TRANSFORMER MAINTENANCE, LOADING AND RELIABILITY

A DISSERTATION

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requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(System Engineering and Operation Research)

By

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CERTIFICATE

Certified that the dissertation entitled "TRANSFORMER MAINTENANCE, LOADING AND RELIABILITY" which is being submitted by Shri.T.B. Singh in partial fulfilment for the award of Master of Engineering degree in "System Engineering & Operation Research" of the University of Roorkee, Roorkee, is a record of student's own work carried out by him under our supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is to further certify that he has worked for a period of one and half year from October, 1984 to March, 1986.

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ABSTRACT

The substation is serving a load demand of a geographical defined area. When load demand of the area is increased, substation modification is required. The substation planner is having two alternatives, either existing facilities may be over loaded or extra facilities may be added earlier before load growth. Since transformer is a costly piece of equipment in a substation, transformer loading, maintenance and reliability should be studied carefully, so that maximum benefit is derived from the investment on the transformer.

Transformer loading limits are mainly due to thermal limits. In practice, these limits are not experienced most of the time and ambient temperature conditions are less most of the period. So there is always a margin available to overload the transformer. When overloading is done proper maintenance is required and health of the transformer can be estimated by conducting tests recommended by manufacturers and users.

Optimal transformer loading has to be decided after quantifying and analysing the cost structure for the available alternative. The costs involved are capital cost of the transformer, repair and replacement cost, maintenance and testing cost, failure cost, energy loss cost, interest on capital, depreciation and salvage value. The mathematical optimization technique i.e., Dynamic programming is used for making decision at each stage (year). Finally the optimal transformer loading policy, for a given example, is found to be 110% of the name plate rating.

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NOTATIONS

a	Age of transformer
A_n	Addition of transformer in year n
$C_n(X_n, A_n)$	Total cost of owing and operating transformer in year n
CC(n)	Capital cost in year n
d	Ratio of load loss to no load loss
FC(n)	Failure cost in year n
IR	Interest rate
K	Load MVA in fraction of rated MVA
LL(t)	Life loss in time t
Lmin	Minimum loading limit
Lmax	Maximum loading limit
LL	Load loss in KW/transformer
MC(n)	Maintenance cost in year n
n	Year of study
N	The horizon period
PE	Price escalation
$P_{RF}(n, a)$	Probability of failure in year n of age a
$Q_n(X_n, A_n)$	Total cost upto year n
S	Replacement cost in fraction of capital cost
T_O	Rated oil temperature-rise
T_W	Rated hot-spot temperature rise
V	Relative rate of using life
X_n	Available capacity in year n
n	
1	Failure rate due to insulation loss of life
2	Failure rate due to other causes
θ_a	Weighted ambient temperature
θ_{oa}	Rise of oil temperature over ambient
θ_{wo}	Rise of winding temperature over ambient

CONTENTS

CHAPTER I

INTRODUCTION

An electric power substation usually serves a geographically defined area. As the load grows in an area transformers and other associated equipments may load to a limit when substation and area modification are required. If this growth phenomenon is considered from a substation view point, two primary alternatives are available to the planners which is described as:

(a) The existing station facilities may be loaded higher reducing the reliability of equipment and increasing the probability (risk) of suddenly curtailing the load.

(b) Facilities may be added earlier such as new transformer capacity more spares, faster repair and installation facilities new station resulting higher availability and lower risk environment with associated penalty of additional investment.

Therefore, for alternative selection it is required to determine the economic consequences of various loading policies and to minimize the total cost of owing & operating transformers to meet demand with acceptable levels of service reliability. Transformer life is mainly considered since transformer usually represents the most costly piece of equipment in a substation.

The thermal loading limits of electrical transformers are determined by the hot-spot winding temperature, generated through power losses within a transformer. Guidelines for loading and relationship between overloads and expected service life, are reported in several published standards and the technical papers.

Beavers [4] had reported in 1964 that Ammerican Standards Association loading guide are conservative for distribution transformers. This is also generally confirmed by users and manufacturers based on field experience. He reported that a more realistic life versus temperature relation ship would be represented by chemical reaction theory i.e. Arrhenius relationship. Using this relationship and the transient temperature or commulative aging procedure, the estimated loss of life is approximately one-half to one-sixth that obtained by assuming the constant temperature, peak duration and using ASA loss of life curve, Which is based on expectancy of 7 years at a contineous 95°C hot-spot temperature and load time combinations were based, on the assumptions that each of these combinations produces the same amount of aging per cycle as 1 day at 95°C.

Acker [1] had reported in September 1964 loading guide for 65°C rise distribution transformers. He had taken transformer loss of life expectancy of 30 years at a contineously sustained hot-spot temperature of 120°C. Hot-spot temperature curves were calculated for loads from 90% to 280% in ambient temperatures from 0°C to 50°C. The change in time constant with changing loads was considered.

Thus Hot-spot temperature curves were converted to aging factor curves. He compared area under the aging factor curve with a standard area representing a hot-spot temperature of 120°C contineously sustained for 24 hours. Thus transformer load capability table was presented.

Again in 1969, Beavers [2] had reported the equation for life expectancy, or loss of life Vs temperature relationship based on Arrhenius Law for thermal aging. He formulated a relationship for calculating a constants of Arrhenius law which is previously supplied by charts or graphs.

Ossman and his colleague [6] had reported in 1969 the analytical and probability techniques for evaluation of substation expansion plan and transformer loading policies. They developed a method for calculating the probabilities of exceeding of maximum transformers temperatures and the expected loss of transformer life utilizing local historical substation load and ambient temperatures environmental conditions. Alternate substation expansion plans to meet forecast of area load demand were compared on the basis of cost versus reliability.

Blake&Kelly [5] had develope a mathematical relation for calculation of overload of a oil immersed power transformer. They had given comprehensive discription of the philosophy of overloading, transformer life curves, and a working method of calculation incorporating these factors with increased accuracy and reduced time. Recommendations are made regarding life curves, ambient temperature selection, resistance correction for temperature variation and daily load cycle evaluation.

Bae, Adkins and Bree [2] had develop a method which quantitatively define the total cost of owing and operating the transformer where the total cost includes both the capital cost and loss cost as well as cost incurred due to increased loss of life of transformer due to overloading throughout the expected life of transformer. They framed the problem in state transition matrix and calculate the probability of failure for each state. They were using a hit and trail method for deciding the policy cost using different loading limits (i.e. LMIN & LMAX) and for different type of cooling. They had suggested that to increase the minimum peak load level and loading the transformer more than this value.

In chapter II for calculating the hot-spot temperatur rise for overloads with specified load cycle curve and other limiting factors. Normal life of transformer is taken 40 years on the basis of Acker [1] suggestion and aging of insulation slightly modified by Arrhenius to Montsinger relation which is based on field experience.

The maintenance and test recommendations rather than normal routine maintenance when transformer being overloaded is described in chapter III. The test results are useful for predictions of transformer health before going to sudden failure.

A method to determine the optimal loading of the transformers has been developed in chapter IV. Dynamic programming has been used for determining the optimal policy for adding the transformer during the course of time and their over loading.

CHAPTER II

TRANSFORMER LOADING

2.1 INTRODUCTION

The transformer installed in a substation usually serves a area which having the different types of loads like residential and industrial load. As the load demand grows in that area the transformers and other associated equipments may be loaded beyond a limit for which they are designed for normal operation. Since transformer is costly piece of equipment so more attention is given on transformer loading.

The transformers are designed to carry continuously the rated load at certain specified ambient temperature and output is almost limited by hot-spot winding temperature. Whereas accessories like tape changers and bushing etc. are having mechanical and electrical limitations. Before going to overload a transformer its accessories is capable to withstand this overloading. The selection of the permissible maximum safe operating temperatures for transformers would be comparatively simple indeed, if transformer insulation possessed a critical temperature above which very rapid deterioration takes place. However, since deterioration takes place practically at all temperatures and amount of deterioration is a function of time and temperature. It is impracticable to fix the exact allowable temperature above which transformers should not be allowed to operate. When insulation of transformer is subjected to high temperature for long duration the reduction of life of insulation is more. Therefore, insulation can be subjected to relatively high temperature provided that their duration is sufficiently short. It is this fact that make it possible to operate transformer at frequent but short intervals, such as emergencies, transformer insulation can be subjected to still higher temperatures without any damage to insulation. Transformer can safely carry, for few seconds, short circuit currents with resulting temperature as high as 250°C [9]

In this chapter a procedure to determine the hot-spot winding temperature θ_C and relative rate of using life of insulation is described. Some practical considerations for overloading are discussed. Lastly the merits of overloading and guidelines are given.

2.2 THERMAL LOADING LIMITS

The thermal loading limit of electrical transformers are determined by hot-spot winding temperature through power losses within the transformer. The hot-spot winding temperature should not increase more than 140°C. This temperature is calculated according to the load curve of the transformer. The hot-spot temperature of the winding is the sum of the oil temperature rise, hot-spot temperature of the winding above oil and ambient temperature i.e.

$$\theta_C = \theta_{oa} + \theta_{wo} + \theta_a \qquad \ldots(2.1)$$

The steady state top oil rise for constant load K is given by following relation:

$$\theta_{oa} = T_o \left[\frac{1+dK^2}{1+d} \right]^x \qquad ...(2.2)$$

Where

x = 0.8 for self cooled transformer

= 0.9 for forced air cooled transformer

= 1.0 for forced oil forced air cooled transformer

The steady state of hot-spot rise above oil for constant load K is given by

$$\theta_{wo} = (T_w - T_o)\ (K^2)^x \qquad ...(2.3)$$

The top oil temperature at any time t after the change in load is given by

$$\theta_{oa}(t) = \left[\theta_{oa}(\infty) - \theta_{oa}(0)\right](1-e^{-t/\tau}) + \theta_{oa}(0) \qquad ...(2.4)$$

Now the hot-spot winding temperature θ_C is calculated form equations (2.1 to 2.3). The value of the θ_{wa} so calculated should not exceed the prescribed limit of 140°C.

2.3 LOSS OF LIFE OF INSULATION

Experience shows that insulation subjected to temperature over prolonged periods losses its elasticity, gets brittle and crackes even under low mechanical stresses which always takes place when a transformer is in operation.

It results in a failure of electrical insulation and damage to the transformer. The mechanical strength of insulation is measured by a tensile or bending test.

The lift of insulation as affected by deterioration due to temperature and time is given by the Arrhenius as

$$\text{Life} = e^{\left(A + \frac{B}{T_C}\right)} \qquad \ldots (2.5)$$

Where A and B are constants and T_C is the hot-spot temperature in OK. In the range of 80°C to 140°C this law can be expressed by the more convenient Montsinger relation as

$$\text{Life} = e^{-p\,\theta_C} \qquad \ldots (2.6)$$

Most of the investigators agree that over the range of 80°C to 140°C, the rates of using life of transformer is doubled for every temperature increase of 6°C and that insulation deterioration occurs at normal rate at the winding hot-spot temperature of 98°C. The periods of accelerated ageing when the hot-spot temperature is greater than 98°C are compensated by the periods of slow aging when the hot-spot temperature is less than 98°C.

The relative rate of using life at any hot-spot temperature compared with the normal rate of using life at rated hot-spot temperature of 98°C can be written by using equation (2.5) as follows:

$$V = \frac{\text{Rate of using life at } \theta_C}{\text{Rate of using life at } 98^{\circ}C}$$

$$= e^{0.693 \frac{(\theta_C - 98)}{6}}$$

$$= e^{0.1155 (\theta_C - 98)} \qquad \ldots(2.7)$$

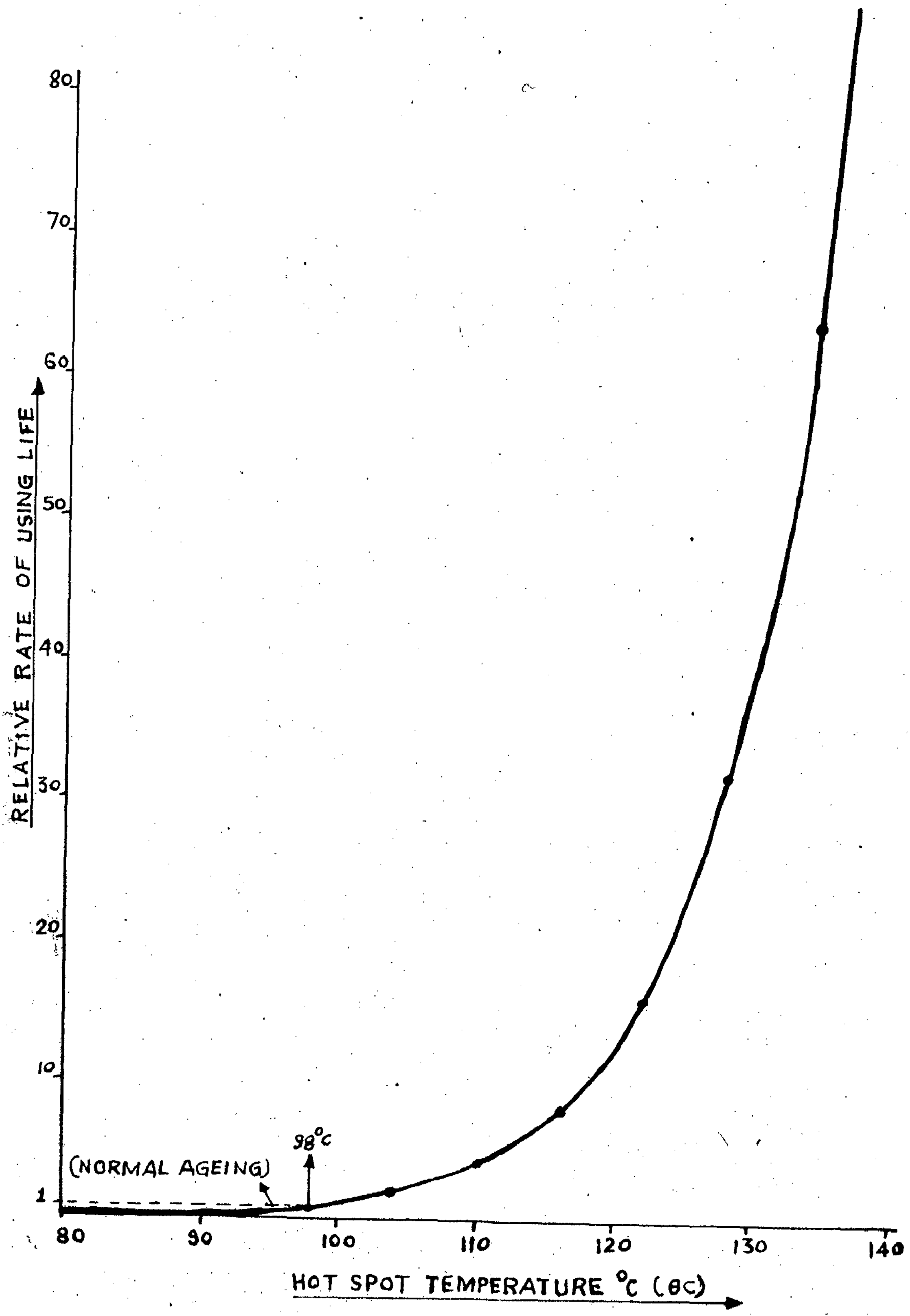
Therefore the life consumed in time t is given by

$$LL(t) = \int_0^t e^{0.115 [\theta_C(t) - 98]} dt \qquad \ldots(2.8)$$

$\theta_C(t)$ is the hot-spot winding temperature at time which depends upon the loading. From equation 2.6 and 2.7, the relative rate of using life for any hot-spot temperature and transformer life consumed in time t can be calculated. Also the relative rate of using life can be obtained by using a graph as shown in Figure(2.1).

2.4 PRACTICAL CONSIDERATIONS FOR THE OVER-LOADING

During actual operation of transformers in field, there are many site factors, these are allowed to over-loading the transformer. It has been noticed that failure due to overloading is not more than 1 to 2% of total failure caused by other reasons like lightning, shoft-circuits, mal operations and poor maintenance. The following practical considerations are utilized to overload the transformer continiously or during selected periods when the system requires so.



80
70
60
50
40
30
20
10
1
RELATIVE RATE OF USING LIFE
(NORMAL AGEING)
98°C
80
90
100
110
120
130
140
HOT SPOT TEMPERATURE °C (θC)

FIGURE :- 2.1

2.4.1 Exploiting the Design Margins

The transformer ratings are generally somewhat conservatively based on hot-spot winding temperature. The θ_{oa} and θ_{wo} in many cases observed to be less than the permitted value. Taking advantage of these margins it is possible to over-load a transformer depending upon the actual conditions obtained in practice. As an example in case of a 220/11 KV, 100 MVA transformers, the actual oil and winding temperature rise at full rated load is 33°C and 47°C against the guarnteed design figures of 55°C and 66°C respectively.

Further the difference in actual ambient temperature or cooling medium temperature, as the case may be and the corresponding figures assumed in design calculation can be used to definite advantage. As per IS: 2026, it is possible to operate a transformer at load above its rated KVA by 1% per degree centigrate less in cooling medium temperature with reference to ambient temperature and thus maximum limit of over loading being 10%. AIEE standard committee carried out the studies on standard transformers subjected to loading cycle with hot-spot temperature upto 220°C, and periodically these are subjected to over potential impulse test and short circuit test and finally found that transformer did not break down under the severe conditions. These transformers continued to work for 6 to 8 years without failure continiously at hot-spot winding temperature of 125^{o}C. From these results, it can be concluded that maximum temperature limit adopted by ISI are within the safe limit.

While considering the ageing effects due to operation of transformers at high temperature it is to be kept in mind that the insulating oil also deteriorates leading to increase in its acidity level. As soon as acidity tends to increase beyond 0.2 mg/KOH per gram of oil, the sludge formation starts. The sludge so formed deposite on the winding and metal parts which hampers the rate of heat dessipation from these components. Its commulative effect is to increase the working temperature of the transformers thereby accelerating the aging process. But in actual practice, so high temperature are not experienced and there is always a margin for over loading a transformer without substaintially enhance the aging rate of insulating oil.

2.4.2 Cyclic Loading

Taking advantage of the fact that consumption requirement of any system largely varies during 24 hours of a day. It means that transformer will work at uprated capacity during the peak load hours and at reduced load at low periods of the day. It has observed that for a distribution substation which having a load mostly residential and lighting as compared to industrial load, the ambient temperature during peak load hours i.e. 6 to 12 P.M. is less than the design limit specially during winter seasons.

The peak load hours are differed from peak temperature hours. Under such a favourable duty cycle the transformers can be considered for overloading.

2.4.2.1 Transient Temperature Considerations

Another more realistic approach in estimating aging of insulation by means of actual temperature variation throughout entire daily load cycle rather than the assumption that all of the aging takes place only and completely during the peak load duration and at the maximum temperature for the peak duration.

A mathematically accurate approach would be to integrate the effects of aging due to the heating and cooling through out the entire 24 hours period.

The actual variation of top oil and hot-spot winding temperature is shown in figure 2.2 . The temperature rises due to oil and winding are depends upon the thermal time constant (τ) of the transformer, in practice, the for oil is 2 to 3 hours and for winding 10 to 30 minutes are mostly founds. It is obvious from figure the final or steady temperature of hot-spot winding is not reached during the peak load due to thermal time constant and actual rise of hot-spot temperature is always less than the mathematically calculated by relation 2.1 . Thus it is apparant that a large portion of the conservatism in the loading guide may be attributable to an overconservative loss of life

DAILY LOAD CYCLE CURVE

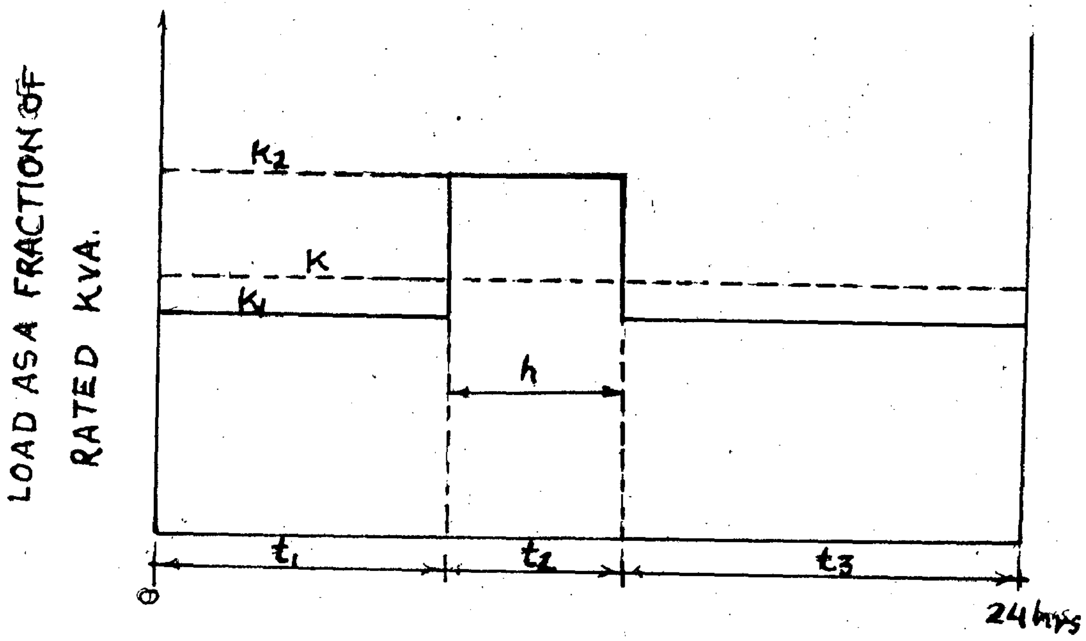


FIG:- 22 a

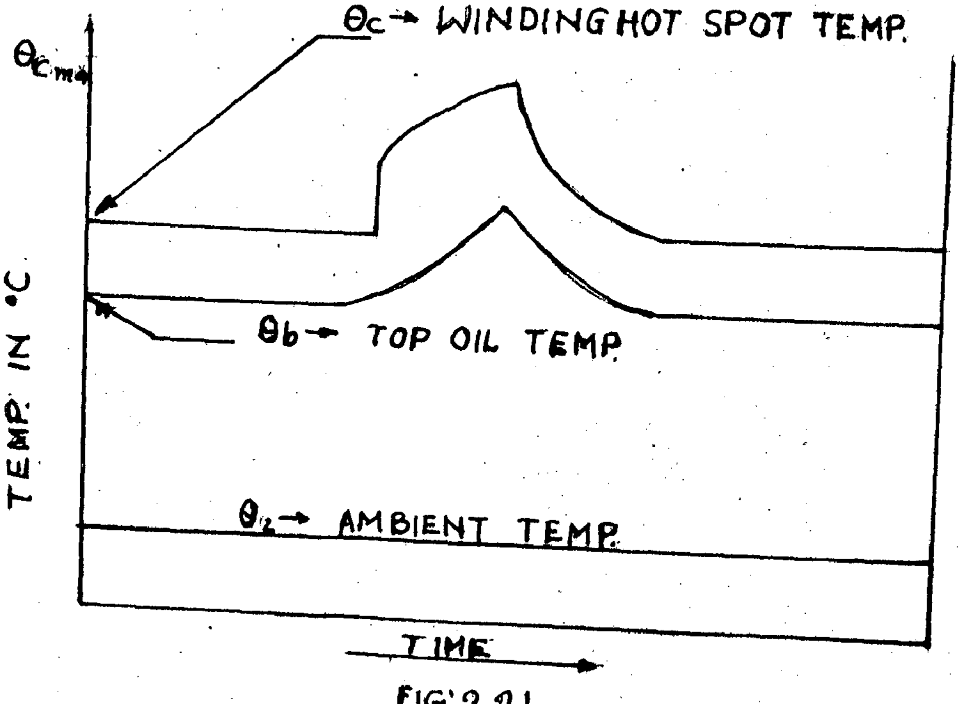


FIG. 2.2 b

curve and to the oversimplified assumptions that the maximum temperature exists throughout the peak duration. These considerations seems to provide logical reasons why the loading schedules are basically conservative.

2.4.3 Merits of Over-Loading

In case the margins available for short time over-loading the transformer on account of high aging rate at hot-spot winding temperature more than 98°C and below 140°C, there are some merits and demerits associated with this decision which is described below:

(i) It will help planners in choosing rated KVA of transformers new installation so as to draw maximum possible benefit out of the investment made. At present it is practice to install transformers of sufficiently large capacity or to keep spare trans-formers to meet any emergency requirement or future increase in load. By availing overload margins, lower installed capacity can serve the purpose.

(ii) Future augmentations can be differed or reduced, thus resulting in saving of capital expenditure.

(iii) Switching of feeders on account of limitations of the transformer capacity can be avoided by short time overloading of transformer as an when need arises.

(iv) Saving in additional core losses during lean periods by eliminating spare transformers.

2.5 GUIDELINES FOR OVER LOADING

The KVA rating is a conventional reference for un-interrupted continious operation for any transformer with normal expected life. Indian standard 6600 - 1972 lays down the limitations for overloading the oil immeresed transformers, which is similar to other standards adopted in other countries, these are described as follows:

(a) Under no circumstances, a hot-spot of winding temperature should not be allowed to go beyond 140°C because deterioration of oil and winding insulation after this temperature is greatly enhanced.

(b) At winding hot-spot temperatures of 98°C the deterioration of insulation is considered to be occuring at normal rate and rate of deterioration at other temperature is compared with this normal rate.

(c) With winding hot-spot temperatures below 80°C the use of life can be considered as negligible, whereas over the range of 80° to 140°C the rate of using life of transformer is doubled for every temperature increase of 6°C.

(d) The periods of accelerated aging when the winding hot-spot temperature is greater than 98°C are compensated for, by periods of slow aging when winding hot-spot temperature is less than 98°C.

(e) For normal cyclic duty, the current does not exceed 1.5 times the rated value. If current go beyond this value and duration permitted by IS: 6600, are carried by terminal outlets like tap changers bushing and similar attachments with safety.

CHAPTER III

MAINTENANCE AND TEST RECOMMENDATIONS

3.1 INTRODUCTION

The failure of a transformer may be attributed due to many causes starting from the commissioning stage to the operation and maintenance. Many a times it is difficult to pin point the causes of damage after the failure has taken place. Inspite of this, the bad maintenance or not proper maintenance may be one major cause of transformer failure. The maintenance prescribed by manufacturers and standards should be followed strictly, which gives better life and performance.

When transformers are overloaded, it is necessary to periodically check and ascertain the condition of transformer from time to time. By this, any tendency for rapid deterioration can be stopped and corrective measures taken. Thus the transformer being overloaded, needs more attention and quantum of maintenance. It is possible to monitor the health of the transformer by carrying out periodical tests on the transformer or its cooling medium. The corrective action to restore the health of transformer may be taken as when tests reveal abnormality.

The transformer oil is a very complex mixture of over 200 different compounds which can be broadly grouped into aromatic, and paraffinic hydrocarbons. The transformer oil which has been accepted is essentially a non-polar petroleum liquid. The analysis of oil is done by many instrumental method in the laboratories, to determine its composition and minor constituents thermal characteristics and many other data required to study the properties and quality of transformer oil.

In this chapter, it is proposed to discuss the maintenance and tests recommendations for transformer. Main emphasis is given on the oil testing, its analysis and maintenance.

3.2 MAINTENANCE OF TRANSFORMER

Maintenance means routine inspection, testing cleaning and adjustments which are carried on a transformer in service to avoid its break down. The maintenance should not be confused with repair work which is carried out after the breakdown of transformer in service. This basically covers the following:

(i) Periodical tightening of nuts and bolts.

(ii) Leakage of oil or low oil level - inadequate quantity of oil level results in overheating thus causes failure.

(iii) Oil testing - the transformer oil should be periodically checked for presence of moisture in oil, acidity of oil dielectric strength (40 KV for 1 minute with 4 mm. gap). When acidity below 0.5 mg. KOH/gm, no action should be taken and between 0.5 mg. KOH/gm. and 1.0 mg. KOH/gm. oil must be kept under observation.

(iv) The transformer must be subjected to dissolved gas analysis once in a year.

(v) Checking connection of grounding.

(vi) Colour of silicagel, if it is white or pink. It requires replacement.

(vii) Any transformer in service for a period of 4 to 5 years is expected to have deficiencies like shrinkage of windings, loose clamping, localized insulation failure etc. Hence once in a four years the core and winding must be inspected.

(viii) The insulation resistance should not be less than the value is given below for a transformer measured with 1 KV or 5 KV megger.

Voltage of winding	Minimum safe resistance in Mega Ohm.			
	$30^{\circ}C$	$40^{\circ}C$	$50^{\circ}C$	$60^{\circ}C$
11 KV	400	200	100	50
L.V.	200	100	50	25

3.3 TEST RECOMMENDATIONS FOR OIL AND WINDING OF TRANSFORMER

During schedule maintenance, it is necessary to check all data like condition of oil and windings by suitable testings and rectify any abnormalities found before failure. These tests are framed on the basis of the different transformer manufactur's and user like Bhilai Steel Plant and M.P.E.B. The tests required to be carried out are described.

3.3.1 Testing of Insulating Oil

The health of transformer greatly depends on how the oil is maintained, it is necessary, therefore, to carry out periodical tests of oil samples. The following tests are normally carried out:

3.3.1.1 B.D.V.

The 2.5 mm. gap between cylindrical electrodes according to IS: 335. This test is carried out once in a year for transformers of capacities upto 10 MVA and twice in a year in case of transformer more than 10 MVA. Minimum value of B.D.V. for different voltage classes of transformers which are in service, upto which the transformer can be allowed in service as follows:

Upto 15 KV class	25 KV
15 - 35 KV	30 KV
60 - 220 KV	40 KV

3.3.1.2 Acidity

Acidity of new oil is less than 0.02 mg. KOH eq/gm. of oil according to IS: 335. During service the acidity value can be permitted upto 0.4 mg./gm. oil although there are practices which allow higher values. The frequency of the testing oil for acidity could be once in two years for transformer upto 15 KV class and 2 MVA and once in a year larger transformer. The acidity of the oil goes up due to formation of fatty acids which is accelerated at high temperatures, as also in the presence of moisture. As acidity goes up, the volume resistivity comes down and consequently insulation resistance of the transformer. Fatty acide affects the cellulose insulation also.

3.3.1.3 Moisture Content

Moisture gets into oil in a transformer through mainly three paths. (i) Through breathing action of transformer, (ii) Through sludging action of oil, and (iii) Through thermal disintegration of paper used as insulation. The electric strength of oil drastically reduces with moisture contents exceeding 5 - 10 PPM especially in the presence of particle impurities as shown in figure 3.1 . It requires sophisticated equipment to measure moisture contents at levels lower than 5 - 10 PPM. There are some field tests like crackle test which can roughly indicates the extent of moisture present in oil.

3.3.1.4 Mechanical Impurities

The impurities are generally estimated as Benzene insolubles, particles of dust, metal and fibres which may find their way into oil and reduce the electric strength as is evident from figure 3.2 . The presence of these particles lower the partial discharge inception voltage leading to break down.

3.3.1.5 Flash Point

The flash point of new oil according to IS: 335, shall not be less than 140°C. However, the flash point goes down during the service life of the transformer due to the evolution of gases and their absorbtion of oil. The value of flash point of oil for transformers in service should not go below 125°C. Even at this level if there is a sudden lowering of flash point, it calls for investigations. The condition of transformer can be estimated by analysing the gases present in oil. The gases usually present are H_2, CO, C_2H_2, CH_4, C_2H_6 etc. From the quantities of these gases present, the deteriorating part in the transformer can be identifies.

To maintain the stability and quality of oil in a transformer, it is necessary to prevent entry of moisture into it. There are practices to filter the oil periodically once in a year. This is mostly due to the high temperatures obtained at the surface of immersion heaters used in the filter machines. The filteration of oil should be done only if the test results indicate.

MOISTURE CONTENT

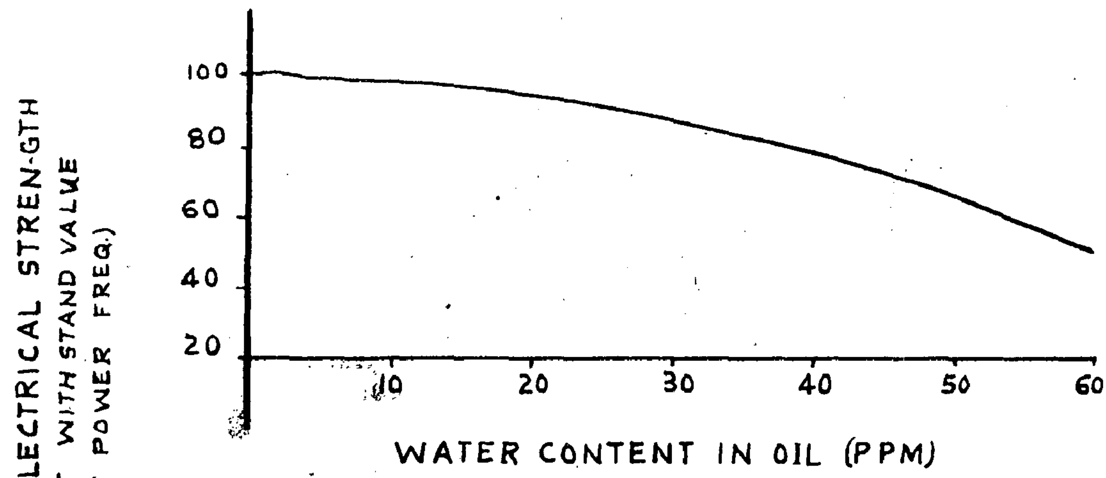


FIG 31

MECHANICAL IMPURITIES

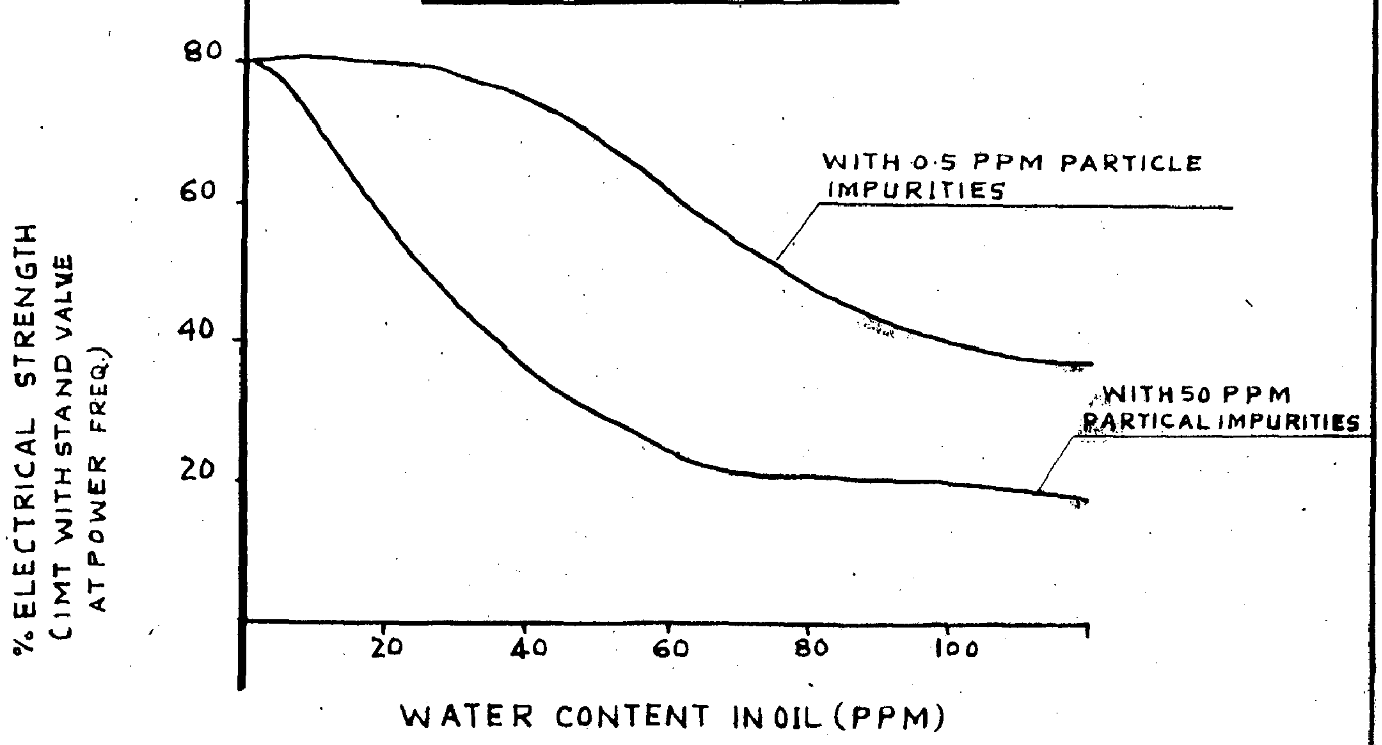


FIG 32

3.3.1.6 Other Test of Oil

The work has been done in direction to evaluate various accelerated life test for the transformer oil. These tests will help to evaluate the degradation of the oil. It will also be possible to compare various oils and their combinations to recommend the transformer oil to the particular operation. These day many laboratories tests has been developed to analyse the composition and quality of oil. By instrumental method which offers good scope in determining the quality, composition, performance reliability, deterioration rate and extent of stability [14].

The effect of chlorinated solvents on electrical and chemical properties of transformer oil is described [15]. The experiment conducted with carbontetra chloride, chloroform and tetrachloro ethylene and found that tetra chloro ethylene is best suited for possible addition to increase flash point and reduce viscosity. Also when added to the extent of 1 part to 4 parts in the transformer oil, it does not affect electrical properties. Thus, there is enough scope in the development of transformers with the above admixture in fire hazardous area.

The effect of transformer materials on the degradation of transformer oil under semiactive condition has been observed [16]. The above observations indicate that in a transformer with temperature stresses alone, water content should come down to 4 ppm. if suitable breathing arrangements and proper manufacturing practices are adopted. Electrical strength should not deteriorate. Oils with lower arromatic content perform better. It is also seen that around 60 to 70% of increase in neutralization value take place withing the 5 months itself.

It is recommended that various accelerated life tests be developed for the evaluation of quality of transformer oil.

3.3.2 Testing of Magnetic Circuit

There has been a vast improvement in the quality of steel used and in methods of construction in the last two decades. The no load losses of transformer have come down drastically in this period. As an example, a 132/7.2 KV, 40.5 MVA transformer manufactures in early 60's had an iron losses of 120 KW according to the test at the manufactures factory. After 20 years of working this figure has risen to about 250 KW. As against this the iron losses of present day transformer of the same rating may be about 20 - 25 KW. The changes in construction has also brought about reduction in maintenance needs. The practice has been to tighten the core bolts etc., once in 6 - 10 years which may not be necessary for present day transformers.

It is difficult to asses the condition of the magnetic circuit thoroughly without dismantling it. An emperical test to assess the health of magnetic circuit may be carried out. After removing earth connection of the core, the resistance 'R' between the two extreme limitations may be measured and the coefficient of resistance may be calculated from the following formula:

$$K_1 = \frac{RA'}{n}$$

Where

K_1 is the coefficient of resistance.

R is the resistance between extreme laminations in ohm.

A' $3\ A_c + 3A_y'$

A_c is mean surface area of core limb laminations in cm^2.

A_y is mean surface area of yoke laminations in cm^2.

n' is number of laminations = $\frac{\text{core width}}{\text{thickness of one lamination}}$.

For magnetic circuits in good conditions, this value can be higher than 100. For a working transformer, if the value goes below 15, it indicate high losses and extensive damage to insulation of the laminations.

The present day CRGO laminations with chemically applied insulation, generally give good service in their life time. In a working transformer, the indication of a deteriorated magnetic circuit are higher top oil temperature at no load and even evolution of gases operating the Bulchholtz's relay. It is necessary to disconnect the transformer in such cases immediately and take out the core and windings for investigations. The effect of moisture on a paper is well known. Paper insulation of windings quickly absorb moisture from the cooling medium and attain a state of equallibrium. Some investigators have studied this phenomenon and have shown the relationship between moisture content in oil and moisture in paper. Fig. 3.3 illustrates this point, fig. 3.4 illustrate the effect of moisture in oil impregnated paper. This relation holds good when paper does not have particle impurties, the presence of which brings down the electric strength further in the presence of moisture.

There are no. of tests that are usually carried out to assess the health of transformer.

3.3.2.1 Insulation Resistance & Absorption Ratio

Insulation resistance measurement is a very simple test and goes a long way to monitor the health of transformer if carried out at regular intervals. The value obtained have to be corrected for temperature before comparison. The following relationship can be used for this purpose and these relations hold good if the acidity of oil in the transformer is not high as given in table (3.1).

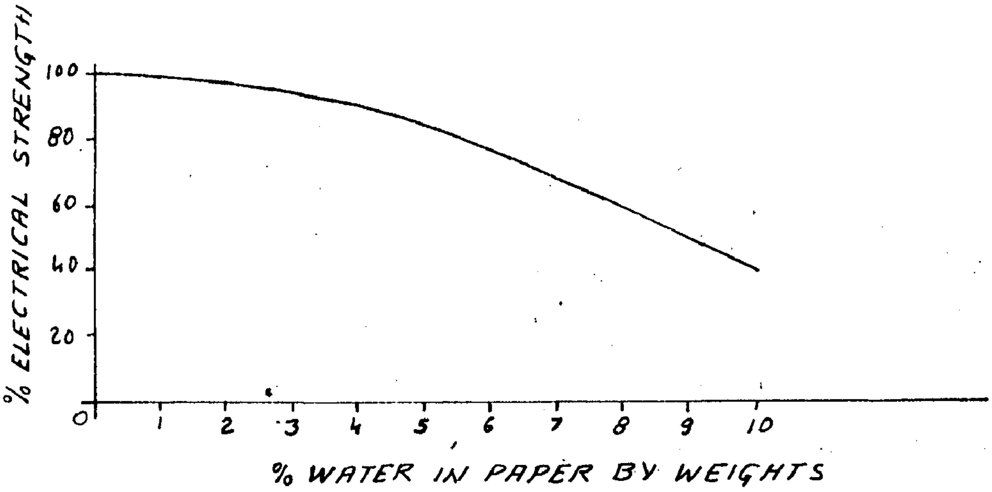

% ELECTRICAL STRENGTH
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
% WATER IN PAPER BY WEIGHTS

FIG. 3.3

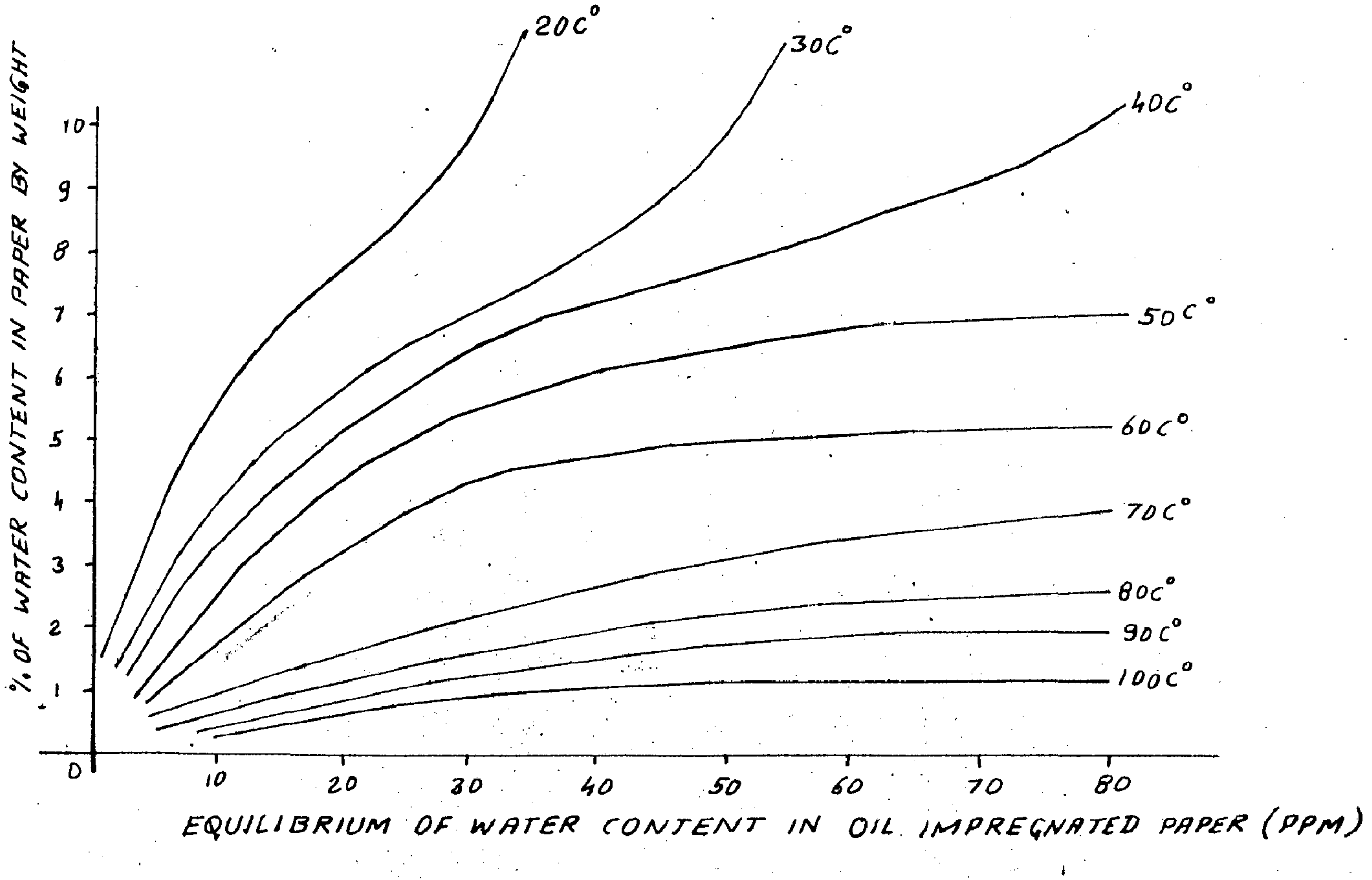

20C°
30C°
40C°
50C°
60C°
70C°
80C°
90C°
100C°
% OF WATER CONTENT IN PAPER BY WEIGHT
10
9
8
7
6
5
4
3
2
1
0
10
20
30
40
50
60
70
80
EQUILIBRIUM OF WATER CONTENT IN OIL IMPREGNATED PAPER (PPM)

FIG. 3.4

Table (3.1)

Temp. °C	5	10	15	20	25	30	35	40	45
Factor	1.23	1.5	1.34	2.25	2.75	3.4	4.15	5.1	6.2

Temp. °C	50	55	60	65	70
Factor	7.5	9.2	11.2	13.9	1.7

The minimum insulation resistance required for connecting a transformer in circuit may be taken as 70% of the factory value or the following value whichever is less, as given in Table (3.2).

Table (3.2)

Voltage Class KV	Temperature °C 20	30	40	50	60	70
3 - 10	200	130	80	50	35	25
20 - 35	300	200	130	90	60	40
110 - 120 (Not larger than 10 MVA)	600	400	260	180	120	80

During the course of operation, the insulation resistance of the transformer tends to go down, if this value is below 70% of the commissioning value, an investigation is called for an remedial action taken. The ratio $\frac{R_{60}}{R_{15}}$

i.e. the ratio of insulation resistance after applying the voltage for 60 sec. to 15 sec. value called the absorption coefficient should not be less than 1.3 for transformers in service. However, for new transformer or those after repairs, a value not less than 1.4 can be permitted.

3.3.3.2 Measurement of the Dielectric Loss Angle (TAN δ)

This test is frequently done for extra high voltage transformers. It indicate the presence of moisture, particle impurities and deterioration due to partial discharges etc. The maximum values that can be taken as given in Table (3.3).

Table (3.3)

Temp. °C	10	20	30	40	50	60	70
Trf. Capacity upto 2.5 MVA	1.5	2.0	2.6	3.4	4.6	6.0	8.0
4 - 6.5 MVA	1.2	1.5	2.0	2.6	3.4	4.5	6.0
Above 10 MVA	0.8	1.0	1.3	1.7	2.3	3.0	4.0

For transformer in service 30% higher values can be permitted.

3.3.2.3 Measurement of Moisture Ratio

The moisture ratio is a very dependable test. The ratio C_2/C_{50} which is the ratio of capacitance of windings measured with 2 Hz and 50 Hz supplies is termed as moisture ratio. This ratio is very useful in assessing whether the windings are dry or not. The maximum permissible values are given in Table (3.4).

Table (3.4)

Temp. °C		10	20	30	40	50	60	70
Upto 35 KV & 10 MVA	A*	1.25	1.30	1.40	1.50	1.60	1.80	1.90
	B*	1.20	1.25	1.30	1.40	1.45	1.57	1.70
110 KV or 10 MVA	A*	1.15	1.20	1.30	1.40	1.50	1.60	1.70
	B*	1.12	1.16	1.20	1.30	1.40	1.50	1.60

A* = Maximum values in service.

B* = Maximum value for commissioning.

3.3.2.4 Step Voltage Test

This test to indicate the moisture and particle impurities in windings. The insulation resistance is measured at two different voltages. The relationship between the insulation resistance (R 60 value) and voltage of measurement is shown in fig. (3.5.a). This test is normally done with two voltages in the ratio 1:5 and the value obtained with

STEP VOLTAGE

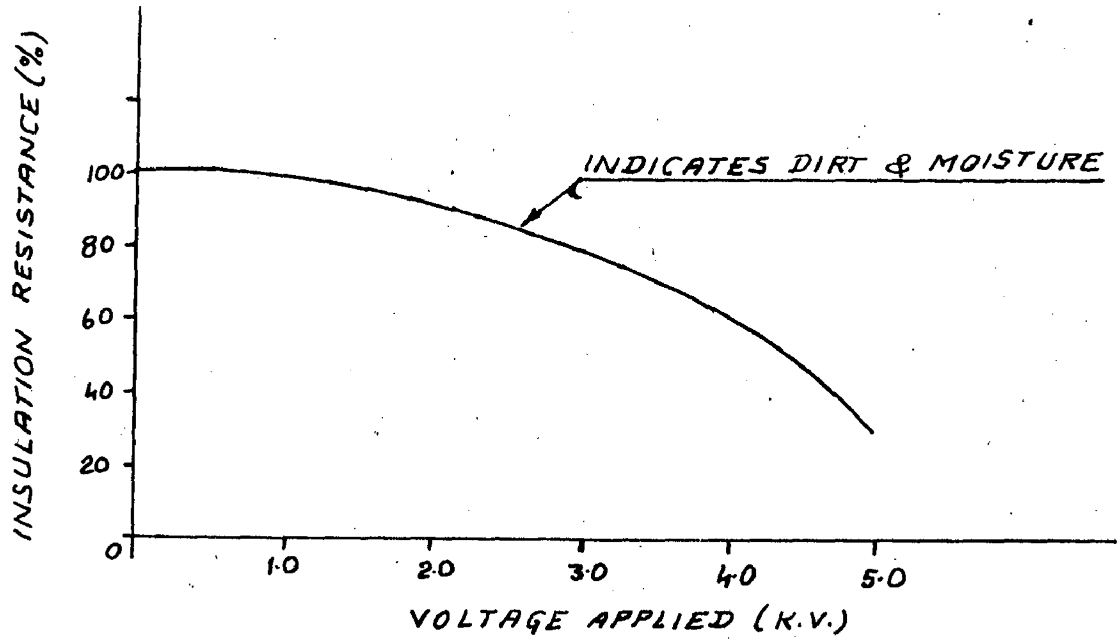


Fig-3.5a

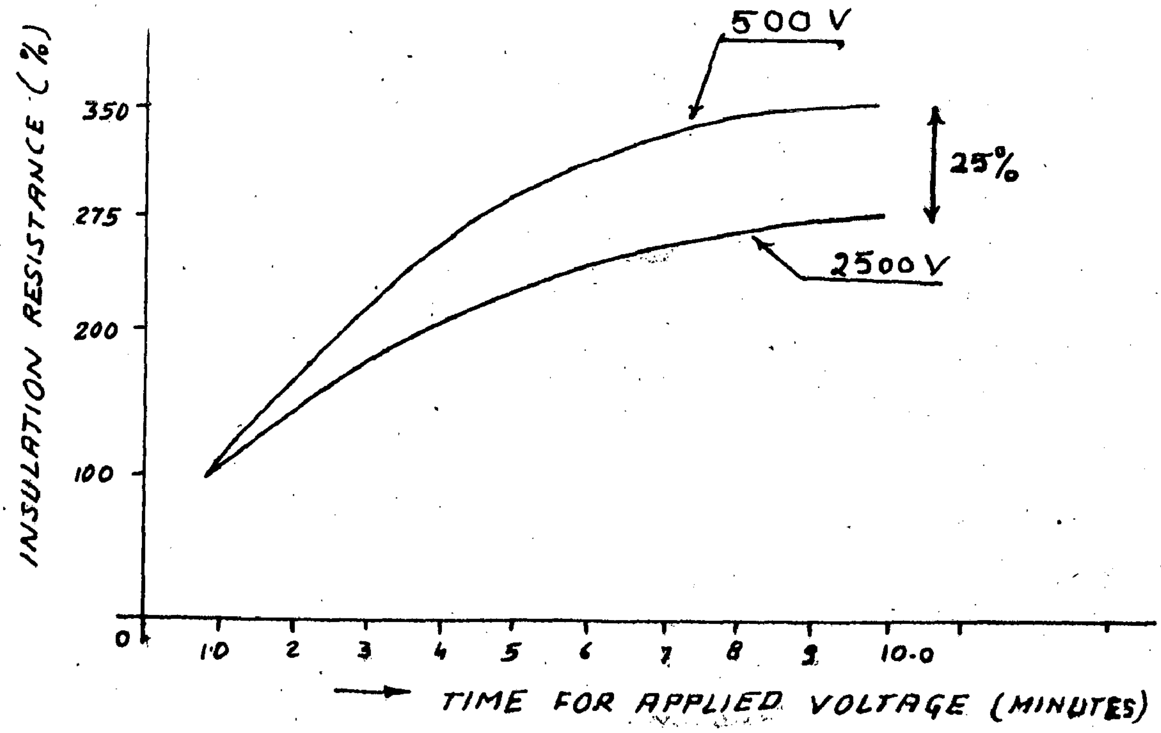


Fig-3.5 b

higher voltage should not be less than 25% of the value obtained at lower voltage as clear from fig.(3.5-b).

3.3.2.5 Functional Life Test

In an oil immersed transformer insulation system is the weakest link, and hence the functional life of insulation is very important for manufactures and users both. Normal life expentency figures are determined on the basis of accelerated ageing test at three elevated temperatures of the oil paper combinations in a sealed glass tube, testing for tensile strength of paper as an end point criteria and extra-polarity the results for ageing at normal temperature.

In this test, the transformer are subjected to accelerated ageing at a minimum of three test temperatures. The test temperature being produced by circulating the a.c. current of a rated frequency through the windings of transformer. Depending upon the value of the test temperature, this current will be higher (1.2 to 1.75 times) than the normal fall load current of the transformer and it has to be ensured that the termination, bushings and other peripheral equipments are capable of withstanding these currents on continuous basis.

At each of the hot-spot temperature, the transformer is to be aged through overloads for a total period, which is five times the expected life expentancy period, at that temperature. This period is divided into 50 equals test periods.

The life of the transformer is considered to have ended when the thermal degradation has progressed to a point that the unit can not withstand anyone of the series of test as given below which simulates the abnormal currents and voltage commonly experienced in service.

(a) Short circuit test at 25 times the rated current for 2 sec.

(b) Full wave impulse test at 65% of the value specified for new transformer.

(c) Induced potential test that at 130% of rated voltage for 7200 cycles.

The transformer under accelerated ageing is subjected to the above test period. The life of the transformer at the elevated temperature so measured is than extra polated by standard methods to determine the life expentancy in normal service.

In some western countries, this test have been used by manufacturers with great success to evaluate new materials for use in transformer, for instance a thermally upgraded collulose paper Vs a standard Kraft paper, acid refined oils Vs hydrorefined oil and new film insulated wire versus standard proven wire.

For users, this test mean a realistic estimate of life expectancy of various designs and comparative evaluation of designs for quality and reliability and a correlation of the above factors with price. It also implies that since a design is functionally tested and proved, responsibility for any failure in system will have to be borne by the user.

There are several other tests to monitor the health of transformer such as measurement of polarization ratio, and impulse sketching which may be recommended for only large sized transformer.

CHAPTER VI

OPTIMAL TRANSFORMER LOADING

4.1 INTRODUCTION

It may be more economical to overload some transformers already in service and accept the penality of probable shorter life rather than to relieve them with additional units. Similarly, it sometimes may be justified to install new units and deliberately reduce copper losses since energy costs go up every year. In either case, considerable saving in present capital outlay are weighted against a probable increase in future replacement. The result establish an appropriate transformer loading policy in terms of minimum operating cost is known as optimal transformer loading. However, no systematic methods, therefore, existed for systematic evaluation of transformer loading policy. Bae, Adkins and Bree had done work in this field but they had decided the policy hit and trail method taking into account the total cost of owing and operating.

Optimal transformer loading problem is formulated to determine the addition of transformer in each year with growing load of the system considering the failure cost maintenance cost, energy cost, interest on capital investment and price escalation of the transformer. To determine the optimal policy, the problem is converted to the dynamic programming problem. The example is solved using dynamic programming to determine optimal transformer loading policy.

4.2 PROBLEM

The problem is to determine addition and therefore loading of transformer every year in the substation to serve the given load reliably and economically with constraints over maximum loading and capital investment.

4.2.1 System Load Growth

The system load growth can be obtained by any forecasting method. After having the load growth, system planner can take a decision about the quantity of the addition of a transformer each year with specified substation minimum and maximum loading limits (Imin & Imax).

4.2.1.1 Daily Load Curve

The loading guide gives clear instruction for loading a transformer to the short interval. Also daily load cycle play important role in overloading. The actual fluctuating load cycle shall be converted to a simple equivalent reactangular load cycle as shown in figure 2.2(a) .

4.2.1.2 Ambient Temperature

The ambient temperature is not constant for throughout a year. The annual weighted temperature is considered for calculation which is 32°C as specified by IS: 2026 Part-I.

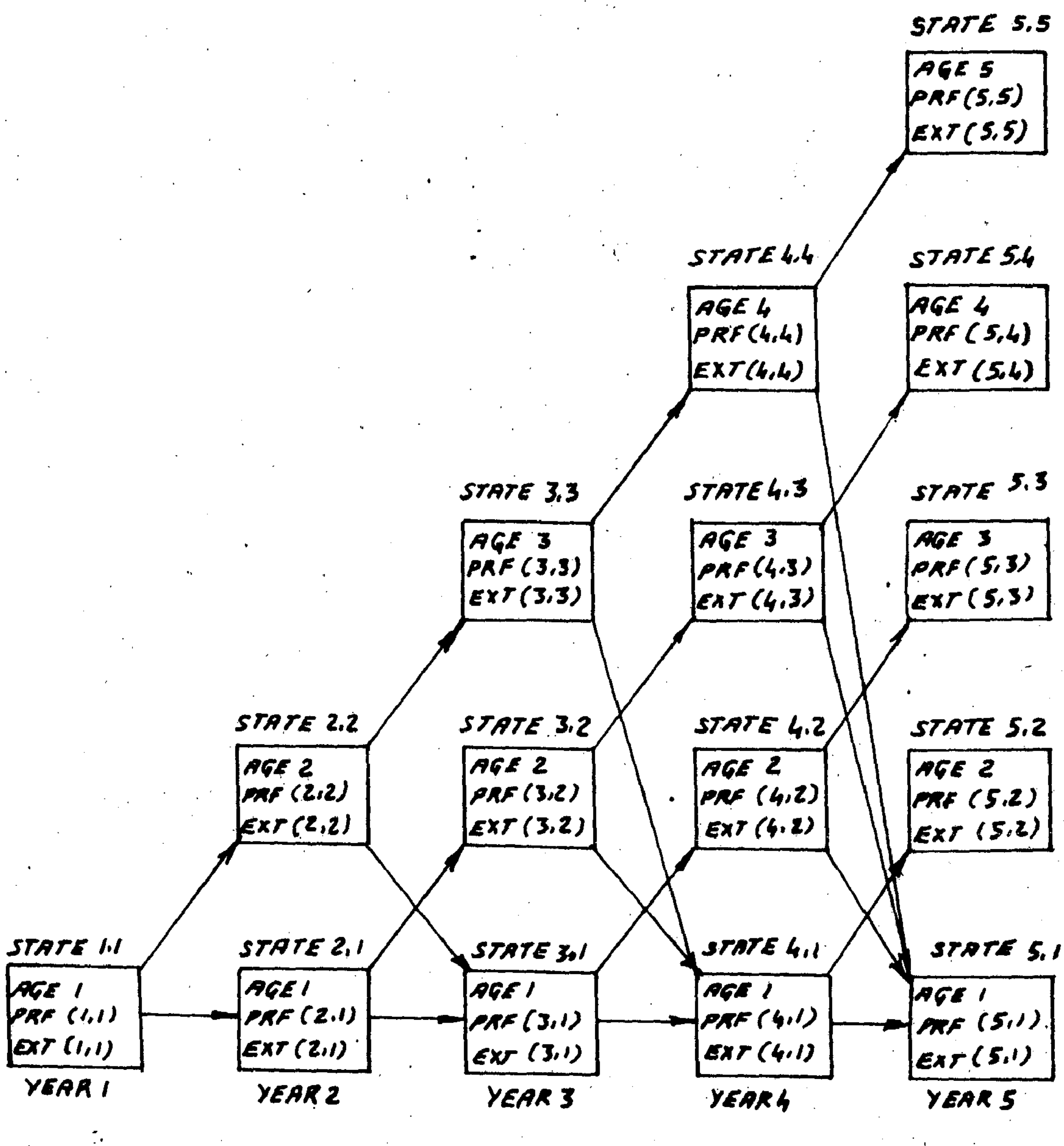
4.2.2 Transformer State Matrix

The transformer state matrix is shown in figure (4.1). (The state (I, J) represent year I, age J.). An arrow represents an event (transition from one state to another) in life of each transformer. Arrows directed up and to the right represents survival, such as event in year 4; a two year old transformer state (4, 2) = year 4, age 3 survines to year 5 and becomes 3 years old state (5, 8) . Arrows directing to the right and downward represents transformer failures. In year 4, transformer in 2, 3, 4-year old states may fail and be replaced by a new transformer and become 1-year old transformer state (5, 1) in the next year.

4.2.3 Transformer Failure Probability

Transformer failure probability for given period is defined as chance of transformer failure during continuous operation. The failure rate of the transformer comprises, a component due to insulation deterioration (λ_1^n) and one due to all other causes. The failure rate λ_1^n is determined by the life remaining in the transformer insulation. The life consumed in a year is a function of hourly loading and ambient temperature condition under which the transformer has operated and determines by using Monstinger relation.

Thus the failure rate λ_1^n , due to insulation loss of life is written as follows:



= PROBABILITY OF FAILURE IN STATE (I,J) EXPECTED NUMBER OF TRANSFORMER IN STATE (I,J).

FIG 4.1 SUBSTATION STATE TRANSITION DIAGRAM.

$$\lambda_1^n = \frac{\text{Life consumed in year n}}{\text{Remaining life}} \qquad \ldots (4.1)$$

The failure rate due to all other causes are framed as:

$$\lambda_2 = \frac{1}{\text{Maximum life of a transformer}} \qquad \ldots (4.2)$$

Thus the transformer will fail after certain specified life, however, it is loaded or not. The total failure rate

$$\lambda^n = \lambda_1^n + \lambda_2 \qquad \ldots (4.3)$$

The probability of failure of transformer is taken as exponential dependency and written as:

$$P_{RF}\ (n, a) = 1 - e^{-\lambda^n t} \qquad \ldots (4.4)$$

4.2.4 Cost Functions

In policy decision making cost is essential factor which are used to examine the trade off between saving in installed capacity and expected loss of life due to overloading. The cost functions which are dominant in system operation for owing and operating the transformers are as follows:

4.2.4.1 Capital Cost

For our model the capital cost is defined as owing and installation cost of transformer and other accessories. The price escalation is also taken into account. The capital cost for adding A_n transformer capacity in year n is given by:

$$CC(n) = (1 + PE)^{n-1} \, UCT(1) \quad A_n \qquad \ldots(4.5).$$

4.2.4.2 Maintenance Cost

Maintenance cost covers all the running cost like changes of oil, routine maintenance, small repairs and salaries of maintenance staff which are spend every year on the total installed capacity. The maintenance cost for any year n is given by:

$$MC(n) = M \quad (1 + PE)^{n-1} \, UCT(1) \quad X_n \qquad \ldots(4.6)$$

Where

M = 0.03 to 0.07 i.e. maintenance cost is 3 to 7% of capital investment.

4.2.4.3 Energy Loss Cost

Due to shortage of energy, these days power suppliers are taking more attention about the wastage of energy. For transformer, there is always a no load loss and load loss varying according to load of the transformer. This cost is play major role of deciding the addition of new unit or over-load the existing substation capacity.

The energy loss cost in year n is written by following relation:

$$ELC(n) = 8760. \, EC. \left[NLL + LL \, (K)^2\right] X_n \qquad \ldots(4.7)$$

4.2.4.3 Failure Cost

The failure cost is defined as the cost of replacement of failed transformers due to over loading. It is calculated by multiplying the probability of failure of each transformer and replacement cost per transformer.

The failure cost in year n is given by

$$FC(n) = (1 - s)\ (1 + PE)^{n-1} \left[\sum_{n=1}^{n} P_{RF}\ (n, a)\ EXT(n, a) \right] UCT(1). \qquad \ldots(4.8)$$

4.2.5 Total Cost

Total cost for operating the transformers in year n with addition A_n is given by:

$$C_n\ (X_n, A_n) = \frac{CC(n) + MC(n) + ELC(n) + FC(n)}{(1 + IR)} \qquad \ldots(4.9)$$

Using the equation (4.6 to 4.8) can be obtained total cost $C_n\ (X_n, A_n)$.

4.2.6 The Objective Function

The objective function consists of the cost associated with interest on capital investment, maintenance cost, energy loss cost and failure cost.

The total cost of owing and operating the transformer in year n with A_n additions and total available capacity X_n is given by:

$$Q_n(X_n, A_n) = \sum_{n=1}^{N} C_n(X_n, A_n). \qquad \ldots(4.10)$$

Thus our objective is to determine the minimum cost of owing and operating in each year and obtain the total optimal cost of owing and operating for certain specified horizon N. Our constraints are witten as:

$$\frac{L_1}{Lmax} + 1 \leq A_1 \leq \frac{L_1}{Lmin} \qquad \ldots(4.11)$$

$$\frac{L_2}{Lmax} + 1 \leq A_1 + A_2 \leq \frac{L_2}{Lmin} \qquad \ldots(4.12)$$

$$\frac{L_n}{Lmax} \leq A_1 + A_2 + \ldots\ldots + A_n \leq \frac{L_n}{Lmin} \qquad \ldots(4.13)$$

$$Lmax \quad Lmin \quad 0 \qquad \ldots(4.14)$$

$$A_1, A_2 \ldots\ldots A_n \geq 0 \qquad \ldots(4.15)$$

$$L_1, L_2 \ldots\ldots L_n > 0 \qquad \ldots(4.16)$$

$A_1, A_2, \ldots\ldots A_n$ are integers only.

Thus the constraints are limited no. of additions each year possible and thus limited resources are available.

4.3 OPTIMIZATION BY DYNAMIC PROGRAMMING

The dynamic programming is a mathematical optimization technique used for making the decision at each stage of serially interrelated decision and give final optimal value. Thus our objective function is:

Minimize the cost function

$$F_n(X_n) = \underset{A_n}{\text{Minimize}}\ Q_n(X_n; A_n) \quad \text{for } n = 1, 2 \ldots N$$

Where

$$Q_n (X_n, A_n) = C_n (X_n, A_n) \quad \text{for } n = 1$$

and $$Q_n (X_n, A_n) = C_n (X_n, A_n) + F_{n-1} (X_{n-1}, A_{n-1})$$

with $$X_{n+1} = X_n + A_n \qquad n = 2, \ldots . N.$$

The constraints are obtained by equation 4.11 to 4.16 The flow chart of solving above problem is shown in Figure (4.2).

4.4 EXAMPLE

A distribution substation is supplying a load to the area which load demand is 10 MVA initially and loadgrowth expected is 1 MVA each year. The daily load cycle curve is having a 6 hours peak load and rest is normal constant load of 40% of its rated capacity. All transformers installed in a substation is equally loaded. The allowable minimum loading of the each transformer is 80% and maximum is 130% of the rated capacity.

Then obtain a minimum no. of transformers in sub-station each year to serve the load demand of area with reliably and economically for a 5 years planning period on the based of the following data:

The rated capacity of each transformer = 1 MVA

No load loss = 2.0 KW/transformer

Copper loss = 10.0 KW/transformer

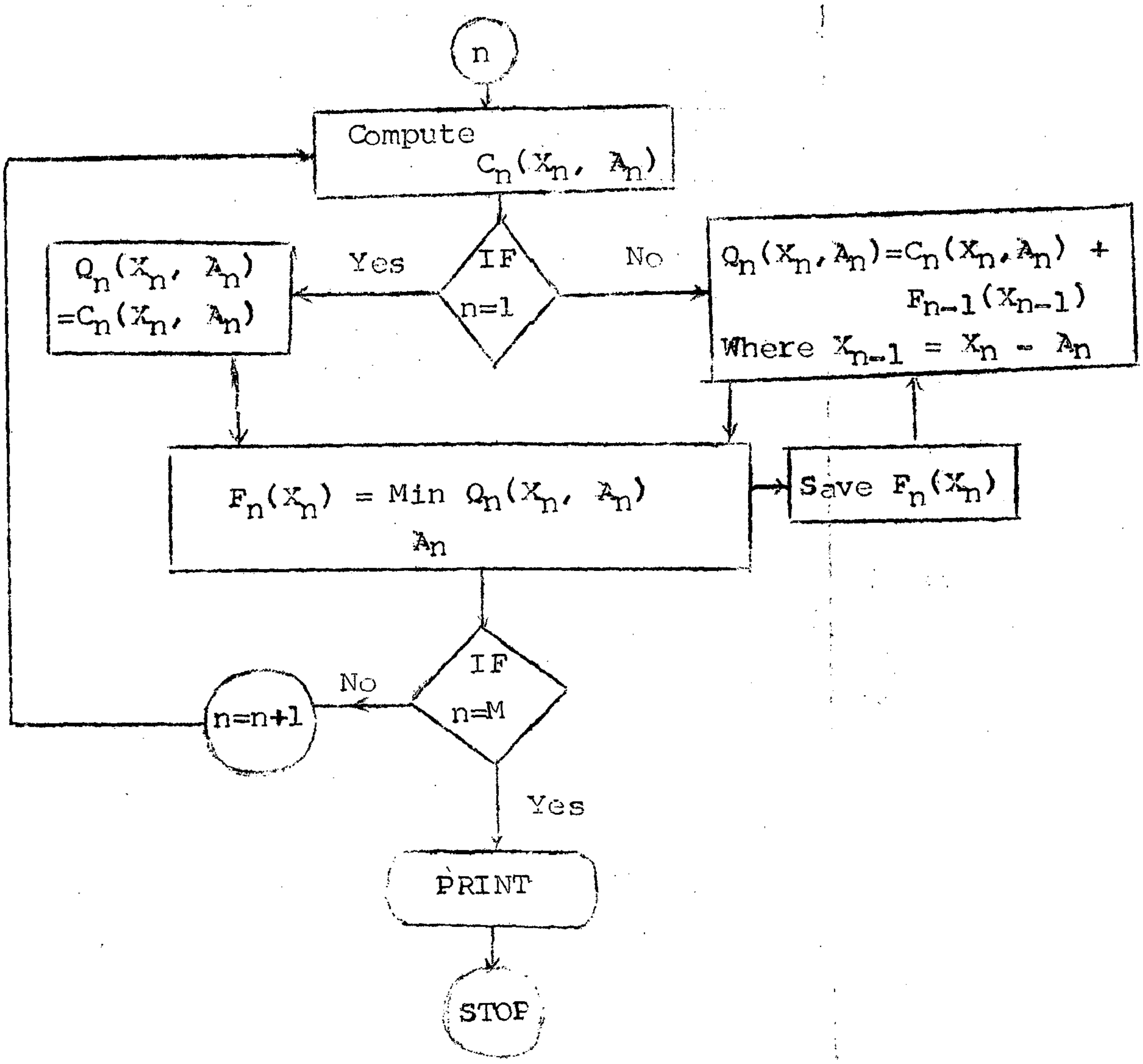


Figure (4.2): Flow Chart for solving dynamic programming problem.

Thermal time constant for oil τ_o = 3 hours.

Thermal time constant for winding τ_w = 20 minutes.

Capital cost = Rs. 3 x 10^5 per transformer

Maintenance cost = 5% of capital cost per transformer

Replacement cost of transformer = 50% of capital cost per transformer.

The price escalation of transformer = 5% per year.

Interest rate on total cost = 15% per year.

4.4.1 Solution

The problem is solved and cost functions of each year is given in the table.(4.1). **Every** stage optimal value is shown with * mark.

Table (4.1)

Year n	Load of the system L_n MVA	Addition A_n MVA	Available capacity X_n MVA	Total cost of owing and operating the transformer $C_n(X_n, A_n)$. Rs.... x 10^5
1	2	3	4	5
1	10	8	8	10.5049
1	10	9	9*	7.9159*
1	10	10	10	7.9392
2	11	0	9	10.8653
2	11	1	10*	8.9712*
2	11	2	11	9.0439
3	12	0	10	10.5235
3	12	1	11*	10.1884*
3	12	2	12	10.4806

contd..

1	2	3	4	5
4	13	0	11	12.4837
4	13	1	12*	11.1204*
4	13	2	13	11.1535
5	14	0	12	12.4381
5	14	1	13*	12.3175*
5	14	2	14	12.3175

The final result is shown in the Table (4.2).

Table (4.2)

Year n	Load of the system L_n MVA	Addition A_n MVA	Capacity of the system X_n MVA	Capital investment in year n Rs. .. $\times 10^5$	% overloading of the transformer
1	10	9.0	9.0	7.9159	11.11
2	11	1.0	10.0	8.9712	10.00
3	12	1.0	11.0	10.1884	9.09
4	13	1.0	12.0	11.2040	8.33
5	14	1.0	13.0	12.3175	7.69

The total cost of owing and operating the system is Rs. 50.5134×10^5.

CHAPTER V

CONCLUSION

The transformer should be overloaded for a short term interval. The only limitation on the transformer laoding is that the hot-spot winding temperature should not go beyond 140°C. The failure of the transformer is not due to overloading. The life of the transformer can be maintained by proper maintenance and test recommendation supplied by manufacturers. The result of this study show that there is no longer any economic incentive to overload transformers significantly above 110 percent of name palte rating. Whenever, overloading of transformer is done above 110 percent energy loss cost play important role and not allow to go beyond this limit. Failure cost also increases as loading is more than 110 percent. Thus the higher cost of copper losses of the transformer offsets saving in capital outlay associated with overloading.

This study suggests a concerted effort that transformer in the system should be loaded upto 110 percent of name plate rating and minimum peak load level should be increased to name plate rating avoiding wastage of energy due to no load loss of transformer and increase in capital investment. Thus, more emphasis should be put on increasing the minimum peak load level because of the relatively larger cost penalties associated with under-utilization.

Transformer loading problem can be framed as integer programming problem considering more realistic daily load curve and ambient temperature variation. The various cost can be further sub-divided into sub-component to make the cost structure more realistic. The load curve and ambient temperature variation can be taken probabilistic and stochastic optimization problem can be framed which is expected to give more realistic results.

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