloaded and when the ambient temperature increases above normal. The standard *IEC 354: Loading guide for oil immersed power transformers* [1] indicates how transformers may be loaded in excess of the nameplate rating (abnormal loading) for load curves with a two step approximation. Based on this guide, a software package [2] has already been developed to provide guidance for daily cyclic loading of ONAN type distribution transformers without on-load tap changing complying with IEC 76: Power Transformers. This package indicates how transformers, with a maximum rating of 2500 kVA three phase and high voltage 33 kV, may be loaded in excess of their nameplate rating, within limitations. It can also be used to select a transformer of optimum capacity for a given loading condition and to check the utilisation of an existing transformer.

A distribution transformer is usually rated 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. It has been identified that the consequences [3,4] of loading a transformer beyond name-plate rating are (i) the temperatures of windings, insulation, oil etc. increase and can reach unacceptable levels, (ii) the leakage flux density outside the core increases, causing additional eddy current heating in metallic parts linked by the flux, (iii) the moisture and gas content in the insulation and in the oil increase with the temperature increase, and (iv) bushings, tap-changers, cable-end connections and current transformers are exposed to higher stresses. 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.

2. EFFECT OF THERMAL PARAMETERS ON TRANSFORMER LOADING

The IEC 354 - Loading guide for oil immersed power transformers gives the method of selecting a transformer based on its thermal parameters using Tables and Graphs. The equations given in this standard have been suitably modified and used in the software method. The main thermal parameters are the temperature rise of the top oil, hot spot temperature and ageing.

2.1 Top Oil Temperature Rise

According to the standard, the top oil temperature rise $\Delta\theta_{ot}$, after time interval ‘ t’, is given by equation (1).

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

where $\Delta\theta_{oi}$ = Initial top oil temperature rise, τ_o = Oil time constant and the Ultimate top oil temperature rise $\Delta\theta_{ou}$ is given by equation (2).

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

where $\Delta\theta_{or}$ = Top oil rise at rated current, K = Load factor during 't' = $\frac{\text{Load}}{\text{Transformer capacity}}$,

R = Loss ratio, and X = oil exponent

2.2 Hot Spot Temperature

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

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

where θ_a is the ambient temperature. The temperature difference between hot spot and top oil $\Delta\theta_{td}$ is given by equation (4).

$$\Delta\theta_{td} = Hg_r K^y \qquad (4)$$

where Hg_r = Temperature difference between hot spot and top oil at rated current

and y = winding exponent

It is seen that with changes in load both the top oil temperature rise as well as the hot spot temperature changes.

2.3 Thermal ageing

Thermal ageing is the deterioration of the insulation due to thermal processes. For derating purposes, what is important is the relative rate of thermal ageing. For transformers designed in accordance with IEC 76, it 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 (5).

$$V = \frac{\text{ageing rate at } \theta_h}{\text{ageing rate at } 98^\circ\text{C}} = 2^{(\theta_h - 98)/6} \qquad (5)$$

IEC354 gives the hot spot to top oil temperature gradient as 23°C, so that

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

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 temperature is 30°C , the allowable hot spot rise is 68°C.

The relative ageing (or relative loss of life) over a certain period of time is given by equation (6).

$$L = \frac{1}{T}\int_{t_1}^{t_2} V \, dt \qquad (6)$$

where L = Loss of Life in per unit days; t_1, t_2 = period under consideration;

$t_2 - t_1$ = T = total time interval of application; and V = Relative ageing rate

2.4 The Manual Two Step Approximation

The IEC guide requires a two step approximation to the Load Curve with the manual method (Figure 2.1). The load step K_1 is selected as the average value of the off-peak portion of the curve such that

area **1** = area **2** + area **3** + area **4**

while the load step K_2 is selected equal to the peak load of the curve. The duration of the peak $\mathbf{T_p}$ is calculated such that

area **a** + area **b** = area **c** + area **d**

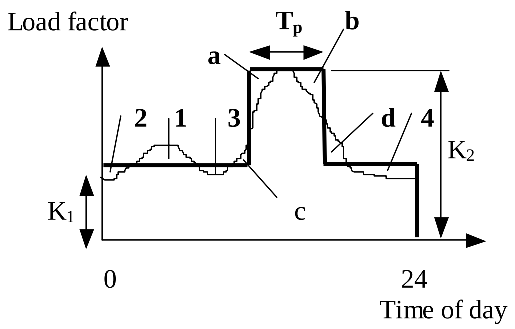

Figure 2.1- Two-Step Approximation method

When the profile of the load curve changes, such that a two step approximation does not follow the actual shape, the two step approximation ceases to be accurate. A software method then becomes a necessity as it models all levels of load steps and thus becomes more accurate .

3. DEVELOPMENT OF THE COMPUTER PROGRAM

Figure 3.1 shows the main flow chart for implementing the equations for determining the top oil temperature rise, the hot spot temperature and the thermal ageing [equations 1 to 6], suitably modified for repetitive calculations.

In Module A, the optimum value of the transformer capacity required is selected for a given load profile. In Module B the set of thermal parameters and the optimum load curve multiplier are determined for an already installed transformer.

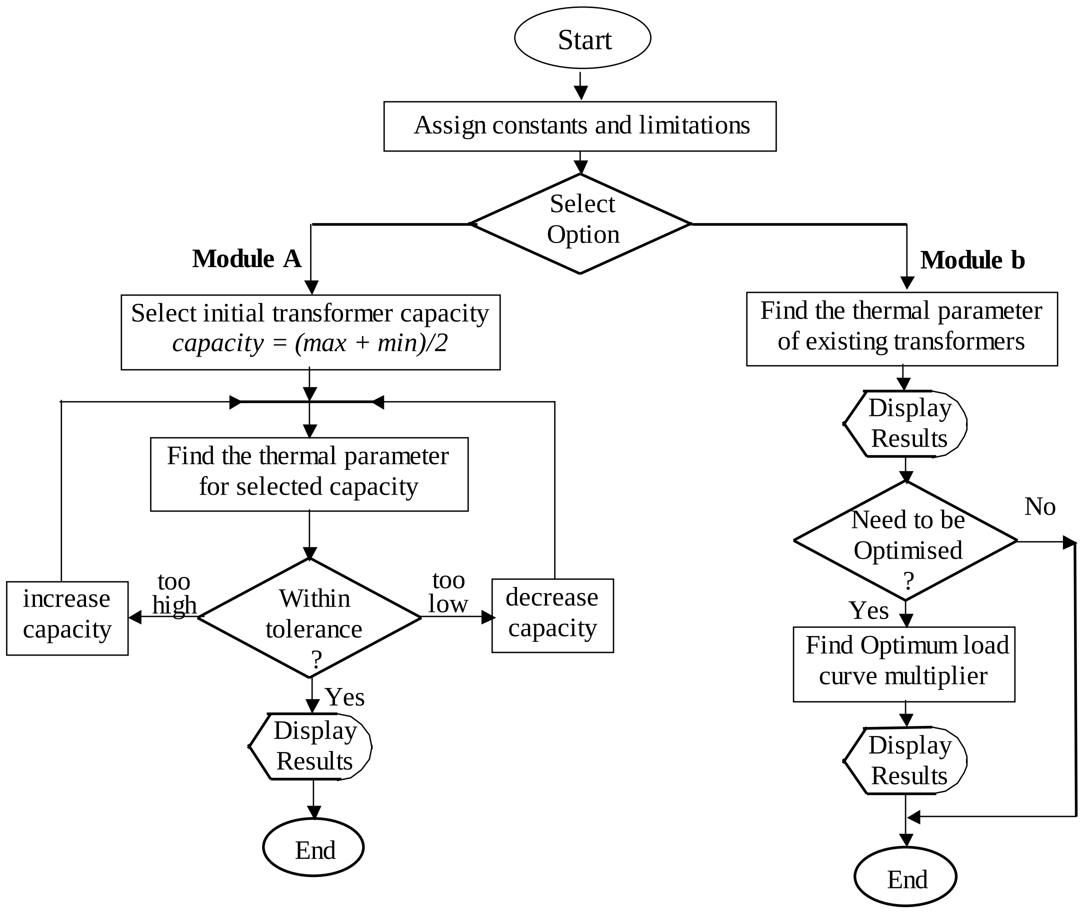

Figure 3.1 - Flow Chart for thermal parameters

3.1 Calculation of the Top Oil & Hot Spot Temperatures

In the formulation, any change in the load conditions is treated as a small step change. Therefore for a continually varying load, a step function has to be applied over small time intervals, throughout the load cycle. A computer program thus eases the burden of calculating the thermal parameters throughout the load cycle.

To obtain the top oil temperature rise in each time interval of the load cycle, some adjustments have to be made to the equation (1), taking into consideration the different loads before that particular time interval.

Consider a load cycle with equal time intervals, each of duration 't' (Figure 3.2). 't' is selected corresponding to availability of data.

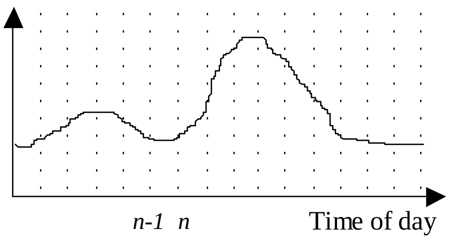

Figure 3.2 Load Curve

For this the equation (1) can be modified as equation (7).

$$\Delta\theta_{on} = \Delta\theta_{o(n-1)} + (\Delta\theta_{oun} - \Delta\theta_{o(n-1)})(1 - e^{-t/\tau o}) \qquad (7)$$

Rearranging Equation (7)

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

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

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

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

Equation (8) can be extended to represent the total duration of the load cycle by a series of equations, which will form the 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 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 (9) gives equation (10).

$$\begin{bmatrix} 1 & 0 & 0 & --- & 0 & (C-1) \\ (C-1) & 1 & 0 & --- & 0 & 0 \\ 0 & (C-1) & 1 & --- & 0 & 0 \\ : & : & : & :\ :\ : & : & : \\ 0 & 0 & 0 & --- & (C-1) & 1 \end{bmatrix} \begin{bmatrix} \Delta\theta_{o1} \\ \Delta\theta_{o2} \\ \Delta\theta_{o3} \\ : \\ \Delta\theta_{on} \end{bmatrix} = \boldsymbol{C} \begin{bmatrix} \Delta\theta_{ou1} \\ \Delta\theta_{ou2} \\ \Delta\theta_{ou3} \\ : \\ \Delta\theta_{oun} \end{bmatrix} \qquad (10)$$

Equation (10) 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:

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

The ultimate hot spot temperature θ_h is calculated using equation (3)

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

The hot spot temperature has to be found for each time interval in the load cycle and stored in an array [θ_h]. The mean monthly maximum temperature is used as the ambient temperature for hot spot calculations.

Top oil temperature rise for each time interval is calculated and is stored in an array [$\Delta\theta_{on}$]. The temperature difference between hot spot and top oil is calculated by equation (4). 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}).

3.2 Calculation of Ageing

Relative loss of life is calculated with reference to equations (5) and (6). To obtain this, the relative ageing rate V was integrated using the Simpson's rule.

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

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

3.3 Load Curve Multiplier

The Load curve multiplier (F) 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.

If all the parameters are within limits, F is increased by a fine or coarse increment dependant on whether a previous decrease has been made or not. Similarly, if any of the thermal parameters have exceeded the limitations, F is decreased by a fine or coarse increment.

3.4 Case Studies

3.4.1 Variation of hot spot temperature with load factor

The variation of the excess temperature rise and hot spot temperature can be determined for standard operating conditions ($\Delta\theta_{our} = 55^oC$, $\Delta\theta_{tdr} = H_{gr} = 23^oC$, R = 5, x = 0.8, y = 1.6) of IEC354 using equations (2) and (4) and addition of the 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 temperature rises and hotspot temperature with load factor

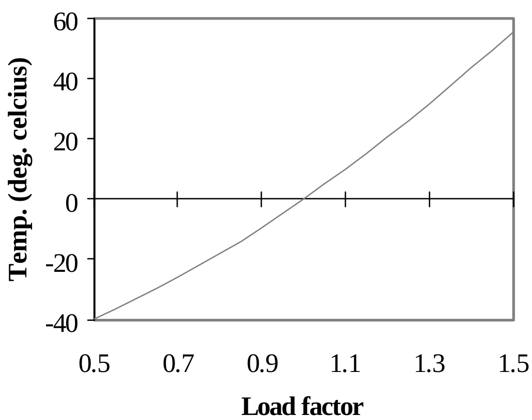

Figure 3.3 – Excess in Hotspot temperature with load factor

Table 3.1 shows the excess in the Ultimate top oil temp. rise ($\Delta\theta_{ou}-\Delta\theta_{our}$), the temperature difference between hot spot and top oil ($\Delta\theta_{td}-\Delta\theta_{tdr}$), and the hot spot temperature ($\theta_h-\theta_{hr}$), over rated value with change in load factor. From the table and the corresponding graph shown in figure 3.3 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 .

3.4.2 Inaccuracy of the two step approximation

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 as has been observed by the several case studies performed. This inaccuracy caused by the two step approximation is illustrated by a sample case study presented.

An industrial load with an installed transformer capacity of 175kVA, analysed using demand readings at 15min intervals, is shown in figure 3.4. 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 IEC 354 guideline, is superimposed on the diagram. The results of the load curve analysed using the software package are given in Display 3.1.

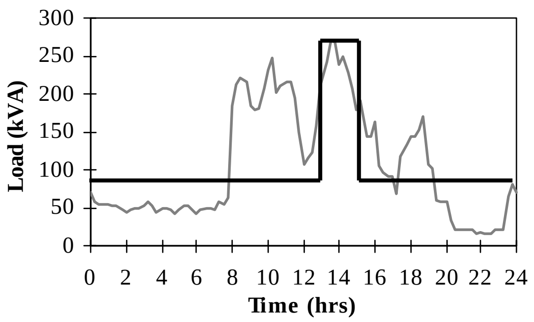

Figure 3.4 - Daily Load Profile of Industrial Load

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

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

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 (12) was used for the calculation of percentage voltage regulation [5] at a current loading of *a* times the rated full load current .

$$R(a) = a(V_r \cos\theta 2 + V_x \sin\theta 2) + \frac{a^2}{200}(V_x \cos\theta 2 - V_r \sin\theta 2)^2 \quad (12)$$

where

θ2 = 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.

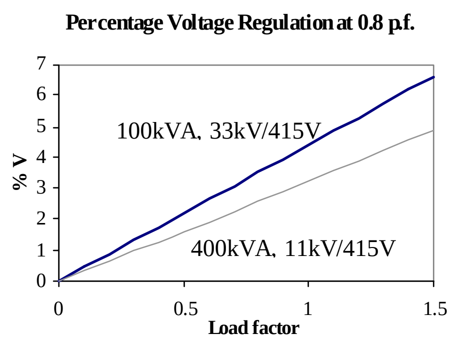

Figure 4.1 – Percentage Voltage Regulation at 0.8 pf

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

4.2 Effects on Motor Efficiency

It was observed in section 4.1 that the voltage regulation increases when the load factor increases. The variation in efficiency in motor loads due to this reduction in terminal voltage is presented in this section using a 55 kW squirrel cage type induction motor. The efficiency equation (13) used for the calculation is

$$\text{Efficiency} = \frac{1}{\left(1 + \dfrac{\text{losses}}{\text{output power}}\right)} \qquad (13)$$

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

For the determination of these losses, the tests carried out were the no-load test, short circuit test, ohmic resistance when cold and hot stage and the total loss readings at variable voltage and constant power output. The parameters for the equivalent circuit (figure 4.2) were found using these data.

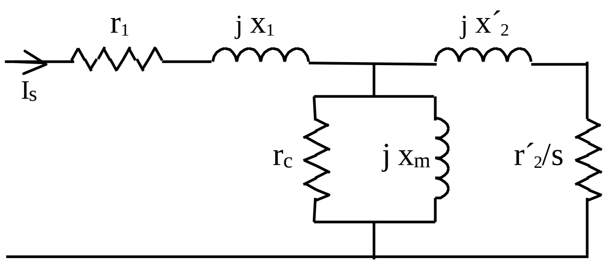

Figure 4.2 - Equivalent circuit used for the induction motor

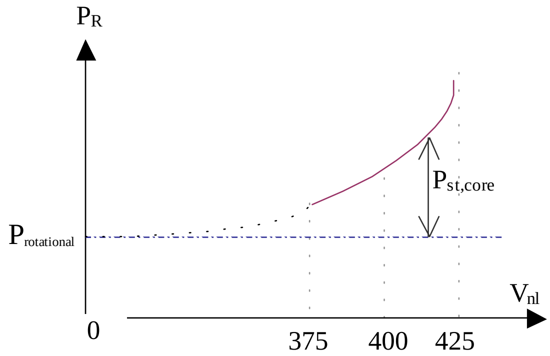

Figure 4.3 - Variation of rotational loss with voltage

The rotational loss was found using the loss readings at different voltages and extrapolating the graph as shown in figure 4.3.

The full-load efficiency calculation was then carried out with a Thevenin's equivalent circuit for a range of terminal voltages and the results are illustrated in figure 4.4. This indicates that even with 10% reduction in terminal voltage, the effect on the motor efficiency is of no significance (less than 2%).

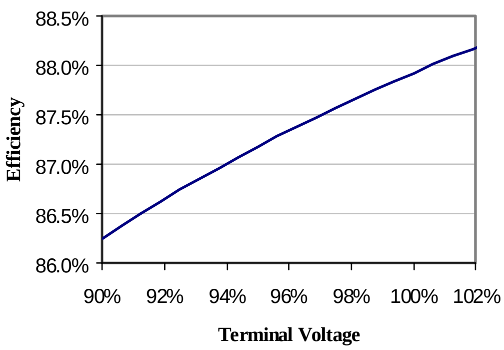

Figure 4.4 - Variation of full-load efficiency with a reduction in terminal voltage

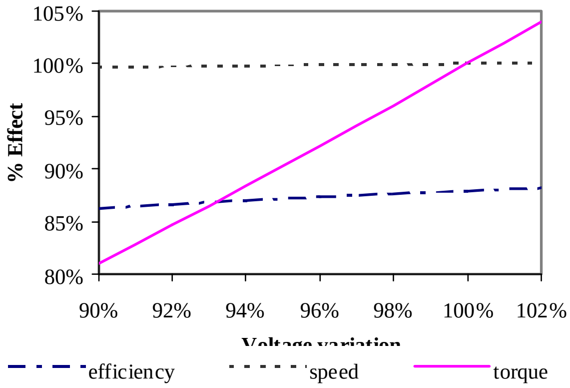

Figure 4.5 – Variation of motor performance with reduction in terminal voltage

IEEE Standard 141:1993 gives the general effect of voltage variations on induction motor characteristics. The performance for voltage reductions down to 10% are shown in figure 4.5.
It is seen that the full-load efficiency variation is and the full-load speed variations are insignificant. However the starting and maximum running torque decreases to about 81% at a maximum voltage reduction of 10%. This is because the torque is proportional to the square of the 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 other than for the reduction in the starting and maximum running torque.

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

6.0 REFERENCES

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