MEASUREMENT OF TEMPERATURE OF UNDER GROUND POWER CABLES

A DISSERTATION
submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(Power System Engineering)

By

VIKRAM SINGH

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE-247667 (INDIA)

JULY, 1986

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled "MEASUREMENT OF TEMPERATURE OF UNDER GROUND POWER CABLES" in partial fulfilment of the requirements for the degree of MASTER OF ENGINEERING IN ELECTRICAL ENGINEERING (Power System Engineering) submitted in the Department of Electrical Engineering, University of Roorkee, Roorkee, is an authentic record of my own work carried out under the supervision of Dr. Suleebka, Reader, Electrical Engineering Department, University of Roorkee, Roorkee.

The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

Vikram Singh
(VIKRAMSINGH)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

P Suleebka
(Dr.P.SULEEBKA)
READER (H.V.)

ROORKEE

DATED 31st July,1986

ACKNOWEDGEMENTS

The author feels priviledged in extending his heartiest obligations and indebtedness to Dr. P.Suleebka, Reader (H.V.), Department of Electrical Engineering for his keen interest, inspiring guidence, helpful suggestions and constant encouragement in carrying out the present investigation at University of Roorkee, Roorkee.

The author is obliged to Dr. P.Mukhopadhyay, Prof. and Head, Prof. R.N.Agrawal and Sri Bharat Gupta, Electrical Engineering Department for providing the necessary facilities for carrying out the experimental work.

Author's special gratitude are due to technical staff of high current laboratory Sri Kalyan Singh and Sri Narendra Kumar for their nice co-operation throughout the work.

I am also thankful to Sri Ram Gopal, typist for his careful typing.

Last, but not the least my special thanks are due to my wife, who took all the brunt in order to give me free time to complete the work.

Vikram Singh
(VIKRAM SINGH) 31/7/86

ROORKEE

July 31,1986

ABSTRACT

Several experiments were performed in our high current laboratory to measure the cable temperature, when laid in air as well as when buried directly in ground. The results of these experiments show very good agreement with the estimated values based on the thermal equivalent circuit under steady state condition.

The short time loading and emergency loading were also tested and verified in both the cases and results were found quite satisfactory.

The transient temperatures upto steady state were also noted and attempts were made to match them with the values estimated. But, inspite of our best efforts we were not able to get good agreement in the time constant values. Further experimental work and analysis is necessary in this direction.

CONTENTS

F - Effect of moisture on soil resistivity.

G - Estimation of thermal capacitance

H - Calculation of earth thermal capacitance

I - Solution of thermal circuit

J - Calculation of short time loading capacities of the cable.

LIST OF FIGURES

CHAPTER-1

INTRODUCTION

Now a days, there is a preference to use underground cable for transmission and distribution of power because it has several advantages. For example, in highly populated cities it is quite undesirable to install an O.H. Transmission line because it is unsafe, costly and environmentally unacceptable. Another principle application is, where safety, security and reliability are the main problems, these include airport approaches, station and substation exits, long water crossing and areas with extreme vulnerability to damage by natural forces or Vandalism [B1].

One of the main hurdles in the use of underground cables is its prohibitive cost. If, however, we are able to find means for better utilization of the cable, for example, by increasing the current carrying capacity of a given size of cable, the use of the cable will be better justified.

In this dissertation report an attempt has been made to measure the temperature of the cables in operation and isolate the parameters, which could assist in increasing its current carrying capacity.

The measured cable temperatures are compared with the temperature estimated on the basis of available theory.

CHAPTER-2

ESTIMATION OF CABLE TEMPERATURES: REVIEW

In the initial days of the cable system the engineers were only concerned with the steady state thermal performance of the cable. The method of cable installation was considered one of the most important factor on which cable thermal performance depends.

The current carrying capacity of the high voltage cables may be governed by economics laws or considerations of temperature rise. The temperature rise factor is of more importance since it establishes a definite physical limit to the current rating. On account of their high cost it is most important that the cable should be loaded to their safe limit, and a great deal of research work had been done in early years of this century to establish safe current carrying capacities.

The various methods were tried to solve the steady state temperature rise problem of the cable and finally a much accurate method was developed by developing the equivalent thermal circuit of cable system which was analogous to electrical circuit. This thermal circuit obeys the ohms law of electric circuit, as under

$$\text{Heat flow} = \frac{\text{Temperature Difference}}{\text{Thermal resistance}}$$

In the early days of Electrical industry most people were not greatly concerned with transient ratings. In early years of the nineteenth century lot of work was done in connection with transient ratings of the cable syst in Britian and America.

In 1929, N.P.Bailey published a formula for transien heating of buried cable [1]. In 1930, W.B.Kirke published a transient technique for the use on cables in ducts but he neglected the soil component of the transient [2] In 1931 and again in 1935, E.A.Church presented a very interesting theory, based on Fourier Analysis for solution of both transient and cyclic loads on the duct cables. He include the thermal constants of duct bank but neglect those of the soil in obtaining his results [3]. In 193 Shanklin and Buller published an transient analysis for cable in air. They give a simple (and approximate) correction factor to allow for the effect of the earth in case of buried cable and duct cables [5]. In 1933 Miller and Wollaston in a slightly different approach to the same problem omitted the earth component of the transient from his mathematical work and suggest that an empirical correction be used to take care of it [6]. Later on 1935, Church [4] and Kidder [7] had also published some methods to tackle the problem of transient loading.

In 1931, Elwood A. Church [3] had made an attempt to solve the problem of temperature rise under variable loading in order that the maximum use may be made of the large investment in power cables. He tried a rigorous solution to estimate the temperature rise from sheath surface to conductor, making use of Bessel functions.

The problem was solved rigorously for single core and three core 'H' type cable. The corrections to be applied in case of standard belted cable were also discussed. The possible error involved in the assumptions necessary in the solution were also discussed and it was shown that knowing the temperature of the air at the sheath surface (sheath surface temperature) the temperature of the conductor can be estimated within ± 4-5% of the correct value, if the constants of cable are known with this accuracy. The method can also be applied to solution of the temperature rise of the sheath surface provided the constants of complete thermal circuit are known with sufficient accuracy.

In 1939, Kidder, A.H. [8] published a paper on emergency ratings of cable system. In this paper he describes the place of emergency ratings in the system plan, the magnitude of emergency loads, approximate frequency of cable future in service, approximate probability of emergency load occurrence and voltage regulation. He also described the temperature transients in a buried cable system. The thermal circuit which was considered is shown in fig. (2.1) and the solution of this circuit is given

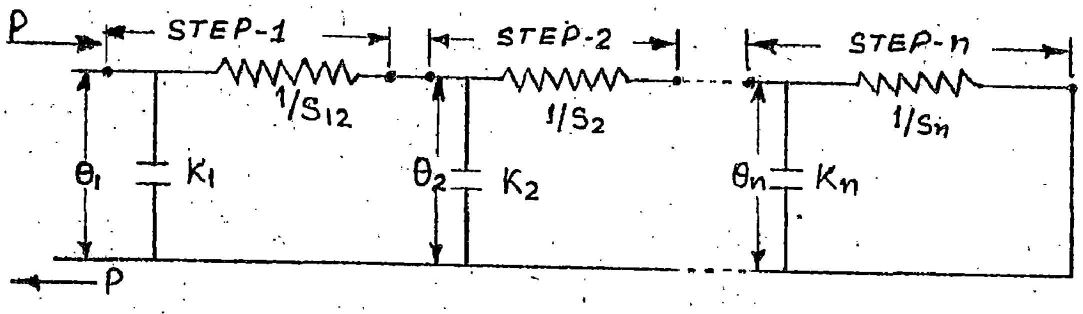


FIG [2.1] THERMAL CIRCUIT

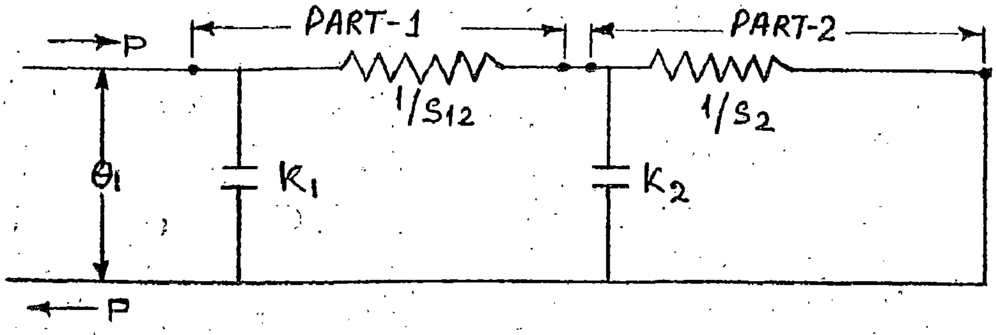


FIG. [2.2] APROXIMATE CIRCUIT

by the equation

$$\theta = A\ H(1-e^{-at}) + BH\ (1-e^{-bt}) \ldots + NH(1-e^{-nt}) \quad \ldots(2.1)$$

For solution of the circuit it was reduced to the form shown in fig (2.2). The solution of this thermal circuit was obtained by writting two heat flow equations as under :

$$h.dt = (\theta_1 - \theta_2)\ S_{12}\ dt + K_1 d\theta_1 \quad \ldots(2.2)$$

$$(\theta_1 - \theta_2) S_{12}\ dt = \theta_2 S_2 dt + K_2 d\theta_2 \quad \ldots(2.3)$$

The solution of the circuit is given as under

$$y = \theta_1/H = A\ (1-e^{at}) + B(1-\ e^{-bt})$$

where, a,b, A and B are constants.

The method was tried for cable laid in air and directly buried system and found much more accurate as compared to the previously used regorious methods using lumped and distributed parameters. The calculations are much simpler and are less laborious. Since than till 1951 no important work had been done in this field. In 1951, F.H.Buller [9] presented another approach to solve the problem of transient loading. In his publication he developed a equivalent electrical circuit of a buried cable system as shown in fig. (2.3) and then derive a formula for calculating various temperature rise of the cable system. The working formula

R_1 → INSULATION THERMAL RESISTANCE OF THE CABLE
R_2 → THERMAL RESISTANCE OF OUTERSHEATH ETC.
θ_1 → THERMAL CAPACITY OF THE CONDUCTOR + 1/2 OF THE THERMAL CAPACITY OF CABLE INSULATION
θ_2 → THERMAL CAPICITY OF SHEATH, ARMOURING ETC + 1/2 THE THERMAL CAPACITY OF CABLE INSULATION

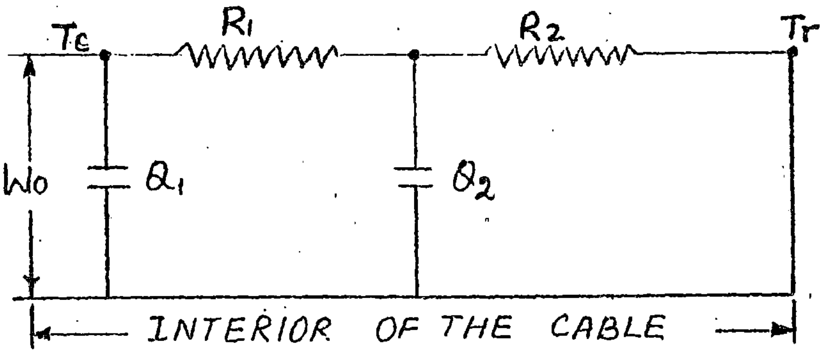


FIG.[2.3]
THERMAL CIRCUIT

is given below :

$$T_r = \frac{W_o}{4\pi} p' \left[-E_i\left(\frac{-r^2}{4\ kt}\right) + E_i\left(\frac{-D^2}{kt}\right) \right] \times \left[1 - \frac{p'Q}{4\pi t} e^{-r^2/4kt} \right] \qquad \ldots(2.8)$$

where,

W_o = Loss in cable watt/cm.

T_r = Cable surface temperature rise in °C

p' = Soil thermal resistivity °C-cm/watt

r = Radius of the cable in cm

k = Soil thermal diffusivity $= \frac{1}{p'q}$ cm^2/hr

t = time in hours.

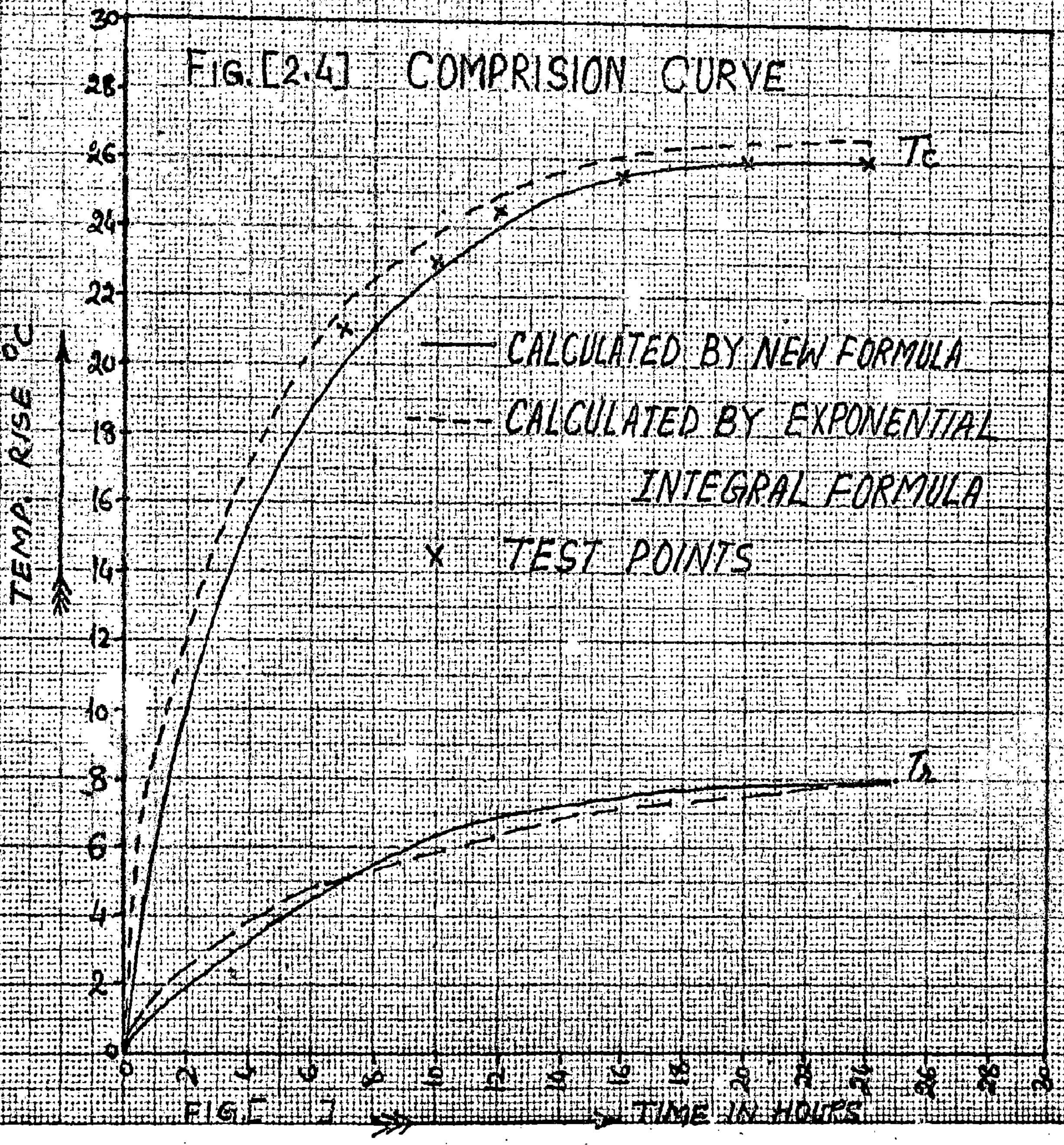
D = Depth of burial in cms

Q = Total thermal capacity of buried cable W H/°C-meter

The author had presented a graph shown in fig. (2.4) showing the comparison between the calculated values of temperature by using his formula and old available exponential integral formula. It is quite evident from this graph that the results are farely accurate: This formula does not apply to cables in duct.

In 1953, Neher J.H. [10] presented a simplified mathematical procedure by which the transient temperature after a given time interval under constant load may be determined at any point in the thermal circuit of a cable system.

FIG.[2.4] COMPRISION CURVE



This method involves the determination of the real component of the effective thermal impedance of the cable system at that point at which the transient temperature rise is desired This part of the procedure require lot of labour involve the repeated solution of a simple electrical network by use of vector algebra.

In this method the main deficiencies of the previously available methods given by Buller E.A. Church and Shanklin had been minimised such as:

(1) This method is much sound theoretically.

(2) This gives sufficient accurate results in all types of cable systems.

(3) The theory used is easily understandable.

(4) The method is less laborious.

In 1955, Van Wormer F.C. [11] had published a paper in which an improved approximate technique for calculating cable temperature transients had been discussed. The author solved the thermal circuit of cable system by three different methods and comparative curve plotted shows the accuracy of these methods separately.

In first method equivalent circuit as shown in fig. (2.4) was used, lumping the thermal capacity of the main conducter insulation 50% at the conducter and 50% at the sheath. This method gives considerably lower temperature

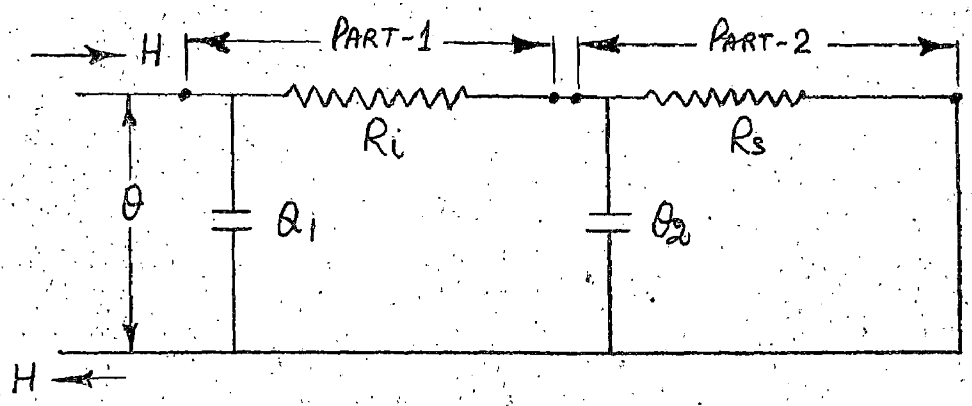


FIG.[2.4a] THERMAL CIRCUIT WITH LUMPED PARAMETERS rise than the exact solutions using distributed constants.

In second method, again using an equivalent π circuit, lumping P-times thermal capacity of the insulation at the conductor and rest (1-p) times at the sheath fig (2.5). The value of P is obtained by the expression

$$P = \frac{1}{2 \ln \frac{R}{r}} - \frac{1}{\frac{R^2}{r^2} - 1}$$

where,

R = Overall radius of the cable upto sheath in cms.

r = Conductor radius in cms.

This method gives a considerable improvement in accuracy, but for small conductor with heavy wall of thickness, there is still a considerable difference between this approximation and the solution using distributed constants.

In third method, the author used the modified equivalent 'T' circuit as shown in fig. (2.6), lumping the thermal capacity of insulation at the conductor sheath and mid way point through the insulation thermal resistance. This method gives a very close check with the solution using the distributed constants.

So, for cables with large conductors and moderate walls of insulation or small conductors with thin wall of insulation can be solved by second method using equivalent π circuit quite accurately. And for the cables with small

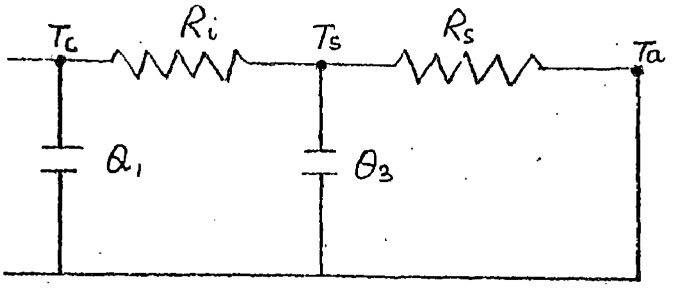


FIG.[2.5]. EQUIVALENT π ELECTRIC CIRCUIT FOR THE THERMAL CIRCUIT OF CABLE

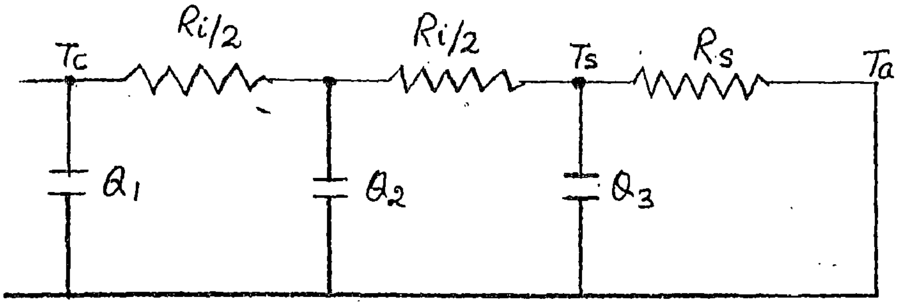


FIG.[2.6]. MODIFIED EQUIVALENT T ELECTRIC CIRCUIT FOR THE THERMAL CIRCUIT OF THE CABLE.

conductors and heavy walls of insulat on the third method using equivalent T circuit was found much accurate. In some case first method was also used and found accurate.

CHAPTER-3

THERMAL PERFORMANCE OF CABLES

3.1 Heat Produced within the Cable

The heat produced within the cable which is mainly responsible for its temperature rise will depends upon following factors:

(a) I^2R losses in the conductors.

(b) Dielectric lasses

(c) Losses in the metallic sheathing and armouring.

3.1.1 I^2R Losses

In case of single core cable this loss is I^2R only, while in case of balancely loaded three core or $3\frac{1}{2}$ core cable this loss will be $3\ I^2R$ Watts. If the multicore cable is not balanced loaded then this loss can be estimated as under :

$$\text{Total } I^2R \text{ Loss} = I_{eq}^2 R + I_N^2 R_1 \qquad \ldots(3.1)$$

where,

$I_{eq}^2 = I_R^2 + I_y^2 + I_B^2$

I_N = Neutral current

R = Conductor a.c. resistance in Ohm.

R_1 = Neutral conductor a.c. resistance in Ohms

3.1.1.1 Estimation of 'R'

Knowing the value of the specific resistance of the aluminium, the d.c. resistance of the conductor per unit length can be found easily The values of d.c. resistance for various size aluminium conductors are given in ISS No.1554 (Part I) table no. 2..

Now following factor should be applied to this value of R_{dc} to get the actual value of 'R'.

(1) The value of R_{dc} given in ISS table are true for 20^o temperature only. To get the resistance at any other temperature R_{dc} should be multiplied by a factor 'Ft' . The values of these correction factors for various temperatures are given in ISS No.1554 (Part I) table No. 4..

(2) So obtained d.c. resistance of conductor at θ^oC must be modified to get a.c. resistance by taking account for skin and proximity effect. The skin effect at normal frequencies are significant and increases with conductor cross section. With large conductors eg 2000 mm^2 the increase in 'R' due to this cause is of the order of 20%. So the value of R_{dc} at 0^oC must be multiplied by a factor 'F_s' to get actual R at 0^oC.

(3) In multicore cable to allow for the lay of the cable the value obtained above is further increased by 2% ie it is multiplied by a factor Fe = 1.02

3.1.2 Dielectric Loss

The dielectric loss due to leakage and hysteresis effects in the dielectric, is usually expressed in terms of the loss angle δ, where $\delta = 90 - \phi$ and ϕ = Power factor angle of the dielectric. The dielectric loss is given by

$$W_d = \omega C V^2 \tan \delta \qquad \ldots(3.2)$$

where,

C = Capacitance to neutral in farad per meter

V = Phase voltage in volts

As this loss is directly proportional to V^2, so very small in case of low voltage cable and generally negligible.

3.1.3 Loss in Metallic Sheathing and Armouring :

The eddy current in metallic sheath of the cable and steel armouring give rise to conductor temperature and hence these two appears as the heat source.

3.2 Development of Thermal Model

The following three main factors decides the safe current rating of the cable :-

(1) The installation conditions and ambient conditions.

(2) The heat dissipating properties of the cable.

(3) The maximum permissible temperature rise at which its components may be operated without harming them.

3.2.1 Mechanism of Heat Flow in Multicore Cables:

The mechanism of heat flow in a 3 $\frac{1}{2}$ core PVC insulated and PVC sheathed armoured cable (on which we worked) will be as shown in fig.(3.1). The heat flow from source ie conductor to atmosphere is assumed to be radial only. The electrical representation of heat flow is shown in fig. (3.2) and fig (3.3) for transient and steady state condition.

It is a well known fact that current in the conductors, eddy currents in the sheaths and dielectric loss increases the temperature of the cable conductors and so produced heat is dissipated to the surrounding medium ie air/soil and temperature of the conductor becomes constant (saturation condition) at that instant when heat generated becomes equal to the heat dissipated. The path of heat dissipation is through dielectric, armouring and air/soil.

The various parameters of electrically represented thermal circuit under both conditions of the cable can be found by using various formulas.

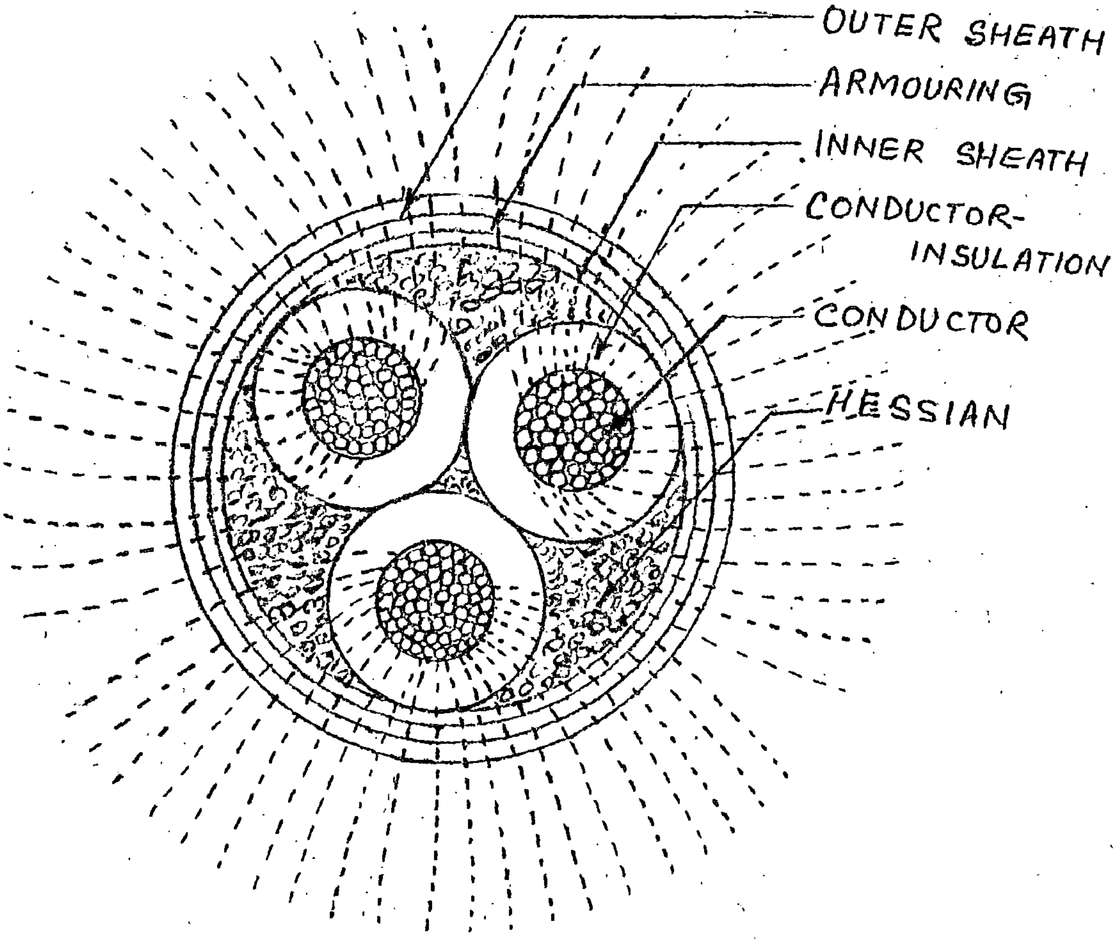
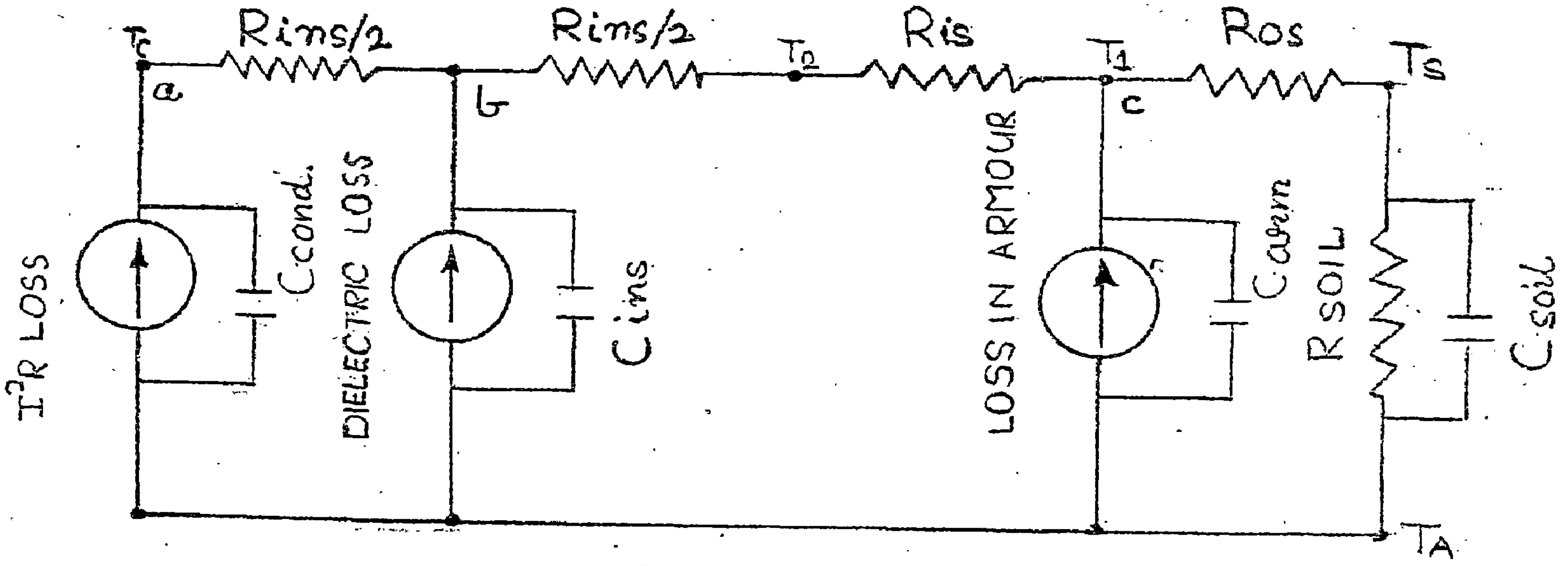


FIG. [3.1] MECHANISM OF HEAT FLOW



TRANSIENT CONDITION

FIG.[3.2]. THERMAL MODEL OF P.V.C. INSULATED & P.V.C. SHEATHED ARMOURED CABLE

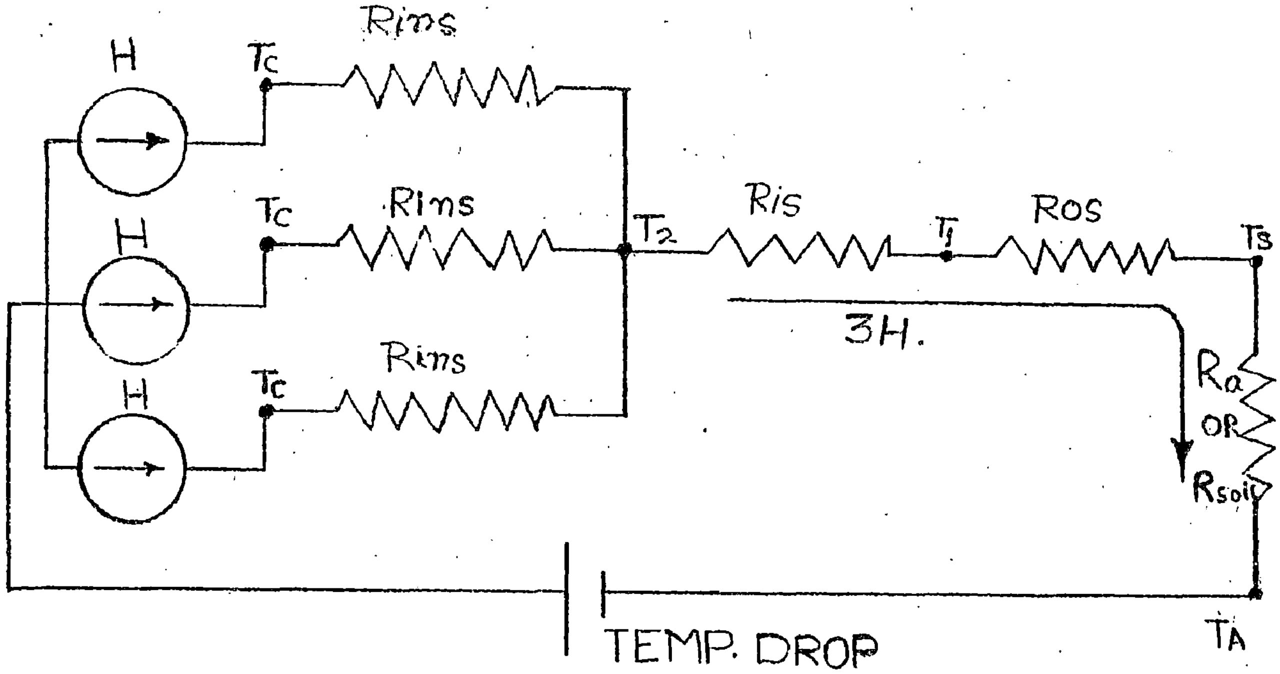


FIG.[3.2a] EXACT THERMAL CIRCUIT
(STEADY STATE CONDITION)

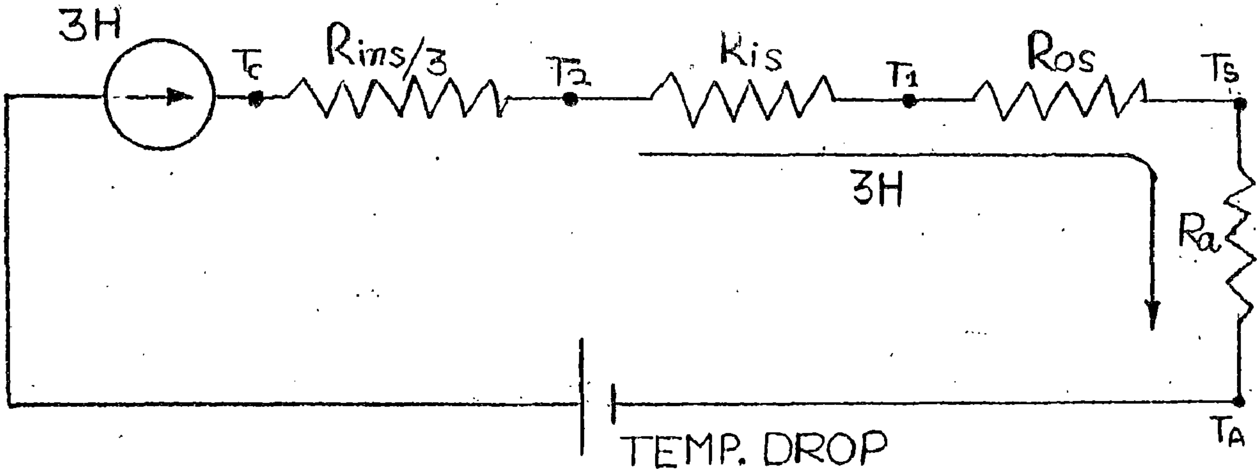


FIG.[3.3] MODIFIED THERMAL CIRCUIT
(ELECTRICALLY REPERSENTED MECHANISM OF HEAT FLOW IN A MULTICORE P.V.C. ARMOURED CABLE)

3.3 Estimation of Various Parameters:

3.3.1 Conductor Insulation Thermal Resistance of Multicore Cable [B2]

The conductor insulation thermal resistance of a multicore cable is given by

$$R_{ins} = \frac{g}{2\pi} \times G \quad \text{Thermal Ohms/meter}$$

where,

g = Thermal resistivity of insulating material (PVC) in 0^oC-m/Watt

G = Geometric Factor

Simon had derived an empirical formula based on experimental results for Geometric factor 'G' as under, [12]

$$G = (0.85 + \frac{0.2t}{T}) \log_e \left[(8.3 - \frac{2.2t}{T})(\frac{T+t}{d}) + 1 \right]$$

where,

T = Thickness of conductor insulation in cms

t = Thickness of the belt insulation in cms

r = Radius of the conductor in cms

d = Diameter of the conductor in cms

So,

$$R_{ins} = \frac{g}{2\pi} \left[(0.85 + \frac{0.2t}{T}) \right] \ln \left[(4.15 - \frac{1.1t}{r})(\frac{T+t}{r}) + 1 \right] \qquad \ldots(3.3)$$

3.3.2 Thermal Resistance of Inner Sheath

The thermal insulation resistance of the inner sheath is given by

$$R_{is} = \frac{g_1}{2\pi} \ln \frac{r_3}{r_4} \text{ Thermal Ohms/meter} \quad \ldots(3.4)$$

where,

g_1 = Thermal Resistivity of PVC

r_3 = Outer Radius of the belt in cms

r_4 = Inner Radius of the belt in cms

3.3.3 Thermal Resistance of Outer Sheath

The thermal insulation resistance of the outer sheath is given by :

$$R_{os} = \frac{g_1}{2\pi} \ln . \frac{r_2}{r_1} \text{ Thermal Ohms/meter} \quad \ldots(3.5)$$

where,

g_1 = Thermal Resistivity of the PVC

r_2 = Outer Radius of the cable in cms

r_1 = Inner Radius of the cable in cms.

3.3.4 Thermal Resistance of the Soil [B3]

When a cable is buried direct in ground, the heat flow in the surrounding soil of the cable follows the same laws that apply to the flow through the cable itself, and it depends on two factors :

(i) the thermal resistivity of the soil

(ii) Lines of heat flow from the cable

The thermal resistivity of the soil largely depends upon the percentage moisture contents in the soil and also partly depends upon the type of the soil. Both these factors have wide variation from point to point along the route of the buried cable, particularly in city areas (in cities % moisture content varies frequently). The table below gives us the idea of the range of values that may be found in practice.

Type of Soil	Moisture Content (%)	Thermal Resistivity (Th. Ohm)
Clay	20-25	80-160
Sandy Loam	10-15	90-130
Gravel	4-8	50-100
Sand	4-12	70-110
Chalk	15-20	90-140
Made-up Soil	12-22	90-140

The important influence of varying moisture content on certain types of the soil is shown in fig.(3.4). These curve are strictly applicable to a particular thermal characteristic of the soil.

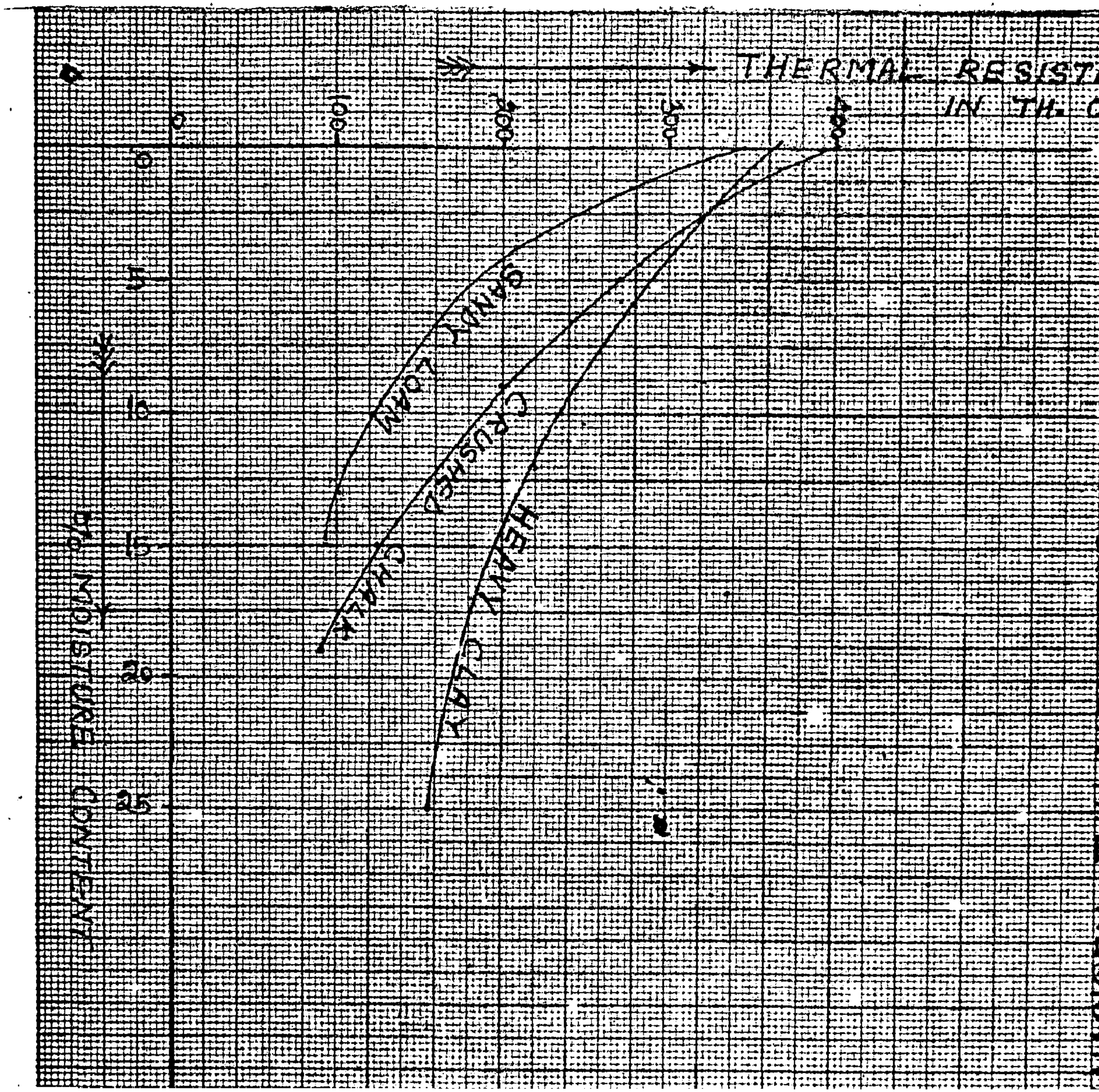


FIG. [3.4] SOIL THERMAL RESISTIV

From the above table and curve it is clear that the nature and moisture content of soils to be met in the cable laying are such as to limit the range of the thermal resistivity of the soil between 70 and 160.

In calculating the thermal resistance of soil, the path taken by the heat dissipated from the cable is of much importance and in this regard two theories have been put forward.

According to the first theory Kennelly assumes that the surface of the soil above the cable is a plane isothermal, and that all the heat is ultimately transmitted to the surface of the earth (ambient). which being in contact with free air, remains at the uniform temperature. On this assumption it can be derived that,

$$R_{soil} = G = \frac{g}{2\pi} \log_e \frac{2h}{r_2} \text{ Thermal Ohms/m} \qquad \ldots(3.6)$$

where,

g = Thermal resistivity of the soil

h = Depth of the cable axis below the ground surface in m.

r_2 = Overall radius of the cable in m.

According to the second theory of R.Apt., the soil surrounding the cable can be considered to be equivalent to that of a cylinder of material, which is having equal resistivity as that of the soil. The radius of this cylinder shall be equal to the depth of the cable axis below the ground surface. On this assumption the cable is surrounded by a series of concentric isothermals and R_{soil} is given by

$$R_{soil} = \frac{g}{2\pi} \ln {}^{h}/_{r_2} \text{ Thermal Ohms/m.} \qquad \ldots(3.7)$$

Experimental results with buried cable shows that neither of the two theories are completely satisfactory but at the same it was observed that the effect of varying depth is represented much better by first theory.

The effect of soil resistivity and depth of lying on the current carrying capacity of a cable depends on the relative values of the thermal resistances of soil and other components of the cable. For a 3 core cable laid under normal conditions, R_{soil} may vary between 1 to 3 times that of the total internal thermal resistance of the cable. Hence if the thermal resistivity of the soil is reduced from 120 to 60 , the current carrying capacity can be increased by 15% to 30%. Similarly variation in depth of laying within reasonable limits affects the permissible current carrying capacity of the cable but to lesser extent.

The reduction in rating due to increasing the depth of lying from one meter to two meter would be approximate 8%.

3.4 Estimation of Various Thermal Capacities

3.4.1 Main Insulation Thermal Capacity

From the geometry of the cable we have fig.(3.5).

Area of the insulation over each conductor = Overall area of the insulated conductor minus area of the conductor

$$= \frac{\pi}{4} D_e^2 - \frac{\pi}{4} D_i^2 = \frac{\pi}{4} (D_e^2 - D_i^2) \text{ cm}^2 \qquad ...(3.8)$$

$\therefore$ Volume of the insulation over each

$$\text{Conductor} = \frac{\pi}{4} (D_e^2 - D_i^2) \times 1 \text{ cm}^3$$

$$= \frac{\pi}{4} (D_e^2 - D_i^2) \text{ cm}^3/\text{cm}. \qquad ...3.9)$$

We know that,

$$\text{Sp. gravity} = \frac{\text{Density of the material}}{\text{Density of the water}} \text{ (For same volume)}$$

$\therefore$ Density of the material = Sp. gravity of the material (as density of water = 1 gm/cc)

$\therefore$ mass of the material = Volume x Sp. gravity

$\therefore$ mass of the conductor insulation

$$= \frac{\pi}{4} (D_e^2 - D_i^2) \times \text{Sp. gravity of PVC} \qquad ...(3.10)$$

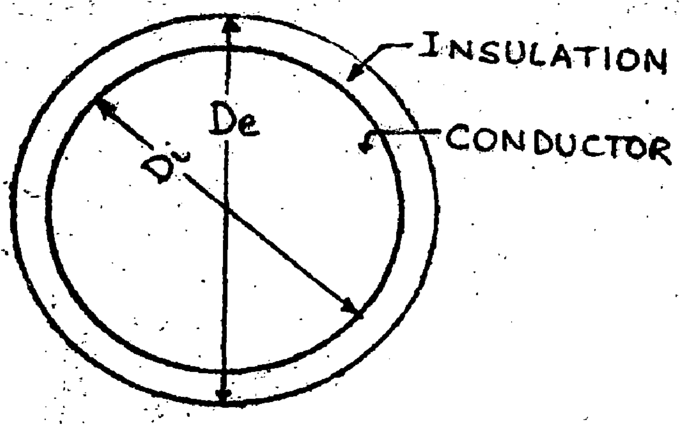


FIG.[3.5] GEOMETRY OF INSULATED CABLE

Again we know that

$$Q = m\ s\ t \quad \text{Cal.}$$

where Q = Heat capacity in cal

m = mass in gms

s = specific heat in cal/gm-°C

t = temperature difference °C

$\therefore\ Q = m \times s$

Also thermal capacitance as per definition, $C = m \times s$

$$\therefore C = \frac{\pi}{4} (D_e^2 - D_i^2) \times s \times \text{sp. Heat} \qquad \ldots(3.11)$$

Now from ref [B4]

Specific heat for PVC(flex) = 0.4 cal/gm °C

Specific gravity for PVC = 1.16 -1.40

by putting $s = 0.4$ and sp. gravity = 1.3 in equation (3.11) we get,

$$C = \frac{\pi}{4} \times 0.4 \times 1.3 \times (D_e^2 - D_i^2) \ \text{Cal/°C .cm}$$

$$= 0.4082\ (D_e^2 - D_i^2)\ \text{Cal/°C-cm}$$

$$= \frac{0.4082 \times 100}{0.239 \times 3600} (D_e^2 - D_i^2)\ \text{WH/°C -m}$$

$$= 0.04744\ (D_e^2 - D_i^2)\ \text{WH/°C-m}$$

$$\therefore C = 0.04744\ (D_e^2 - D_i^2)\ \text{WH/°C-m} \qquad \ldots(3.12)$$

By using the above expression the values of the various thermal capacitances of main conductor insulation C_{ins}, inner sheath C_{is} and outer sheath C_{os} can be calculated.

3.4.2 Conductor Thermal Capacity

In similar fashion the thermal capacitances of conductors and netural wire can be estimated as under.

Sp. Heat 's' for Aluminium = 0.217 [B6]

Sp. gravity for aluminium = 2.7 [B6]

$$\therefore \quad C_{cond} = \frac{\pi}{4} (D_e^2 - D_i^2) \times 0.217 \times 2.7$$

In this case $D_i = 0$ and D_e = conductor diameter

$$\therefore \quad C_{cond} = \frac{\pi}{4} \times 2.7 \times 0.217 \; D_e^2 \quad \text{Cal}/^{o}\text{C-cm}$$

$$= \frac{\pi \times 100 \times 2.7 \times 0.217}{4 \times 0.239 \times 3600} D_e^2 \quad \text{WH}/^{o}\text{C-m}$$

$$= 0.05345 \; D_e^2 \quad \text{WH}/ {}^{o}\text{C-m} \qquad \ldots(3.13)$$

The thermal capacitance of neutral conductor will be half of the C_{cond} capacitance as to the close approximation the cross section area of neutral conductor is half of the main conductor hence volume/mass/thermal capacitance will be half.

3.4.3 Thermal Capacity of the Soil

3.4.3.1 Specific Heat of Soil [B7]

Under actual field condition the soil moisture content determines more than any other factor, the energy required to raise the temperature of soil. For instance, the dry weight specific heat of mineral soil, inspite of variation in texture and organic matter is about 0.20. But if the moisture is advanced to 20%, the specific heat of the wet-mass becomes 0.33 while an increase of 30% moisture raises the wet weight specific heat to 0.38.

Obviously, therefore, since the moisture is one of the major factor in respect to heat capacity of the soil, it has much to do with the rate of the warming up and the cooling up of soils.

3.4.3.2 Specific Gravity of Soil

As per ref [B11] the specific gravity of the soil are as given under :

S.No.	Type of Soil	Sp. gravity
1	Earth dry Loose	1.2
2	Earth dry packed	1.5
3	Earth moist loose	1.3
4	Earth moist packed	1.6

Knowing the depth of the cable burial from surface of the earth, the thermal capacity of the soil surrounding. the cable can be estimated in the usual way by considering the cylinder of the soil of the diameter equal to (2h + D), where, h = Depth between cable surface and earth surface and D = diameter of the cable.

The volume of the earth cylinder will be

$$= \frac{\pi}{4} (D_e^2 - D_i^2)\ \text{cm}^3/\ \text{unit length}$$

where, $D_e = (2h+D)$ cms and

$D_i = D$ cms

$\therefore$ Mass of the soil m = Vol. x specific gravity

$$\therefore m = \frac{\pi}{4} (D_e^2 - D_i^2) \times \text{specific gravity} \ \text{-- gm}$$

$\therefore$ Heat capacity Q = m x s

where s = specific heat

$$\therefore Q = \frac{\pi}{4} (D_e^2 - D_i^2) \times \text{specific gravity} \times s \ \ \text{Cal}/^{\circ}\text{C-cm}$$

Putting the value of specific gravity and s as :

sp gravity = 1.3 s = 0.33 we gets

$$Q = \frac{\pi}{4} \times 1.3 \times 0.33\ (D_e^2 - D_i^2)\ \text{Cal}/^{\circ}\text{C-cm}$$

$$= \frac{\pi}{4} \times 1.3 \times 0.33 \times 100\ (D_e^2 - D_i^2)\ \ \text{Cal}/^{\circ}\text{C-m}$$

$$= \frac{\pi}{4} \times 1.3 \times 0.33 \times 100 \times \frac{1}{0.239}(D_e^2 - D_i^2)\ \ \text{J-sec}/^{\circ}\text{C-m}$$

$$= \frac{\pi \times 1.3 \times 0.33 \times 100}{4 \times 0.239 \times 3600}\ (D_e^2 - D_i^2)\ \text{W-H}/^{\circ}\text{C-m}$$

$$= 0.039\ (D_e^2 - D_i^2)\ \text{WH}/^{\circ}\text{C-m} \qquad \ldots.(3.14)$$

3.5 Solution of Equivalent Thermal Circuit

The solution of equivalent thermal circuit under steady state condition is very simple and be obtained by using the simplified circuit as shown in fig.(3.6). This circuit can now be solved by applying the ohm's law and hence,

$$T_c - T_s = 3H \times (R_{os} + R_{is} + R_{ins}/3) \qquad \ldots(3.8)$$

On the other hand the solution of the circuit under transient condition is some what laborious and complicated, because it is well known fact that the thermal resistance thermal capcity and temperature of the insulation are not linear functions of the thickness of the insulation. Various methods were tried to solve this circuit in the middle of 19th century.

An approximate solution was obtained by Lumping the constants of the cable [11] and forming an equivalent π circuit as shown in fig. (2.4). As in case of transmission line problems half of the thermal capacity of the insulation may be placed with thermal capacity of the conductor at conductor temperature and half may be placed with thermal capacity of the sheath at sheath temperature. Since the temperature gradient through the insulation is not a linear function of insulation thickness, this method of allocating the thermal capacity of the insulation does not accurately represent the total heat stored in the insulation.

The accuracy of this approximate solution using Lumped parameter may be improved by modifying the arrangement fig.(2.5). In new arrangement a fraction P of the thermal capacity of the insulation is placed with conductor at conductor temperature and part (1-P) is placed with sheath at sheath temperature. If P is 0.5, this condion is equivalent to an insulated cylinder of infinite radius. For this case the temperature distribution is known to be a linear function of insulation thickness and so placing the half the thermal capacity at each terminal temperature accurate accounts for the total heat storage.

Also $R_e/R_i = 1$, when insulation thickness is zero and hence thermal capacity is also zero.

The problem of temperature transient can also be solved by the use of modified equivalent T circuit for greater accuracy as shown in fig.(2.6). In this equivalent circuit the thermal capacity of the insulation is placed at three places:

(1) Part at the conductor temperature
(2) Part half way through the insulation thermal resistance and,
(3) Part at the sheath

The method using equivalent π network of fig.(2.5) is simple and accurate. To solve this circuit for temperature transients the value of P can be obtained by using the following expression :

$$P = \frac{1}{2 \ln \frac{R}{r}} - \frac{1}{\frac{R^2}{r^2} - 1} \qquad \ldots(3.15)$$

where

R = Cable radius in cms

r = Conductor radius in cms

After knowing the value of P the heat flow equations can be written as from the circuit it is clear that of the heat, (h.dt) flowing into part one, some $K_1 d\theta_1$ is absorbed by part one and the rest $(\theta_1 - \theta_2) S_{12}$ dt flows on into part two, hence

$$h\,dt = (\theta_1 - \theta_2) S_{12}\,dt + K_1\,d\theta_1 \qquad \ldots(3.16)$$

and similarly, the heat entering part two $(\theta_1 - \theta_2) S_{12}$ dt is partly absorbed and partly dissipated through S_2, or

$$(\theta_1 - \theta_2) S_{12}\,dt = \theta_2 S_2\,dt + K_2\,d\theta_2 \qquad \ldots(3.17)$$

By solving equations (3.16) and (3.17) first to eliminate θ_2 and then θ_1, the two following instantaneous relationship are obtained, one in terms of hot-spot rise (θ_1) and the other in terms of (θ_2) :

$$\frac{d^2\theta_1}{dt^2} + \left(\frac{S_{12}}{K_1} + \frac{S_{12} + S_2}{K_2}\right) \frac{d\theta_1}{dt} + \frac{S_{12}\,S_2}{K_1\,K_2}\,\theta =$$

$$= h\left(\frac{S_{12}\,S_2}{K_1\,K_2}\right) \qquad \ldots(3.18)$$

and,

$$\frac{d^2\theta_2}{dt^2} + \left(\frac{S_{12}}{K_1} + \frac{S_{12} + S_2}{K_2}\right) \frac{d\theta_2}{dt} + \frac{S_{12} S_2}{K_1 K_2}\,\theta =$$

$$= h.\,\frac{S_{12}}{K_1\,K_2} \qquad \ldots(3.19)$$

When the values of circuit parameters are constants and $h = H$, one solution of these linear equations takes the following form :

$$\theta = AH\,(1-e^{-at}) + BH\,(1-e^{-bt}) \qquad \ldots(3.20)$$

where A, B, a and b are constant and can be written as :

$$a = \frac{1}{2}\left(\frac{S_{12}}{K_1} + \frac{S_{12}+S_2}{K_2}\right) + \sqrt{\frac{1}{4}\left(\frac{S_{12}}{K_1} + \frac{S_{12}+S_2}{K_2}\right)^2 - \frac{S_{12}S_2}{K_1K_2}} \qquad \ldots(3.21)$$

$$b = \frac{1}{2}\left(\frac{S_{12}}{K_1} + \frac{S_{12}+S_2}{K_2}\right) - \sqrt{\frac{1}{4}\left(\frac{S_{12}}{K_1} + \frac{S_{12}+S_2}{K_2}\right)^2 - \frac{S_{12}S_2}{K_1K_2}} \qquad \ldots(3.22)$$

$$A = \frac{1}{(a-b)}\left[\frac{1}{K_1} - b\left(\frac{1}{S_{12}} + \frac{1}{S_2}\right)\right] \qquad \ldots(3.23)$$

and

$$B = \frac{-1}{(a-b)}\left[\frac{1}{K_1} - a\left(\frac{1}{S_{12}} + \frac{1}{S_2}\right)\right] \qquad \ldots(3.24)$$

In this way by calculating the values of constant a, b, A and B the complete solution of circuit can be written and temperature at any instant can be estimated.

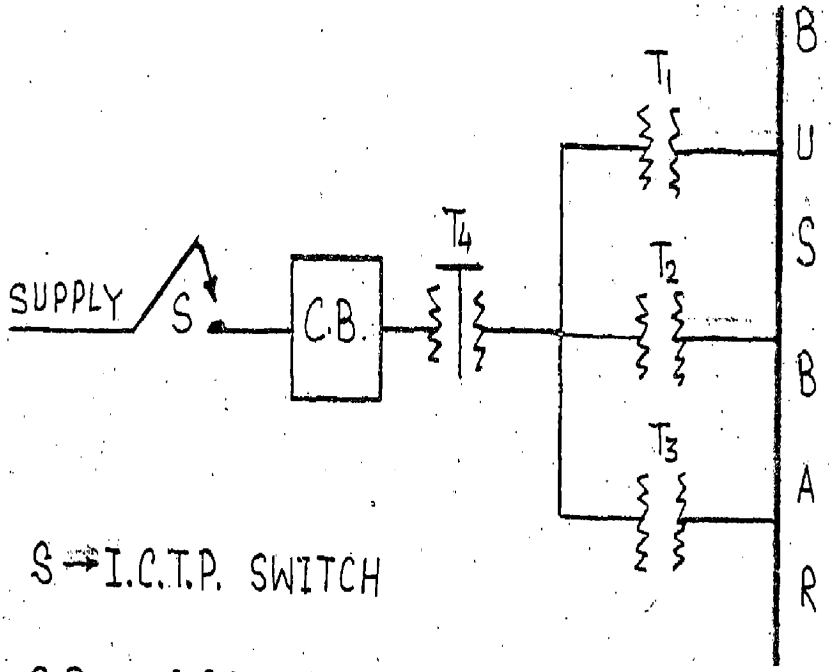
CHAPTER-4

EXPERIMENTAL SET-UP

A very simple experimental set-up was used to measure the cable temperature in laboratory. The single line diagram of the set up is shown in fig. (4.1).

A permanent set up using three high current transformers connected as shown in diagram were used to pass high current in the cable under test. A 3-phase auto transformer was used by which the current of desired value can be passed through the cable. The output of auto transformer was given to 3 nos, 3 phase step down transformer connected in parallel (for detailed specification of these transfor mer please see appendix A_1, A_2). The output of these parallel connected transformers available at four aluminium busbars was connected to one end of the 3 $\frac{1}{2}$ core cable under test. The following other equipments were used for the experiments.

1. A high ratio (5/10,000) current transformer with a milliampere-meter of suitable range to the measure the current in the conductors.
2. A Resistance Temperature Detector (RTD) (for detailed specifications please see appendix A_3).
3. A Temperature Measuring Unit, which was fabricated by the auther during his M.E.Project [13]. This unit



S → I.C.T.P. SWITCH

C.B. → CIRCUIT BREAKER

T1, T2, T3 → 3-ϕ TRANSFORMERS

T4 → DIMMERSTAT

FIG.[4.1] SINGLE DLINE DIAGRAM OF EXPERIMENTAL SET-UP measure the out of balance voltage of the bridge in one arm of which the RTD is connected in amplified form. The out of balance voltage corresponds to the change in the temperature of RTD. (which can be placed, where temperature is to be measured) and with the help of calibration chart it can be converted into temperature units.

4. A standard iron constantant thermo-couple.
5. A standard digital unit to measure the voltage induced in the thermocouple which corresponds to its hot junction temperature at that instant. This unit is calibrated directly in terms of °C.
6. Digital multimeter to measure the output of temperature measuring unit.
7. Mercury Thermometer to measure the ambient temperature.

CHAPTER-5

CABLE IN AIR

The cable used was a 150 mm^2, $3\frac{1}{2}$ core P.V.C. insulated and P.V.C. sheathed armoured cable of approximately 25 meter length which was laid down on the laboratory floor. One end of the cable was connected to the four output bus-bars of the high current, 50 c/s , transformers and at other end of the cable all the conductors were short circuited to get a balanced load on the cable. The armouring was left floating. The applied voltage to the cable can be varied from 0 to maximum 9 volts to get the required loading on the cable.

A 6 mm diameter hole was drilled in the cable near the short circuit end upto the conductor (phase) surface. In this hole an Iron-constantant thermocouple was inserted and placed in such a position that the hot junction of the thermocouple just touches the conductor surface. The thermocouple was fixed in the hole air tight by filling the PVC fillings in the hole. The cold junction of the thermocouple was connected to a standard instrument which is calibrated directly in terms of hot junction temperature in ^{o}C including lead and ambient temperature compensation.

A C.T. connected milliameter (5/10000 was connected in one phase of the cable to read out the conductor current.

Now the cable was loaded by switching the supply on for a particular current. Due to I^2R loss in the conductor the temperature of the conductor starts rising which is read on the unit. The rising temperature readings for that particular current were taken at a fixed time internal till the conductor temperature becomes constant (steady state saturation condition). At each time of the reading the ambient temperature was also noted by thermometer. At saturation condition the cable surface temperature was measured with the thermocouple.

The same experiments were repeated for various currents of 20 Amps, 30 Amps, 50 Amps, 100 Amps and 150 Amps. and the observations were recorded in table No.5.1.. to..5.5

The rise in conductor temperature measured for each current were plotted as a function of time and are shown in fig.(5.1) and fig.(5.2).

5.1 Estimation of Conductor Temperature

For estimating the conductor temperature at saturation for a particular value of current the various cable parameters are calculated first as follows :

1. The various thermal insulation resistance eg. conductor insulation thermal resistance (R_{ins}), outer sheath thermal resistance (R_{os}), Inner sheath thermal resistance (R_{is}) and a.c. conductor resistance 'R' are

TABLE NO 5.1

1. CABLE ON LAB. FLOOR
2. CURRENT PER PHASE - 20A
3. MEASUREMENT POSITION :- NEAR THE S.C. END

S. NO.	TIME IN HOURS	AMBIENT TEMP. T_A °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	$T_{CM} - T_A$ °C
1	0	33	33	0
2	1/4	33	33.6	0.6
3	1/2	33.5	34.3	0.8
4	3/4	33.5	34.7	1.2
5	1	34	35	1
6	$1\frac{1}{4}$	34	35.2	1.2
7	$1\frac{1}{2}$	34	35.3	1.3
8	$1\frac{3}{4}$	34	35.4	1.4
9	2	34	35.4	1.4
10	$2\frac{1}{4}$	34	35.4	1.4
11	$2\frac{1}{2}$	34	35.4	1.4
12	$2\frac{3}{4}$	34	35.4	1.4

CABLE SURFACE TEMPERATURE AT SATURATION - 35.3°C.

TABLE NO 5.2

1. CABLE ON LAB. FLOOR
2. CURRENT PER PHASE - 30A
3. MEASUREMENT POSITION :- NEAR THE S.C.END

S. NO.	TIME IN HOURS	AMBIENT TEMP. T_A °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	$T_{CM} - T_A$ °C
1	0	34	34	0
2	1/4	34	35.4	1.4
3	1/2	34	35.8	1.8
4	3/4	34	36.2	2.2
5	1	34	36.5	2.5
6	1 $\frac{1}{2}$	34	36.7	2.7
7	1 $\frac{1}{2}$	34	36.8	2.8
8	1 $\frac{3}{4}$	34	36.9	2.9
9	2	34	36.9	2.9
10	2 $\frac{1}{4}$	34	36.9	2.9
11	2 $\frac{1}{2}$	34	36.9	2.9
12	2 $\frac{3}{4}$	34	36.9	2.9
13	3	34	36.9	2.9

CABLE SURFACE TEMPERATURE AT SATURATION - 36.3°C

TABLE NO 5.3

1. CABLE AT LAB. FLOOR
2. CURRENT PER PHASE - 50 AMPS
3. MEASUREMENT POSITION : NEAR S.C. END

S. NO.	TIME IN HOURS	AMBIENT TEMP. T_A °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	$T_{CM} - T_A$ °C
1	0	32.5	32.5	0
2	1/4	32.5	35.4	2.9
3	1/2	32.5	36.6	4.1
4	3/4	33	37.3	4.3
5	1	33	37.7	4.7
6	$1\frac{1}{4}$	33.5	38.3	4.8
7	$1\frac{1}{2}$	33.5	38.8	5.3
8	$1\frac{3}{4}$	33.5	39.2	5.7
9	2	33.5	39.7	6.2
10	$2\frac{1}{4}$	33.5	39.8	6.3
11	$2\frac{1}{2}$	34.	39.9	5.9
12	$2\frac{3}{4}$	34	40.0	6.0
13	3	34	40.0	6.0
14	$3\frac{1}{4}$	34	40.1	6.1
15	$3\frac{1}{2}$	34	40.[illegible]	6.0

CABLE SURFACE TEMPERATURE AT SATURATION - 38.2°C

TABLE NO 5·4

1. CABLE ON LAB. FLOOR
2. CURRENT PER CONDUCTOR - 100 AMPS.
3. MEASUREMENT POSITION :- NEAR S.C. END.

S. NO.	TIME IN HOURS	AMBIENT TEMP. T_A °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	$T_{CM} - T_A$ °C
1	0	30	31.0	1.0
2	1/4	30	33.9	3.9
3	1/2	30	36.9	6.9
4	3/4	30.5	40.5	10.0
5	1	30.5	42.5	12.0
6	$1\frac{1}{4}$	30.5	43.8	13.3
7	$1\frac{1}{2}$	31	45.2	14.2
8	$1\frac{3}{4}$	31	46.6	15.6
9	2	31.5	47.1	15.6
10	$2\frac{1}{4}$	31.5	47.5	16.0
11	$2\frac{1}{2}$	32	47.7	15.7
12	$2\frac{3}{4}$	32	48.0	16.0
13	3	32	48.2	16.2
14	$3\frac{1}{4}$	32	48.2	16.2
15	$3\frac{1}{2}$	32	48.2	16.2
16	$3\frac{1}{4}$	32	48.2	16.2
17	4	32	48.2	16.2

CABLE SURFACE TEMPERATURE AT SATURATION = 42.5°C

TABLE NO 5.5

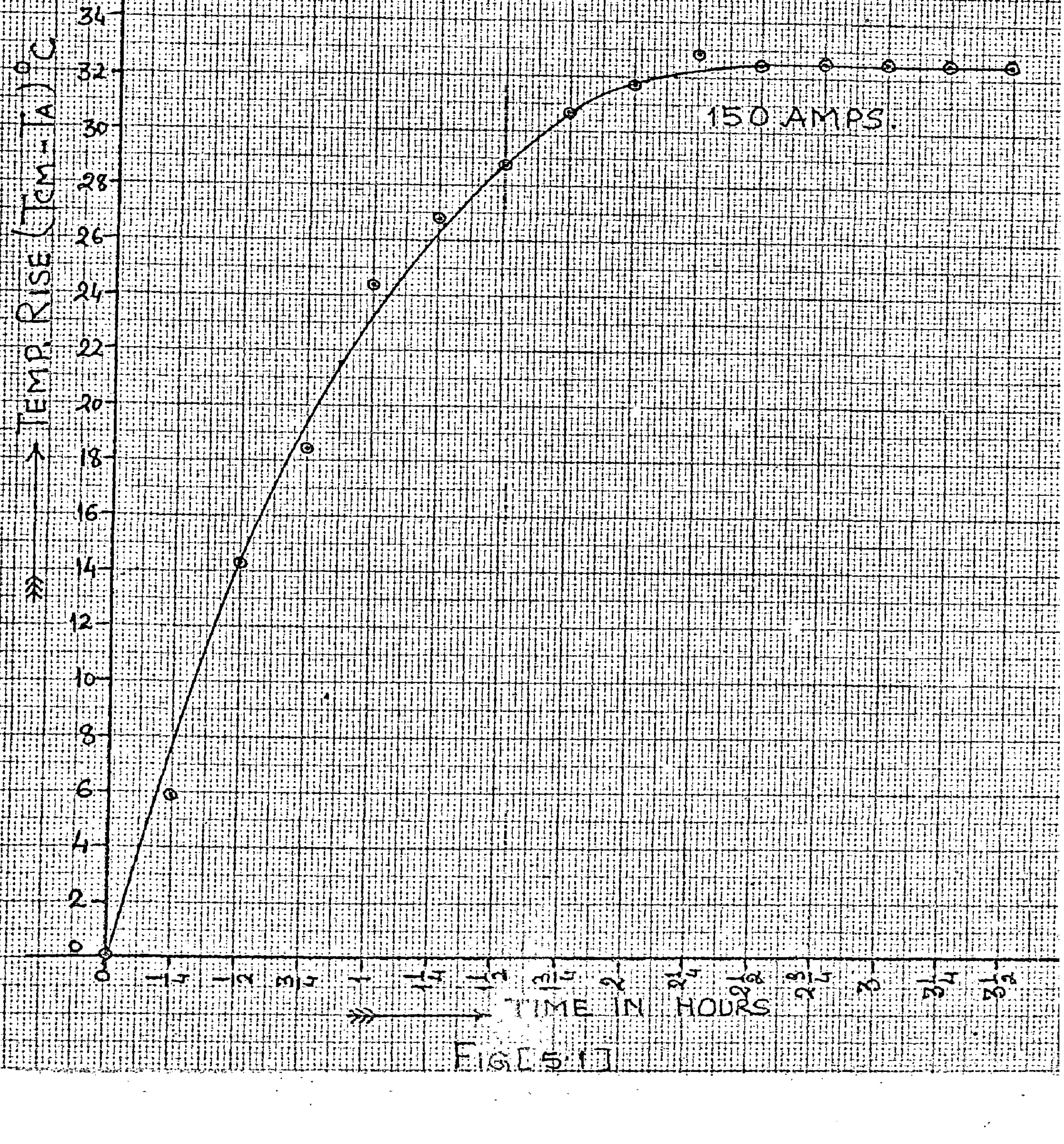
1. CABLE ON LAB. FLOOR
2. CONDUCTOR CURRENT : 150 AMPS
3. MEASUREMENT POSITION : NEAR S.C. END

S. NO.	TIME IN HOURS	AMBIENT TEMP. T_A °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	$T_{CM} - T_A$ °C
1	0	31	31	0
2	1/4	31	36.9	5.9
3	1/2	31	45.3	14.3
4	3/4	31	49.4	18.4
5	1	31	55.4	24.4
6	$1\frac{1}{4}$	31.5	58.3	26.8
7	$1\frac{1}{2}$	31.5	60.3	28.8
8	$1\frac{3}{4}$	31.5	62.2	30.7
9	2	31.5	63.2	31.7
10	$2\frac{1}{4}$	31.5	64.4	32.9
11	$2\frac{1}{2}$	32	64.4	32.4
12	$2\frac{3}{4}$	32	64.5	32.5
13	3	32	64.5	32.5
14	$3\frac{1}{4}$	32	64.5	32.5
15	$3\frac{1}{2}$	32	64.5	32.5

CABLE SURFACE TEMPERATURE AT SATURATION - 50.4°C

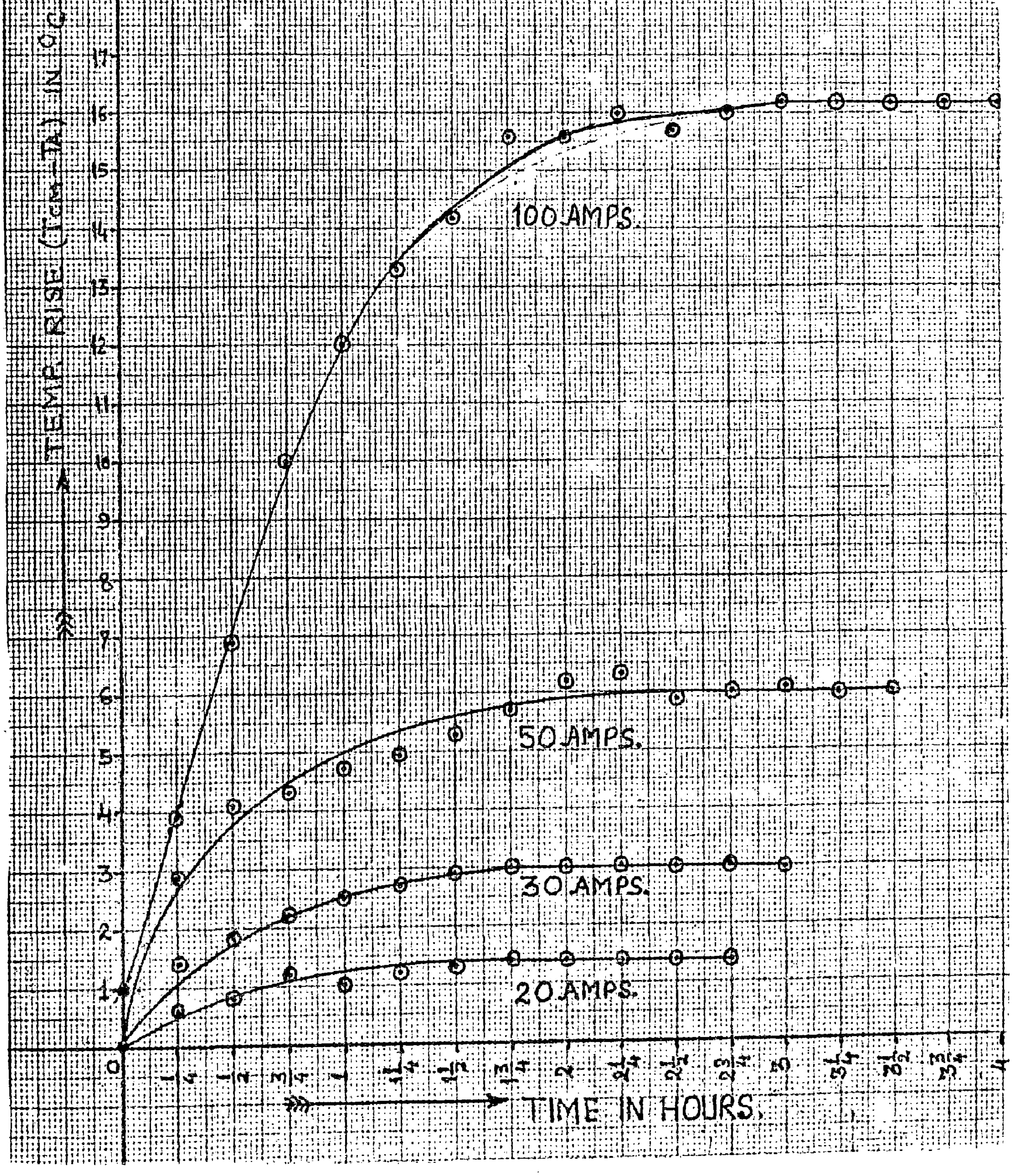
FIG[5-1] SATURATION CURVE FOR $3\frac{1}{2}$ CORE CABLE

CABLE LAID IN AIR AT LAB. FLOOR



FIG[5.1]

FIG.(5.23) SATURATION CURVE FOR 3½ CORE CABLE LAID IN AIR AT LAB. FLOOR



calculated using various formula's described in sec. no.3.

2. Considering the balanced loading of the cable total heat generated in the conductors is estimated by I^2R (Neglecting dielectric loss and loss due to armouring).
3. Knowing the values of heat generated 'H' watt per conductor, R_{os}, R_{ins}, R_{is} and 'R', we can calculate various temperature drops as follows (considering electrical equivalent circuit of the thermal circuit of fig.(3.3) Let,

   T_s = Cable surface temperature in ^oC
   T_1 = Temperature at armouring in ^oC
   T_2 = Temperature at insulation surface in ^oC
   T_c = Conductor temperature in ^oC

and, $T_2 - T_1 = \theta_{m_1}$, $T_2 - T_1 = \theta_{m_2}$ and $T_c - T_2 = \theta_{m_3}$

Then,

$$\begin{aligned} \theta_{m_1} &= 3H \times R_{os} \\ \theta_{m_2} &= 3H \times R_{is} \\ \theta_{m_3} &= H \times R_{ins} \end{aligned} \qquad \text{-------} \qquad \ldots(5.1)$$

Now using equation (5.1), the various temperature drops θ_{m_1}, θ_{m_2} and θ_{m_3} were calculated. The sum of all these drops was added in the measured cable surface temperature T'_s ^oC to get the estimated conductor temperature T_c ^oC so,

$$T_c = \theta_{m_1} + \theta_{m_2} + \theta_{m_3} + T_s \qquad \ldots(5.2)$$

In this fashion the conductor temperatures at various currents were estimated and recorded in the Table No..5:6. (For calculations please see appendix B,C,D).

After estimating the conductor temperature for various currents it was observed that the measured value T_{CM} and the calculated value T_c are coming same to close approximation. The error as a function of cable loading is shown in fig.(5.3) and has a maximum value of ± 10%.

5.2 Means to Minimise the Error

To minimise this error we though of some other parameter to be considered during experiment such as :

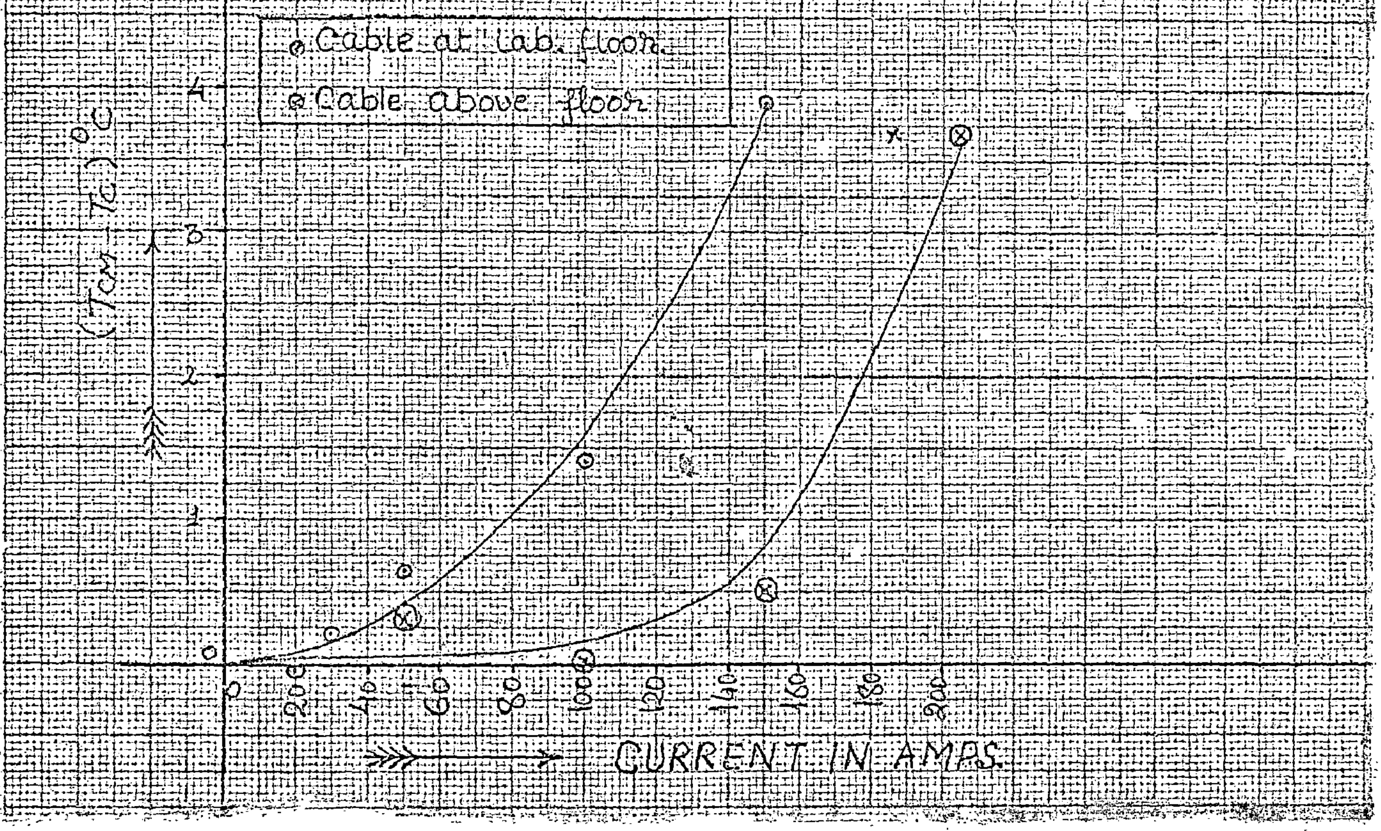
1. To check the load balancing, if the load is not exactly balanced, the neutral current may contribute some heat in the conductor, which have not been considered during estimation of T_c . For this, currents in each phase conductors and in neutral conductor were measured and noticed that the system is approximate balanced system (I_y = 199A, I_B = 198A, I_R =201 Amp and I_N = 3 Amp). This small unbalancing of load may not be responsible for the error.
2. By measurement it was observed that the temperature of the floor was slightly less than the ambient temperature and so this would cause some error

TABLE NO. 5.6

1. CABLE ON LAB. FLOOR
2. MEASUREMENT POSITION : NEAR SHORT CIRCUIT END
3. AMBIENT TEMPERATURE RANGE - 31°C to 34°C

S. NO.	CURRENT I AMPS	HEAT 'H' WATTS	TOTAL HEAT 3H WATTS	MEASURED CABLE SURFACE TEMP. T_S °C	CALCULATED TEMP. DROP θ_{m_1} °C	CALCULATED TEMP. DROP θ_{m_2} °C	CALCULATED TEMP. DROP θ_{m_3} °C	TOTAL CALCULATED DROPS θ_m °C	CALCULATED CONDUCTOR T_C °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	$T_{CM}-T_C$ °C
1	150	6.864	20.592	50.4	3.072	0.3947	6.816	10.283	60.68	64.5	3.82
2	100	2.877	8.631	42.5	1.29	0.165	2.857	4.312	46.81	48.2	1.38
3	50	0.7662	2.2987	38.2	0.343	0.044	0.761	1.148	39.35	40	0.65
4	30	0.248	0.743	36.3	0.111	0.0142	0.246	0.3712	36.67	36.9	0.23
5	20	0.110	0.330	35.3	0.0492	0.0063	0.110	0.1655	35.46	35.4	-0.06

FIG. [5.3] CURVE SHOWING RELATION BETWEEN ERROR AND CABLE LOADING



as the cable was laid on the floor. To check up this effect the same experiment for various currents were repeated but with a modification that the cable was now approximately 15 cms above the lab. floor. In addition a RTD was placed on the armouring surface to record the armouring temperature simultaneously. The observations are tabulated in Table No 5.7. From the table it can be observed that the error in conductor temperature estimation ($T_{CM} - T_C$) is reduced to 5%. In the table the measured and calculated values of temperature drops from cable surface to armouring using armouring temperature (measured by RTD) as a reference are also given , which shows very good agreement.

The another very important fact which has not been considered till now was that we were taking the measurements close to the S.C.end of the cable and it was possible that the heat from S.C. end by radiation, convection or axial flow may effect the measured value of conductor temperature. This fact was observed by measuring the cable surface temperature at the two ends of the cable and at the middle of the cable. It was observed that the temperatures at the ends was about 0.5°C higher than at the middle, obviously due to radiation from the open conductors. The measurements were again made with the thermocouple placed at the middle. During this set of observations the cable surface temperature was measured

TABLE NO 5·7

- CABLE ABOVE FLOOR AT APPRCX 15 CMS HEIGHT
- AMBIENT TEMPERATURE RANGE - 33-36°C

3. MEASUREMENT POSITION- NEAR S.C.END

CURRENT I AMPS	HEAT H WATTS	TOTAL HEAT $3H$ WATTS	CALC θ_{m_1} °C	CALC θ_{m_2} °C	CALC θ_{m_3} °C	MEASURED ARMORING TEMP. T_1 °C	MEASURED CABLE SURFACE TEMP. T_s °C	MEASURED θ_{m_1} °C	CALCULATED CONDUCTOR TEMP. T_c °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	$T_{CM}-T_C$ °C
150	6.864	20.592	3.072	0.394	6.816	57.5	53.9	3.6	64.18	67	2.82
100	2.877	8.631	1.29	0.165	2.857	44.5	43.2	1.30	47.51	48	0.49
50	0.766	2.298	0.343	0.044	0.761	38.3	37.4	0.90	38.55	38.9	0.35

using RTD at the cable surface. These observations and calculated values of conductor temperatures for various currents are recorded in Table No. 5.8 to 5.11. The saturation curve is shown in fig.(5.4).

Now it can be seen the difference between measured value of conductor temperature T_{CM} and calculated value T_C is very small. The error as a function of cable loading is shown in fig. (5.3) and has a maximum value of + 3%.

TABLE NO 5.8

1. CABLE ABOVE FLOOR
2. CURRENT PER PHASE - 50A
3. MEASUREMENT POSITION: MIDDLE OF THE CABLE

S. NO.	TIME IN HOURS	AMBIENT TEMP. T_A °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	MEASUSED CABLE SURFACE TEMP. T_S °C	$T_{CM}-T_A$ °C
1	0	32.5	32.5	32.5	0
2	1/4	32.5	33.7	32.8	1.2
3	1/2	32.5	34.4	33.0	1.9
4	3/4	33	34.9	33.5	1.9
5	1	33	35.3	33.9	2.3
6	$1\frac{1}{4}$	33	35.5	34.2	2.5
7	$1\frac{1}{2}$	33	35.7	34.4	2.7
8	$1\frac{3}{4}$	33	35.7	34.4	2.7
9	2	33	35.7	34.4	2.7
10	$2\frac{1}{4}$	33	35.7	34.4	2.7
11	$2\frac{1}{2}$	33	35.7	34.4	2.7

Calculated conductor temperature at saturation T_C=35.41°C

TABLE NO 5·9

1. CABLE ABOVE FLOOR
2. CURRENT PER PHASE : 100A
3. MEASUREMENT POSITION : MIDDLE OF THE CABLE

S. NO.	TIME IN HOURS	AMBIENT TEMP. T_A °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	MEASURED CABLE SURFACE TEMP. T_S °C	$T_{CM}-T_A$ °C
1	0	30	32.3	31.5	2.3
2	1/4	30	34.2	31.9	3.2
3	1/2	30	30.0	32.7	6.0
4	1/4	30.5	36.9	34.1	6.4
5	1	30.5	37.9	35.0	7.4
6	$1\frac{1}{4}$	30.5	38.5	35.5	8.0
7	$1\frac{1}{2}$	31	39.1	35.8	8.1
8	$1\frac{3}{4}$	31	39.6	35.8	8.5
9	2	31	39.9	36.1	8.8
10	$2\frac{1}{4}$	31	40	36.3	9.0
11	$2\frac{1}{2}$	31	40	36.3	9.0
12	$2\frac{3}{4}$	31	40	36.3	9.0
13	3	31	40	36.3	9.0
14	$3\frac{1}{4}$	31	40	36.3	9.0
15	$3\frac{1}{2}$	31	40	36.3	9.0
16	$3\frac{3}{4}$	31	40	36.3	9.0
17	4	31	40	36.3	9.0

$T_c = 36{\cdot}36$ °C

TABLE NO 5.10

1. CABLE ABOVE FLOOR

2. CURRENT PER CONDUCTOR : 150A

3. MEASUREMENT POSITION: MIDDLE OF THE CABLE

S. NO.	TIME IN HOURS	AMBIENT TEMP. T_A °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	MEASURED CABLE SURFACE TEMP. T_S °C	$T_{CM}-T_A$ °C
1	2	3	4	5	6
1	0	33	35	34.4	2
2	1/4	33	41	37	8
3	1/2	33	44.7	39.2	11.7
4	3/4	33	47.9	41.5	14.9
5	1	33.5	50	43.1	16.5
6	$1\frac{1}{4}$	33.5	51	43.6	17.5
7	$1\frac{1}{2}$	33.5	51.6	44	18.1
8	$1\frac{3}{4}$	33.5	52	44.3	18.5
9	2	33.5	52.4	44.5	18.9
10	$2\frac{1}{4}$	33.5	52.8	44.5	19.3
11	$2\frac{1}{2}$	34	53.4	44.7	19.4
12	$2\frac{3}{4}$	34	53.8	44.9	19.8

Contd....

TABLE NO 5·10 (CONTD.)

1	2	3	4	5	6
13	3	34	54.2	45.3	20.2
14	$3\frac{1}{4}$	34	54.4	45.8	20.4
15	$3\frac{1}{2}$	34	54.4	46	20.4
16	$3\frac{3}{4}$	34	54.4	46	20.4
17	4	34	54.4	46	20.4
18	$4\frac{1}{4}$	34	54.4	46	20.4
19	$4\frac{1}{2}$	34	54.4	46	20.4
20	$4\frac{3}{4}$	34	54.4	46	20.4

Calculated conductor temperature at saturation $T_C = 54.9^{\circ}C$

TABLE NO 5·11

1. CABLE ABOVE FLOOR
2. CURRENT PER PHASE - 205A
3. MEASUREMENT POSITION : MIDDLE OF THE CABLE

S. NO.	TIME IN HOURS	AMBIENT TEMP. T_A °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	MEASURED CABLE SURFACE TEMP. T_S °C	$T_{CM}-T_A$ °C
1	0	32	32	32	0
2	1/4	32	42.6	37.2	10.6
3	1/2	32	48.6	41.5	16.6
4	3/4	32.5	53.2	44.3	20.7
5	1	32.5	57	45.6	24.5
6	$1\frac{1}{4}$	32.5	60.6	49.5	28.1
7	$1\frac{1}{2}$	33	63.5	53.2	30.5
8	$1\frac{3}{4}$	33	66.1	54.8	33.1
9	2	33	68.	56.7	35.
10	$2\frac{1}{4}$	33	68.6	57.2	35.6
11	$2\frac{1}{2}$	33	69.1	57.4	36.1
12	$2\frac{3}{4}$	33	69.4	58	36.4
13	3	33	69.6	58.8	36.6
14	$3\frac{1}{4}$	33	69.7	59	36.7

Contd....

TABLE NO 5.11 (CONTD.)

S. No.	TIME IN HOURS	AMBIENT TEMP. T_A °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	MEASURED CABLE SURFACE TEMP. T_S °C	$T_{CM} - T_A$ °C
15	$3\frac{1}{2}$	33	69.8	59.2	36.8
16	$3\frac{3}{4}$	33	69.9	59.2	36.9
17	4	33	69.9	59.2	36.9
18	$4\frac{1}{4}$	33	70	59	37
19	$4\frac{1}{2}$	33	70	59	37
20	$4\frac{3}{4}$	33	70.1	59	37.1

Calculated conductor temperature at saturation $T_C = 73.8^\circ C$

SATURATION CURVES FOR $3\frac{1}{2}$ CORE CABLE LAID IN AIR

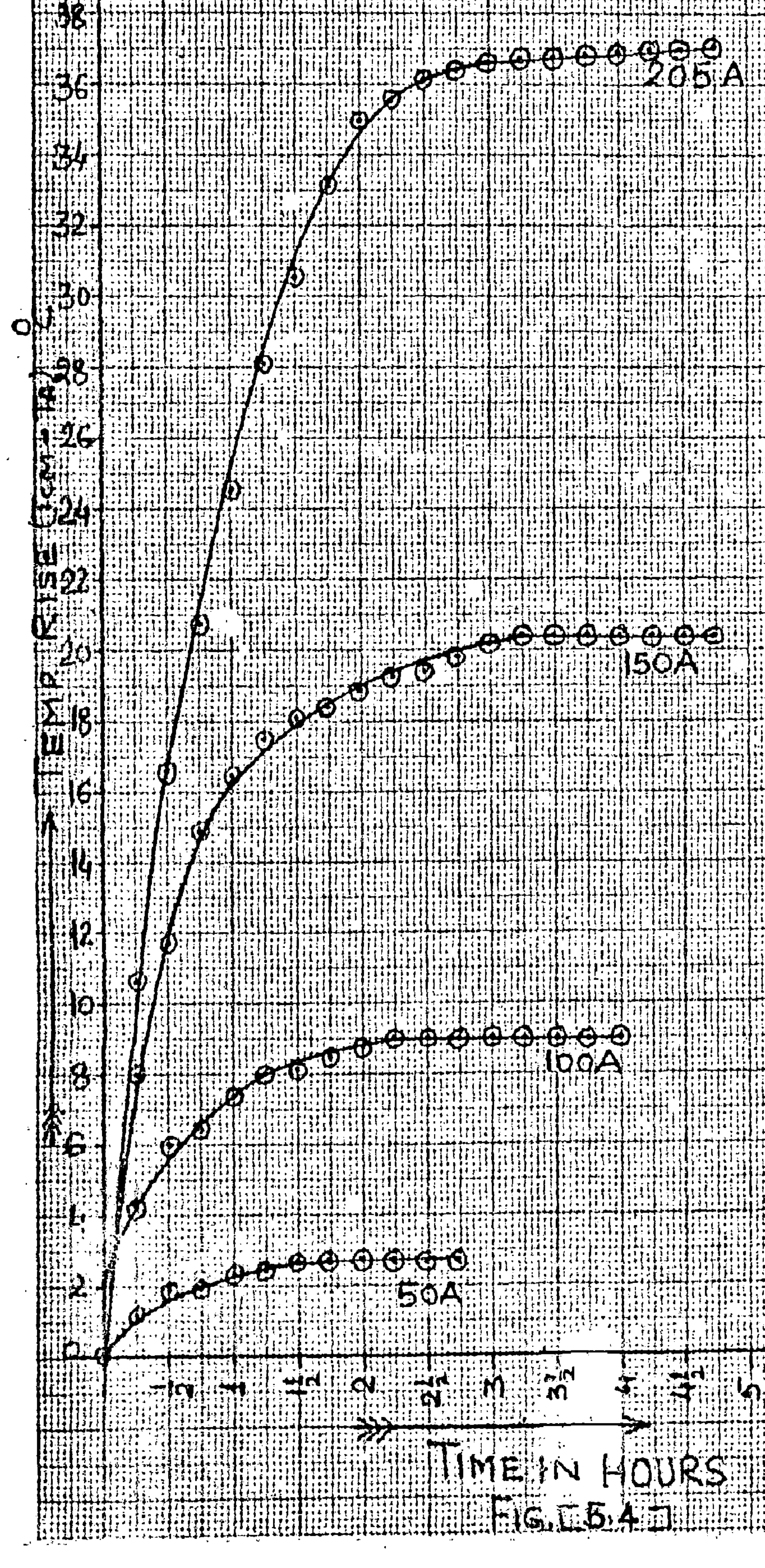


FIG. [5.4]

CHAPTER-6

CABLE BURIED DIRECTLY IN GROUND

Till now, we had discussed the method of temperature measurement when cable was laid in air, when the cable is buried directly, there are some factors which affects the performance of cable such as thermal resistance and thermal capacity of the soil. The values of these two parameters vary with the depth of burial of the cable as well as with the moisture contents in the soil.

To measure the cable temperature when cable was buried directly the same experiments were repeated as in case of cable laid in air. The 0.5 meter deep tranch was dug and approximate 2 meter portions of the cable (along with the thermocouple and RTD placed at their respective positions of conductor and cable surface) was buried in the tranch by back filling it with the same earth. The leads taken out from thermocouple and RTD were connected to their respective measuring units and then supply was switch on and the auto transformer was so adjusted that 200 Amp current passes per conductor. The conductor temperature at a regular time interval was noted till saturation along with the ambient temperature (measured by H_g thermometer) and cable surface temperature by RTD. These observations are recorded in Table No..6.1.. The same experiment was repeated for a current

TABLE NO 6.1

1. CABLE BURIED AT 0.5 METER DEPTH
2. CURRENT PER CONDUCTOR - 200 A
3. EARTH SURFACE TEMPERATURE AT SATURATION - 35.5°C
4. DRY SOIL CONDITION

S. NO.	TIME IN HOURS	MEASURED CABLE SURFACE T_S °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	AMBIENT TEMP. T_A °C	$T_{CM}-T_A$ °C
1	2	3	4	5	6
1	0	31.8	36.0	35	1
2	1/4	34.6	43.9	35	8.6
3	1/2	38.2	50.3	35	15.3
4	3/4	40.3	53.6	35	18.6
5	1	42.3	56.6	35	21.6
6	$1\frac{1}{4}$	44.0	59.0	35	24.0
7	$1\frac{1}{2}$	45.3	61.5	35	26.5
8	$1\frac{3}{4}$	46.3	63.8	35	28.8
9	2	48.2	64.4	35	29.4
10	$2\frac{1}{4}$	49.6	66.0	35	31.0
11	$2\frac{1}{2}$	50.5	67.1	36	31.1
12	$2\frac{3}{4}$	51.5	68.0	36	32.0
13	3	52.2	69.0	36	33.0
14	$3\frac{1}{4}$	53.2	69.8	36	33.8

Contd...

TABLE NO 6·1 (CONTD.)

1	2	3	4	5	6
15	$3\frac{1}{2}$	53.6	70.3	36	34.3
16	$3\frac{3}{4}$	54.3	71.0	36	35.0
17	4	54.7	71.6	36	35.6
18	$4\frac{1}{4}$	55.1	72.1	36	36.1
19	$4\frac{1}{2}$	56.0	72.7	36	36.7
20	$4\frac{3}{4}$	56.5	73.4	36	37.4
21	5	56.9	73.6	36	37.6
22	$5\frac{1}{4}$	57.5	73.8	36	37.8
23	$5\frac{1}{2}$	57.7	74.0	36	38.0
24	$5\frac{3}{4}$	58.2	74.2	36	38.2
25	6	58.2	74.4	36	38.4
26	$6\frac{1}{4}$	58.2	74.4	36	38.4
27	$6\frac{1}{2}$	58.2	74.5	36	38.5
28	$6\frac{3}{4}$	58.2	74.5	36	38.5
29	7	58.2	74.5	36	38.5

At saturation , estimated conductor temp. T_C ,

(i) Taking T_S as ref. $T_C = 74.78^{\circ}C$

(ii) Taking Earth Surface as ref $T_C = 74.43^{\circ}C$

of 150 Amp. and the observations are recorded in Table No. 6.2 The temperature rise as function of time are shown in fig.(6.1).

Mean while there was heavy rain, and so to see the effect of moisture content in the soil (which now increased by a considerable amount due to rain) one more set of observations for 200A were taken which is recorded in table no. 6.3 The saturation curves are shown in fig. (6.2).

Now the depth of burial was increased upto one meter and a set of observation was taken for 200A current under wet condition due to rain. These observations are recorded in table no.. 6.4... During this experiment it was observed that the effect of the surrounding medium heating or cooling of the exposed portion of the cable is effecting the cable conductor temperature by a considerable amount. This fact was observed by circulating the air with the ceiling fans over the exposed portion of the cable and it was found that the cable conductor temperature fell down by approximate 2 to 2.5°C. within 10 to 15 minutes. The saturation curve for this case is shown in fig. (6.3)

To avoid the error in the measurement of conductor temperature due to this fact, now, the cable was buried at 2 meter depth but this time most of the portion of cable was buried leaving a small portion exposed. This time the cable was loaded to its rated value of 228 Amp as per

TABLE NO 6·2

1. CABLE BURIED AT 0.5 METER DEPTH
2. CURRENT PER CONDUCTOR - 150A
3. EARTH SURFACE TEMPERATURE - 29.5°C

DRY SOIL CONDITION

S. NO.	TIME IN HOURS	MEASURED CABLE SURFACE TEMP. T_S °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	AMBIENT TEMP. T_A °C	$T_{CM}-T_A$
1	2	3	4	5	6
1	0	31.5	32.4	30	2.4
2	1/4	33.4	36.6	30	6.6
3	1/2	34.5	40.1	30	10.1
4	3/4	35.0	41.6	30	11.6
5	1	36.2	42.9	30	12.9
6	$1\frac{1}{4}$	36.5	43.9	30	13.9
7	$1\frac{1}{2}$	36.8	44.7	30	14.7
8	$1\frac{3}{4}$	37.5	45.5	30	15.5
9	2	37.8	46.0	30	16.0
10	$2\frac{1}{4}$	38.2	46.5	30	16.5
11	$2\frac{1}{2}$	38.4	46.9	30	16.9
12	$2\frac{3}{4}$	38.8	47.5	30	17.5
13	3	39.0	47.8	30	17.8

Contd....

TABLE NO 6·2 (CONTD.)

1	2	3	4	5	6
14	$3\frac{1}{4}$	39.2	48.0	30	18.0
15	$3\frac{1}{2}$	39.3	48.2	30	18.2
16	$3\frac{3}{4}$	39.6	48.6	30	18.6
17	4	39.8	48.9	31	17.9
18	$4\frac{1}{4}$	40.0	49.5	31	18.5
19	$4\frac{1}{2}$	40.2	49.6	31	18.6
20	$4\frac{3}{4}$	40.4	49.6	31	18.6
21	5	40.6	49.7	31	18.7
22	$5\frac{1}{4}$	40.7	49.8	31	18.8
23	$5\frac{1}{2}$	40.8	49.8	31	18.8
24	$5\frac{3}{4}$	40.8	49.7	31	18.7
25	6	40.8	49.8	31	18.8
26	$6\frac{1}{4}$	40.8	49.8	31	18.8
27	$6\frac{1}{2}$	40.8	49.7	31	18.7
28	$6\frac{3}{4}$	40.8	49.8	31	18.8
29	7	40.8	49.8	31	18.8

At Saturation, Estimated Conductor Temp. T_C

(i) Taking cable surface as ref. $T_C = 49.56^\circ C$

(ii) Taking earth surface as ref. $T_C = 50.06^\circ C$

TABLE NO 6·3

1. CABLE BURIED AT 0.5 METER DEPTH
2. CURRENT PER CONDUCTOR - 200A
3. EARTH SURFACE TEMPERATURE AT SATURATION:- 27.5°C
4. WET SOIL CONDITION

S. NO.	TIME IN HOURS	MEASURED CABLE SURFACE TEMP. T_S °C	MEASURED CONDUCTOR TEMP. T_{CM}°C	AMBIENT TEMP. T_A °C	$T_{CM}-T_A$ °C
1	2	3	4	5	6
1	0	29.7	30.5	29.5	1.0
2	1/4	32.8	38.4	29.5	8.9
3	1/2	36.5	43.5	29.5	14.0
4	3/4	37.8	46.4	29.5	17.3
5	1	38.8	49.4	29.5	19.9
6	1 $\frac{1}{4}$	39.8	50.0	29.5	20.5
7	1 $\frac{1}{2}$	41.2	52.1	29.5	22.6
8	1 $\frac{3}{4}$	42.5	54.0	29.5	24.5
9	2	43.3	55.6	29.5	26.1
10	2 $\frac{1}{4}$	43.7	56.4	29	27.4
11	2 $\frac{1}{2}$	43.8	56.5	29	27.5
12	2 $\frac{3}{4}$	44.0	56.8	29	27.8
13	3	44.3	57.1	29	28.1
14	3 $\frac{1}{4}$	44.5	58.1	29	29.1

Contd...

TABLE NO. 6·3 (CONTD.)

1	2	3	4	5	6
15	$3\frac{1}{2}$	44.7	58.6	29	29.6
16	$3\frac{3}{4}$	44.7	59.2	29	30.2
17	4	44.8	59.3	28.5	30.8
18	$4\frac{1}{4}$	44.8	59.5	28.5	31
19	$4\frac{1}{2}$	44.8	59.6	28.5	31
20	$4\frac{3}{4}$	44.8	59.6	28.5	31.1
21	5	44.8	59.8	28.5	31.1
22	$5\frac{1}{4}$	44.8	60.0	28.0	31.3
23	$5\frac{1}{2}$	44.8	60.1	28	32
24	$5\frac{3}{4}$	44.8	60.2	28	32.1
25	6	44.8	60.2	28	32.2
26	$6\frac{1}{4}$	44.8	60.2	28	32.2
27	$6\frac{1}{2}$	44.8	60.2	28	32.2
28	$6\frac{3}{4}$	44.8	60.2	28	32.2

ESTIMATED CONDUCTOR TEMP. $T_C\,^{\circ}C$

At Saturation

(i) Taking Cable Surface as ref. $T_C = 60.68^{\circ}C$

(ii) Taking earth surface as ref. $T_C = 60.72^{\circ}C$

TABLE NO 6·4

1. CABLE BURIED AT ONE METER DEPTH
2. CURRENT PER CONDUCTOR - 200 AMPS
3. OBSERVATIONS TAKEN AFTER RAIN

S. NO.	TIME IN HOURS	AMBIENT TEMP. T_A °C	MEASURED CABLE SURFACE TEMP. T_S °C	MEASURED CONDUCTOR TEMP. T_{CM} °C	$T_{CM} - T_A$ °C
1	2	3	4	5	6
1	0	29	28.5	30	1
2	1/4	30	30.9	35.9	5.9
3	1/2	30	32.7	40.1	7.1
4	3/4	31	33.8	42.3	11.3
5	1	31	34.7	44.5	13.5
6	1 1/4	32	35.8	46.0	14.0
7	1 1/2	32	36.0	46.6	14.6
8	1 1/4	32	36.3	47.5	15.5
9	2	32	36.9	48.0	16.0
10	2 1/4	32	37.2	48.4	16.4
11	2 1/2	32	37.3	49.0	17.0
12	2 3/4	32	37.8	49.3	17.3
13	3	32	38.2	49.6	17.6
14	3 1/4	32	38.5	50.0	18.0

TABLE NO 6·4 (CONTD.)

1	2	3	4	5	6
15	$3\frac{1}{2}$	32	38.6	50.4	18.4
16	$3\frac{3}{4}$	32	38.8	50.8	18.6
17	4	32	39.2	51.1	19.1
18	$4\frac{1}{2}$	32	39.6	51.6	19.6
19	5	32	40.3	52.0	20.0
20	$5\frac{1}{2}$	32	40.8	52.4	20.4
21	6	32	41.2	52.9	20.9
22	$6\frac{1}{2}$	32	41.4	53.3	21.3
23	7	32	42.5	53.7	21.7
24	$7\frac{1}{2}$	32	43.3	54.0	22.0
25	8	32	43.4	54.3	22.3
26	$8\frac{1}{2}$	32	43.8	55.0	23.0
27	9	32	42.5	55.5	23.5
28	10	32	43.3	57.0	25.0
29	11	32	43.2	56.8	24.8
30	12	32	43.2	56.9	24.9
31	13	32	43.2	56.8	24.8
32	14	32	43.2	56.8	24.8
33	15	32	43.2	56.8	24.8

Contd...

TABLE NO 6·4 (CONTD.)

1	2	3	4	5	6
34	16	32	43.2	56.9	24.9
35	17	32	43.2	57.1	25.1
36	18	32	43.4	58.2	26.2
37	19	32	43.5	58.9	26.9
38	20	31	43.8	59.1	28.1
39	21	31	44.5	59.3	28.3
40	22	31	44.8	60.8	29.8
41	23	31	45.2	61.0	30.0
42	24	31	45.4	61.4	30.4
43	25	31	45.5	61.6	30.6
44	26	31	45.8	62.4	31.4
45	27	31	46	62.8	31.8
46	28	31	46.0	62.8	31.8
47	29	31	46.1	62.7	31.7
48	30	31	46.0	62.8	31.8
49	31	31	46.0	62.8	31.8
50	32	31	46.1	62.9	31.9
51	33	31	46.0	62.8	31.8
52	34	31	46.0	62.8	31.8
53	35	31	46.0	62.8	31.8
54	36	31	46.0	62.8	31.8

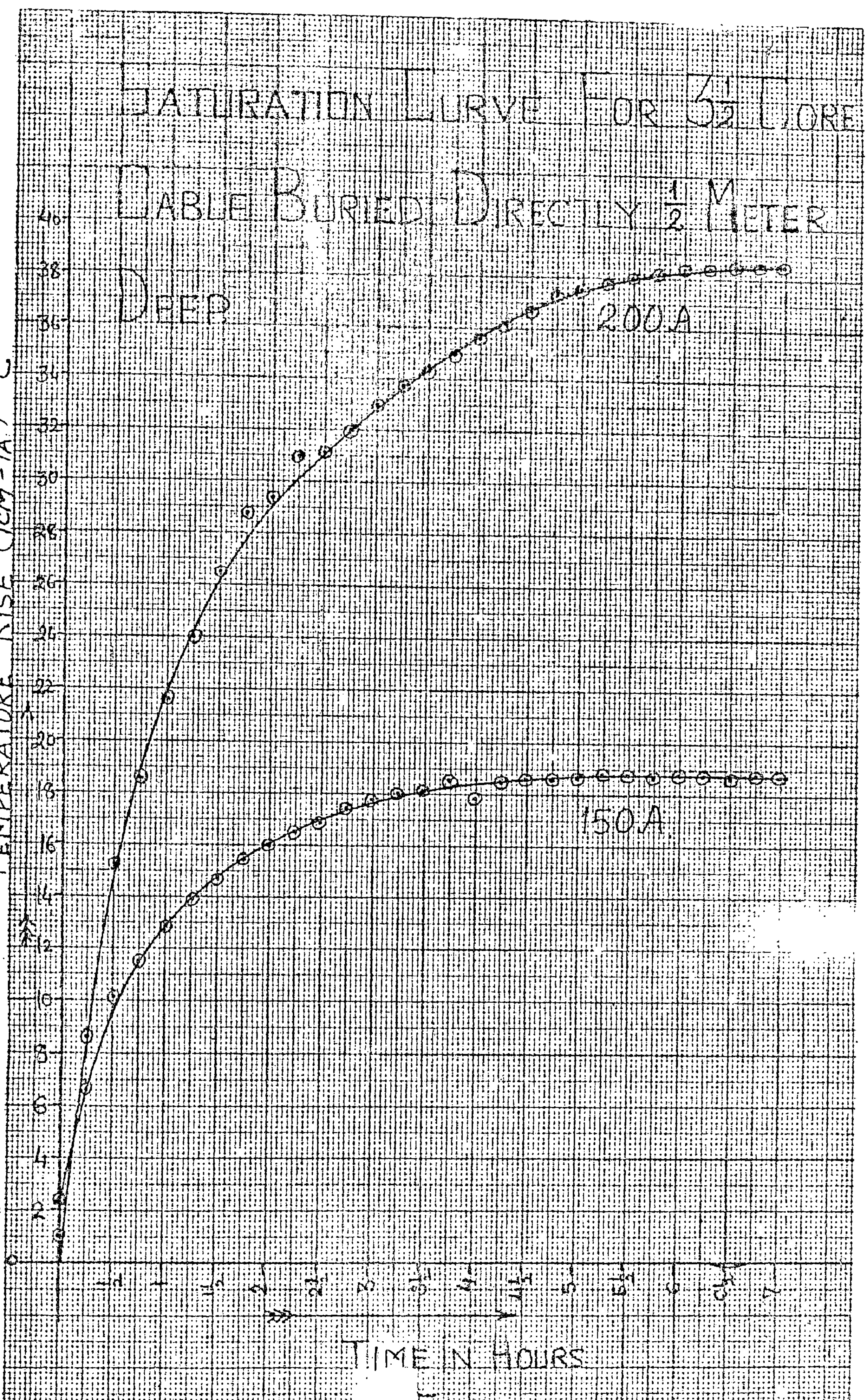

SATURATION CURVE FOR 3½ CORE CABLE BURIED DIRECTLY ½ METER DEEP

FIG 6.13

FIG. 62 SATURATION CURVE

CABLE BURIED ½ METER DEEP

WET SOIL CONDITION

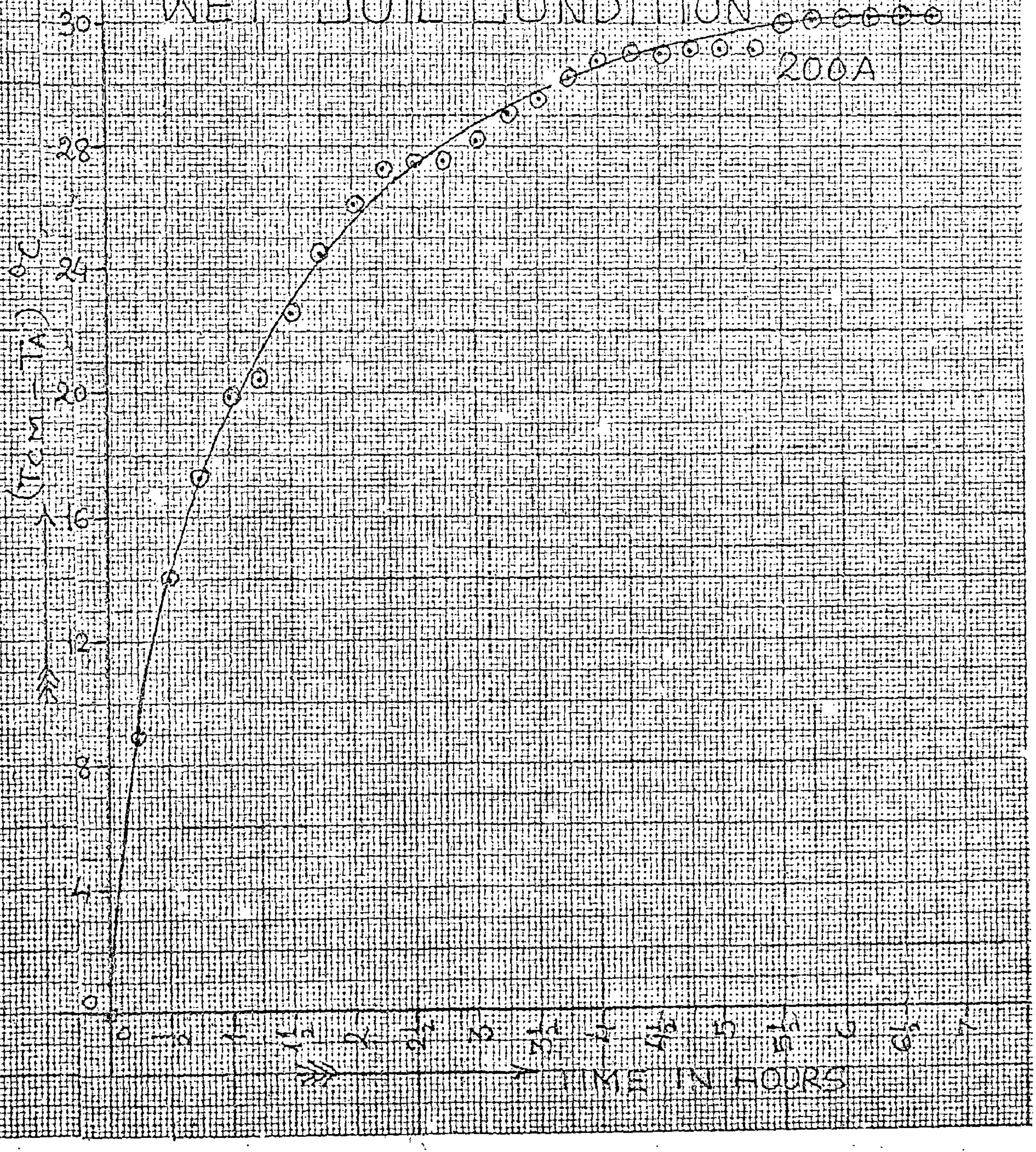
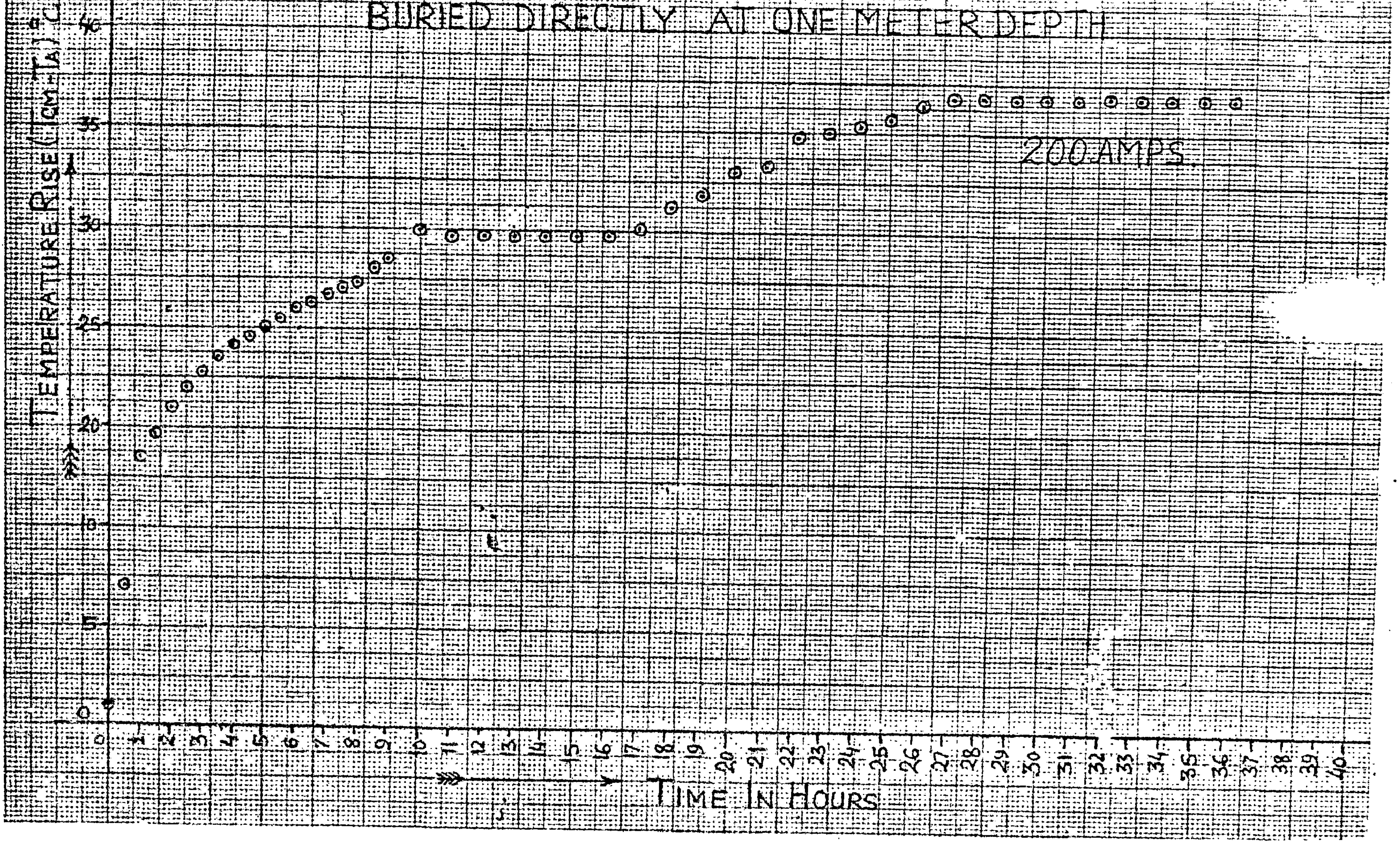


FIG.63 SATURATION CURVE FOR $3\frac{1}{2}$ CORE P.V.C. CABLE
BURIED DIRECTLY AT ONE METER DEPTH



Indian Standards and the observations were taken at a regular time of interval. These observations are recorded in Table No 6.5 Here we would like to mention that during this experiment the ambient conditions were fluctuating continuously, some times it was raining and some times it was bright sun sine. After some time of starting the experiment it start raining, we covered the whole pit surface where the cable was dug by a plastic sheet and it was observed that the cable surface temperature rises tramondously and after removing the sheet it falls immediately The effect of running the fan was also observed and found that it still had some effect on conductor temperature measurement. All these facts can be observed from the table as well as from the curve shown in fig.(6.4)

6.1 Estimation of Conductor Temperature

The conductor temperature of buried cable was estimated in the same way as in case of the cable in air, by considering the thermal equivalent curcuit of cable, when buried, as shown in fig.(3.3) All the parameters of the equivalent circuit except the soil thermal resistance R_{soil} have already been calculated in case of cable laid in air. The thermal resistance of the soil (R_{soil}) can be found by using the formula, $R_{soil} = \frac{g_e}{2\pi} \ln \frac{2h}{r}$ based on Kennelly model [13] for various depths of burial. The calculations of the R_{soil} is given in appendix.

TABLE NO 6·5

1. CABLE BURIED AT TWO METER DEPTH
2. CURRENT PER CONDUCTOR - 228 AMPS
3. OBSERVATION TAKEN DURING VARYING AMBIENT CONDITIONS

S. No.	TIME IN HOURS	AMBIENT TEMP. T_A °C	MEASURED CONDUCTOR TEM T_{CM} °C	MEASURED CABLE SURFACE TEMP T_S °C	$T_{CM}-T_A$ °C	T_S-T_A °C
1	2	3	4	5	6	7
1	0	30°	31	27.2	1	-2.8
2	1/2	30	43.4	32.7	13.4	2.7
3	1	30	47.4	36.8	17.4	6.8
4	1 ½	30	49.7	39.0	19.7	9.0
5	2	30	51.4	40.7	21.4	10.7
6	2 ½	30	52.8	42.3	22.8	12.3
7	3	30	53.5	43.2	23.5	13.2
8	3 ½	30	53.9	43.9	23.9	13.9
9	4	30	54.0	44.1	24	14.1
10	4 ½	28	55.6	44.8	27.6	16.8
11	5	27.5	55	46.0	27.5	18.5
12	5 ½	27.5	54	45.8	26.5	18.3
13	6	27.5	53.9	45.2	26.4	17.7
14	6 ½	27.5	55	46.7	27.5	19.2

TABLE NO 6·5 (CONTD.)

1	2	3	4	5	6	7
15	7	27.5	55.4	46.7	27.9	19.2
16	7 $\frac{1}{2}$	27.5	56.6	49.7	29.1	22.2
17	8	27.5	56.7	49.7	29.2	22.2
18	8 $\frac{1}{2}$	27.5	57	49.7	29.5	22.2
19	9	27.5	55.8	50	28.3	22.5
20	9 $\frac{1}{2}$	27.0	55.3	50	28.3	23
21	10	27.0	55.3	50	28.3	23
22	10 $\frac{1}{2}$	26.5	55.3	50	28.8	23.5
23	11	26.5	55.3	49.9	28.8	23.4
24	11 $\frac{1}{2}$	26	56.6	50.7	30.6	24.7
25	12	26	56.1	50.7	30.1	24.7
26	12 $\frac{1}{2}$	26	56.1	50.8	30.1	24.8
27	13	26	55.8	50.4	29.8	24.4
28	13 $\frac{1}{2}$	26	55.4	50.4	29.4	24.4
29	14	26	55	50.8	29	24.8
30	14 $\frac{1}{2}$	26	54.8	50.8	28.8	24.8
31	15	26	54.6	50.8	28.6	24.8
32	15 $\frac{1}{2}$	26	54.3	51.0	28.3	25.0
33	16	26	54.4	51.0	28.4	25.0
34	16 $\frac{1}{2}$	26	55.3	51.2	29.3	25.2

Contd....

TABLE NO 6·5 (CONTD.)

1	2	3	4	5	6	7
35	17	26.5	55.9	53.7	29.4	27.2
36	17 $\frac{1}{2}$	26.5	52.8	53.7	26.3	27.2
37	17 $\frac{3}{4}$	26.5	54.0	53.7	27.5	27.2
38	18 $\frac{1}{4}$	26	54.6	53.7	28.6	27.7
39	18 $\frac{1}{2}$	26	52.0	53.8	26	27.8
40	18 $\frac{3}{4}$	26	52.5	38.2	26.5	12.2
41	19	26	51.6	38.2	25.6	12.2
42	19 $\frac{1}{4}$	26	52.8	38.5	26.8	12.5
43	19 $\frac{3}{4}$	27	53.7	39.2	26.7	12.2
44	20 $\frac{1}{4}$	27	55	39.8	28	12.8
45	20 $\frac{3}{4}$	28	52.2	40.2	24.2	12.2
46	21 $\frac{1}{4}$	28	57.3	41.5	29.3	13.5
47	21 $\frac{3}{4}$	28	58.5	42.5	30.5	14.5
48	22 $\frac{1}{4}$	28	58.5	42.5	30.5	14.5
49	22 $\frac{3}{4}$	28	57.6	42.5	29.6	14.5
50	23 $\frac{1}{4}$	27.5	55.9	42.5	28.4	15.0
51	23 $\frac{3}{4}$	27.5	54.7	42.5	27.2	15.0

Contd...

TABLE NO 6.5 (CONTD.)

1	2	3	4	5	6	7
52	24 $\frac{1}{4}$	27.5	55.7	42.8	28.2	15.3
53	24 $\frac{3}{4}$	27.5	56.3	43.7	28.8	16.2
54	25 $\frac{1}{4}$	27.5	56.6	43.8	29.1	16.3
55	25 $\frac{3}{4}$	27	55	42.5	28	15.5
56	26 $\frac{1}{4}$	26.5	54	41.5	27.4	15.0
57	26 $\frac{3}{4}$	26.5	52.5	40.8	26.	14.3
58	27 $\frac{1}{4}$	26.5	53.10	41.2	26.6	14.7
59	27 $\frac{3}{4}$	26.5	52.5	40.9	26	14.4
60	28 $\frac{1}{4}$	26.5	52.4	40.8	25.9	14.3
61	28 $\frac{3}{4}$	26.5	52.7	41.2	26.2	14.7
62	29 $\frac{1}{4}$	26.5	53.1	41.3	26.6	14.8
63	29 $\frac{3}{4}$	26.5	52.5	40.9	26.0	14.4
64	30 $\frac{1}{4}$	26.5	52.4	40.8	25.9	14.3
65	30 $\frac{3}{4}$	26.5	53.5	41.5	27.0	15.0
66	31 $\frac{1}{4}$	26.5	54.4	42.4	27.9	15.9
67	31 $\frac{3}{4}$	26.5	56.0	43.8	29.5	17.3
68	32 $\frac{1}{4}$	26.5	56.4	44.5	29.9	18.0

Contd...

TABLE NO 6·5 (CONTD.)

1	2	3	4	5	6	7
69	32 $\frac{3}{4}$	26.5	57	45.5	30.5	19.0
70	33 $\frac{1}{4}$	26.5	57.5	45.7	31.0	19.2
71	33 $\frac{3}{4}$	26.5	57.9	45.8	31.4	19.3
72	34 $\frac{1}{4}$	26.5	58.2	46.2	31.7	19.7
73	34 $\frac{3}{4}$	26.5	58.5	46.4	32.0	19.9
74	35 $\frac{1}{4}$	26.5	57.9	45.8	31.4	19.3
75	35 $\frac{3}{4}$	26.5	57.4	45.6	30.9	19.1
76	36 $\frac{1}{4}$	26.5	56.8	44.8	30.3	18.3
77	36 $\frac{3}{4}$	26	56.0	44.5	30.0	18.5
78	37 $\frac{1}{4}$	26	54.9	43.8	28.9	17.8
79	37 $\frac{3}{4}$	26	54.0	42.5	28.0	16.5
80	38 $\frac{1}{4}$	26	53.7	42.4	27.7	16.4
81	38 $\frac{3}{4}$	26	54.9	43.2	28.9	17.2
82	39 $\frac{1}{4}$	26	55.5	44.2	29.5	18.2
83	39 $\frac{3}{4}$	26	55.9	44.5	29.9	18.5
84	40 $\frac{1}{4}$	26	54.5	44.2	28.5	18.2
85	40 $\frac{3}{4}$	28	58.2	40.6	30.2	12.6

Contd.....

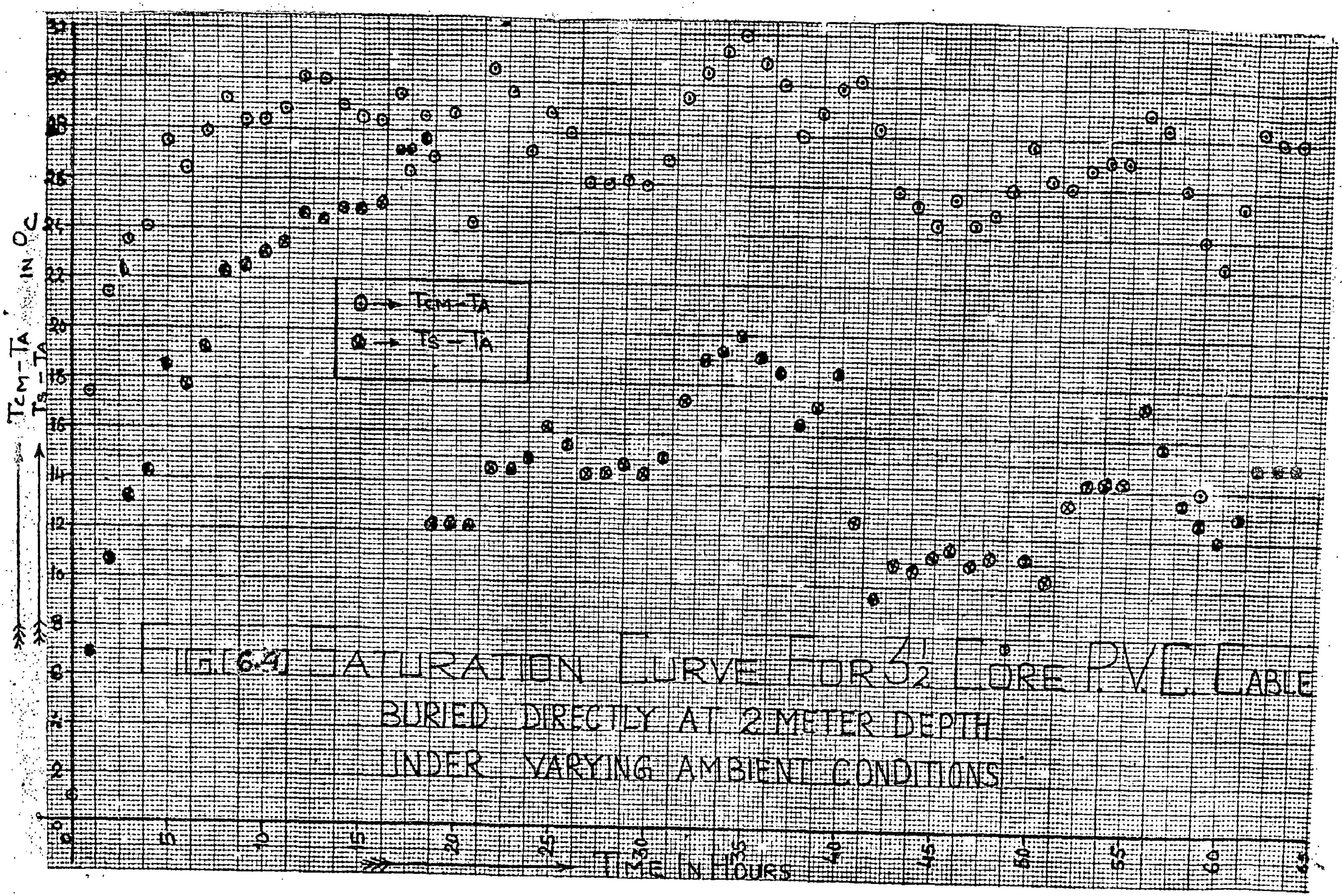
TABLE NO 6·5 (CONTD.)

1	2	3	4	5	6	7
86	$41\frac{1}{4}$	28	58.8	41.6	30.8	13.6
87	$41\frac{3}{4}$	27	55.3	36.5	28.3	9.5
88	$42\frac{1}{4}$	28	54.2	35.2	26.2	7.2
89	$42\frac{3}{4}$	29.5	55.3	40.4	25.8	10.9
90	$43\frac{1}{4}$	29.5	54.5	39.7	25.0	10.2
91	$43\frac{3}{4}$	29.5	54.8	40.2	25.3	10.7
92	$44\frac{1}{4}$	29.5	53.7	39.8	24.2	10.3
93	$44\frac{3}{4}$	29.5	54.0	40.7	24.5	11.2
94	$45\frac{1}{4}$	29.5	54.9	40.9	25.4	11.4
95	$45\frac{3}{4}$	30	55.6	41.5	25.6	11.5
96	$46\frac{1}{4}$	30	55.6	41.6	25.6	11.6
97	$46\frac{3}{4}$	30	54.5	40.9	24.5	10.9
98	$47\frac{1}{4}$	30	54.5	41.0	24.5	11.0
99	$47\frac{3}{4}$	30	54.9	41.2	24.9	11.2
100	$48\frac{3}{4}$	29	54.0	36.5	25.9	7.5
101	$49\frac{3}{4}$	28	55.7	39.2	27.7	11.2
102	$50\frac{3}{4}$	28	54.3	38.2	26.3	10.2

Contd...

TABLE NO 6·5 (CONTD.)

1	2	3	4	5	6	7
103	51 $\frac{3}{4}$	27.5	53.6	40.9	26.1	13.4
104	52 $\frac{3}{4}$	27	53.8	41.2	26.8	14.2
105	53 $\frac{3}{4}$	26.5	53.6	40.8	27.1	14.3
106	54 $\frac{3}{4}$	26.5	53.6	40.8	27.1	14.3
107	55 $\frac{3}{4}$	26.5	55.5	43.8	29.0	17.3
108	56 $\frac{3}{4}$	26.5	54.9	42.2	28.4	15.7
109	57 $\frac{3}{4}$	26.5	52.4	40.2	25.9	13.7
110	58 $\frac{3}{4}$	26.5	50.4	39.2	23.9	12.7
111	59 $\frac{3}{4}$	26.5	49.4	38.5	22.9	12.0
112	60 $\frac{3}{4}$	26.5	51.8	39.5	25.3	13.0
113	61 $\frac{3}{4}$	27.5	55.9	42.5	28.4	15.0
114	62 $\frac{3}{4}$	27.5	55.5	42.5	28.0	15.0
115	63 $\frac{3}{4}$	27.5	55.5	42.5	28.0	15.0



FIG(6.4) SATURATION CURVE FOR $3\frac{1}{2}$ CORE P.V.C. CABLE
BURIED DIRECTLY AT 2 METER DEPTH
UNDER VARYING AMBIENT CONDITIONS

After calculating R_{soil} the various temperature drops θ_{m_1}, θ_{m_2}, θ_{m_3} and θ_e were calculated to get the conductor temperature. The conductor temperatures were be found in two way :

(i) By taking earth surface temperature as reference then,

$$T_c = \theta_{m_1} + \theta_{m_2} + \theta_{m_3} + \theta_e + T_A \qquad \ldots(6.1)$$

(ii) By taking cable surface temperature as reference, then,

$$T_c = \theta_{m_1} + \theta_{m_2} + \theta_{m_3} + T_s \qquad \ldots(6.2)$$

The conductor temperature at the 0.5 meter, one meter and two meter depths were calculated and are recorded in Table no..6.7. This table show that the estimated conductor temperature T_c and measured conductor temperature T_{CM} have a very good agreement except in final case of 2 meter depth, where ambient conditions were very much fluctuating.

6.2 Effect of Moisture on Soil Resistivity

It was evident during the calculations of conductor temperature for 0.5 depth set of observations which was taken after rain, that the conductor temperature considering the value of soil resistivity as 1.1 $^{\circ}$C-m/W (as in case of dry soil condition) is very highly compared to the measured value. This is due to the fact that the soil resistivity and hence the R_{soil} value had decreased due to increase in % moisture. The new value of the soil resistivity was found by using experimental data (measured temperature drop between

TABLE NO 6·7

1. CABLE BURIED AT VARIOUS DEPTHS
2. VARYING AMBIENT CONDITIONS.

S. No.	CURRENT AMPS	DEPTH OF BURIAL = 0.5 METER									DEPTH OF BURIAL= 1METER			DEPTH OF BURIAL1=2METER		
		Dry Soil Condition			Wet Soil Condition Taking,g=1.1			Wet Soil Condition Taking,g=0.88			Wet Soil Condition Taking,g=0.88			Wet Soil Condition Taking,g=0.8		
		T_C Taking T_S As Ref	T_C Taking T_A As Ref	T_{CM} °C	T_C Taking T_S As Ref	T_C Taking T_A As Ref	T_{CM} °C	T_C Taking T_S As Ref	T_C Taking T_A As Ref	T_{CM} °C	T_C Taking T_S As Ref	T_C Taking T_A As Ref	T_{CM} °C	T_C Taking T_S As Ref	T_C Taking T_A As Ref	T_{CM} °C
1	150	49.56	50.06	49.8	-	-	-	-	-	-	-	-	-	-	-	-
2	200	74.78	74.43	74.5	60.68	64.78	60.2	60.68	60.72	60.2	62.1	66.2	62.8	58.1	63.99	55.5

cable surface T_S and earth surface temperature T_A). This difference of temperature ($T_S - T_A$) or θ_e was equated to $R_{soil} \times 3H$. and the new value of R_{soil} was obtained . Corresponding to this new value of R_{soil} the resistivity of soil was calculated and found to be 0.88 °C-m/W. The detailed calculations are given in appendix..F..

CHAPTER-7

INTERMITTENT LOADING OF CABLES

To justify the use of underground cable system for power transmission and distribution in comparison with the over head line system, it is necessary that the system must be utilized to its full capacity and if required the system may be run beyond its capacity without harming the system.

The current ratings for which the cable system can be loaded without any harm to its insulation are called as intermittent ratings. The following three types of intermittent ratings can be considered :

1. Short time rating
2. Emergency rating
3. Short circuit rating

7.1 Short Time Current Rating

The short time current rating of a cable is that current which can be passed through the cable for a particular period of time without any harm to the cable insulation i.e. without increase in the conductor temperature beyond maximum permissible limit (70°C) during that period. The short time current loading can be applied to the cable system for unlimited number of times for shorter duration during the life time of the cable which is assumed to be 20 years. The short time current rating will be decided by initial load on the cable.

7.2 Emergency Loading

It is defined as the current rating of the cable which can be passed through the cable without any harm to the cable insulation. To distinguish between short time current rating and emergency loading the following comparison may be seen :

1. Maximum permissible temperature in case of short time loading is that temperature which is specified for that type of insulation under normal condition (70°C in our case). On the other hand the temperature limit for emergency loading for smaller duration is more than the maximum permissible temperature specified under normal conditions (80°C in our case).
2. The short time current loading can be applied for unlimited number of times during the cable life time, while the emergency loading will be restricted to 100 hours per year and such 100 hours per year loading to be done not more than 5 times during the entire life of the cable.
3. In normal cases the short time loading is applied when initially cable is either unloaded or partially loaded. But the emergency loading can be applied when the cable already carrying the rated current and the temperature of the conductor has already reached

to steady state saturation (maximum 70°C).

7.3 Short Circuit Current Rating

When a short circuit occurs , a very large initial rush of current results during the first fraction of a second, followed by a rapid diminution of the current flowing. Under these conditions it is usual to assume the whole of the heat generated in the conductors is absorbed by the conductors.

The magnetic force acting on conductors usually take the form of a repulsive force between the conductors carrying current in opposite direction. These forces tends to burst the cable. The empirical expression for calculating the short circuit current ratings of the cable is given below : [88]

$$I_{sc} = \frac{K \times A}{\sqrt{t}} \text{ Kilo Amps} \qquad \ldots(7.1)$$

where, K = A constant for aluminium = 0.0751

A = Actual area of the conductor in sq m m.

t = Duration of short circuit time in secs.

Temperature before short circuit = 70°C

Temperature after short circuit = 160°C

The short circuit current is a function of time are shown in fig.(7.1)

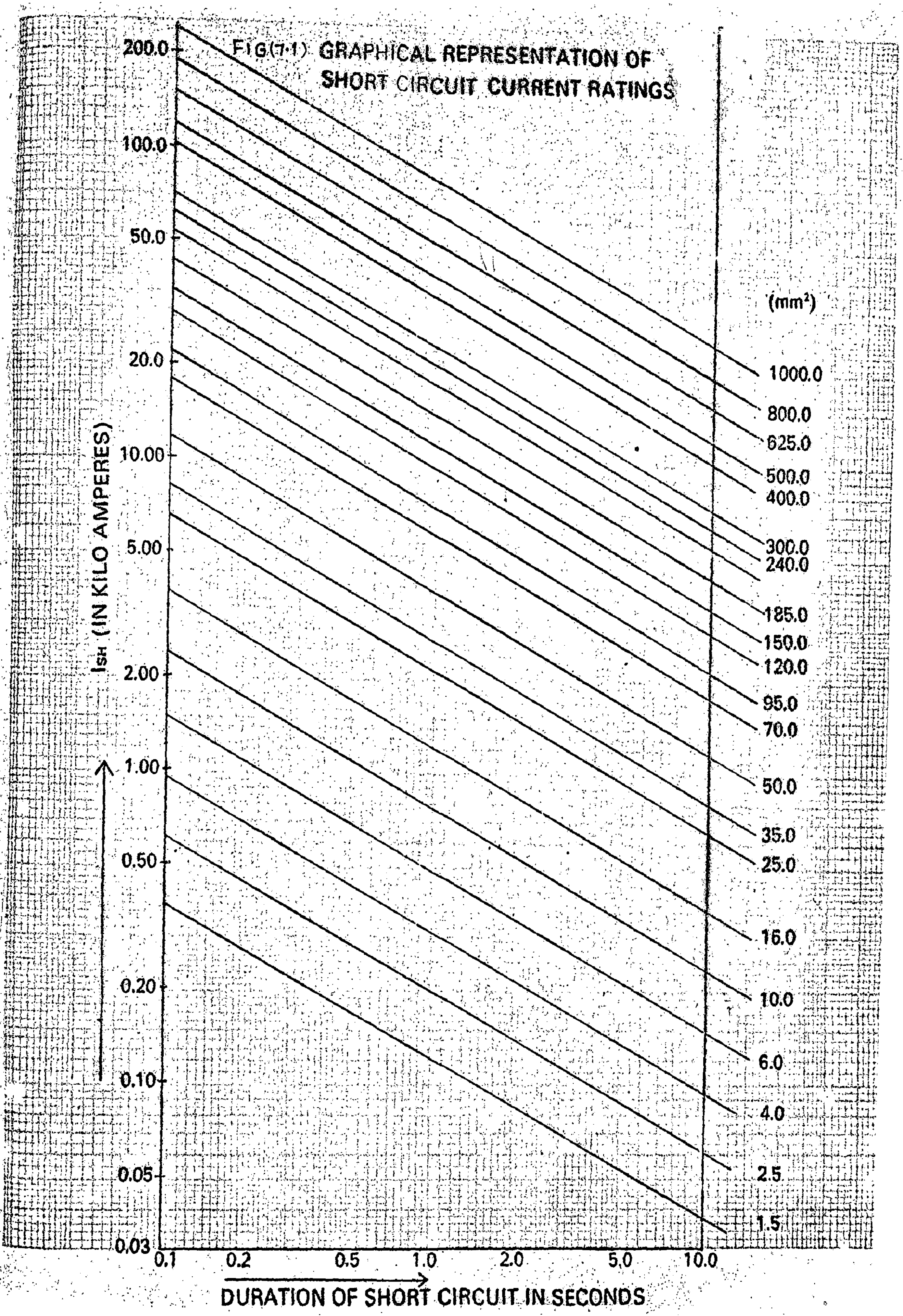


FIG (7·1) GRAPHICAL REPRESENTATION OF SHORT CIRCUIT CURRENT RATINGS

7.4 Experiments on Intermittent Loading

The heating of the cable arise mainly form I^2R losses in the conductors when a steady state continous current is applied to a cable at room temperature, the temperature of the cable rises exponencially upto steady state saturation temperature. The rise in temperature is very rapid during first few hours of loading the cable and then more slow unit it reaches a steady state value. The equation for temperature rise is given below :

$$T = T_m (1 - e^{-t/\lambda}) \qquad \ldots(7.2)$$

where,

T = Temperature of conductor at any instant 't' in °C

T_m = Maximum steady state temperature in °C

λ = Time constant of the cable

t = Time from switching on in secs.

The permissible short time overloading over the continuous rating is affected by the installation method, since the time period required for the cable laid direct in the ground to reach steady state may be days or weeks, whereas cables run in free air requires relatively short time in hour to reach the final conductor temperature, because the thermal capacity of the air is negligible as compared to soil. This is why the short time over loading of the cable run in free air are limited.

Actually speaking, the fact that the cable run in free air heated more rapidly than the cable laid under ground is of much importance in calculating the short time overload ratings of the cable.

In case of buried cable a short length of the cable at both ends remains in the air, the continuous rating of this type installation may be determined by the under ground section, but the intermittent rating will be determined by the portion in air.

Another factor which affect the short time loading is nature of the loading wheather the cable has previously carried no load, it has been lightly loaded or fully loaded

The short time overloading factors can be determined as discussed below for various types of the loading eg.

(i) Cable initially carries no load

(ii) Cable has been previously loaded to 50% or 75% or any other % of the rated load.

7.4.1 Derivation of an Expression for Short Time Loading Factor :

We know that the temperature rise of the conductor at any instant 't' after switching on the supply is given by

$$T = T_m (1-e^{-t/k})$$

Now Let 'To' be the final permissible maximum temperature attained by the cable when running with the rated current I_o . To the first approximation we can say,

$$T_o/T_m = (I_o/I)^2 \qquad \ldots(7.3)$$

where, I = Short time current rating of the cable
Putting the value of $T_m = T_o \, I^2 / I_o^2$ from equation(7.3) in equation (7.2) we get,

$$T = T_\theta \, I^2 \, (1-e^{-t/\lambda}) / I_o^2 \qquad \ldots(7.4)$$

Or $$T.I_o^2 = T_o \, I^2 \, (1-e^{-t/\lambda})$$

Or $$I^2 = \frac{T.I_o^2}{T_o(1-e^{-t/\lambda})}$$

Or $$I = I_o \sqrt{\frac{T}{T_o(1-e^{-t/\lambda})}}$$

Or $$I = I_o \sqrt{\frac{T/T_o}{(1-e^{-t/\lambda})}} \qquad \ldots(7.5)$$

As I is greater than I_o , but T the temperature attained after time 't' is not to exceed T_o ie $T = T_o$, so equation (7.5) becomes

$$I = I_o \sqrt{\frac{1}{(1-e^{-t/\lambda})}} = I_o \frac{1}{\sqrt{(1-e^{-t/\lambda})}}$$

or $$I = n \, I_o \qquad (7.7)$$

where,

$n = \dfrac{1}{\sqrt{(1-e^{-t/A})}}$ and is known as short time loading factor of the cable. Therefore from equation (7.7)

$$n = \frac{1}{\sqrt{T/T_m}} = \sqrt{\frac{T_m}{T}} \qquad \ldots(7.8)$$

7.4.2 Estimation of Short Time Rating Factors and Short Time Loading Capacities for the Cable Under Test - Cable in Air :

Case I :- When cable was previously unloaded (HH initial cold condition)

Referring to the temperature rise curve for rated current fig.(5.4) for cable under test and noting the following:

Ambient temperature $T_A = 32^\circ C$

Maximum conductor temperature $T_{CM} = 70.1^\circ C$

$\therefore$ Maximum Permissible temperature rise $T_m = 70.1 - 32 = 38.1^\circ C$

Now, if it is required to find out the overload short time rating of the cable for a time period of one hour without exceeding the specified maximum temperature rise, from the curve the temperature rise after one hour (starting from cold) is $25^\circ C$. Therefore the factor for multiplying the continuous rating is obtained as $n = \sqrt{\frac{T_m}{T}}$ ie $n = \sqrt{\frac{38.1}{25}} = 1.234$. It means that the overload of approximate 23.4% in excess of the normal current is permissible for one hour. In the similar fashion various other short time loading factors for various time period are calculated and tabulated in the table no.7.1. [Appendix J for calculations]

Case II :- Case of initially partially loaded cables. If the cable has already been loaded partially, the first step will be to ascertain the temperature rise resulting from the load. From table no.5.10 sec.5 the maximum temperature rise for 75% initial loading (approximate 150 Amps) on the cable is 22.4°C. Again referring to the curve no(5·4) we see that a rise in temperature of 22.4°C corresponds to a time period of 50 minutes (approx). If a short time rating for a period of one hour is to be calculated than the total time will be (50+60) = 110 minutes, which corresponds to a temperature elevation of 34.5°C. Therefore the short time rating factor for this case will be $= \sqrt{\frac{38.1}{34.5}} = 1.046$, that means only 4.6% overloading for a period of one hour is possible. In the similar way the various other short time loading factors for various time periods and various % initial loading are calculated and tabulated in table no.7.1.

7.4.3 Experimental Verification of Estimated Short Time Current Ratings :

The short time current rating for cable laid in air as estimated and tabulated in table no. 7.1. were verified by applying these currents to the cable under test for the specified period of time and temperature were recorded in

TABLE NO 7·1

SHORT TIME LODING FACTORS AND SHORT TIME LOADING CAPACITIES OF A 150 mm^2 P.V.C. INSULATED AND PVC SHEATHED ARMOURED 3 $\frac{1}{2}$ CORE CABLE LAID IN AIR

1. AMBIENT TEMPERATURE - 32°C
2. MAXIMUM PERMISSIBLE TEMPERATURE -70°C

S. NO.	PARTICULARS	INITIALLY UNLOADED CABLE				INITIALLY PARTIALLY LOADED CABLE							
						50% of the rated value				75% of the rated value			
		HALF HOUR LOADING	ONE HOUR LOADING	TWO HOUR LOADING	THREE HOUR LOADING	HALF HOUR LOADING	ONE HOUR LOADING	TWO HOUR LOADING	THREE HOUR LOADING	HALF HOUR LOADING	ONE HOUR LOADING	TWO HOUR LOADING	THREE HOUR LOADING
1.	Short time loading factors	1.515	1.234	1.058	1.007	1.367	1.167	1.023	1.005	1.134	1.046	1.010	1.003
2.	Short time loading capacities	310A	253A	217A	206A	280A	239A	210A	206A	232A	215A	207A	205A

each case. The experimental results are tabulated in table no. 7.2.

From the table it can be noticed that in each case the temperature rise of the conductor is well below 70°C (the maximum specified limit for PVC insulated cable). The short time rating for 3 hour were not checked because its calculated value is same as rated current.

The short time ratings for cable huried directly in ground will be same that of the cable laid in air, because the it will be decided on the basis of the cable protion which is exposed in air in case of buried cable.

7.4.4 Estimation of Emergency Loading

7.4.4.1 Cable in Air

To evaluate the emergency loading capacity of the cable under test when laid in air the following two parameters were taken into account.

1. Maximum duration of emergency loading is taken as 15 minutes only as a first approximation.
2. Maximum permissible conductor temperature limit during emergency loading is taken as 80°C for P.V.C. (as per IEEE this limit is 85°C) [B9] .

Now an experiment was performed to evaluate the emergency loading capacity of the cable along with its duration.

TABLE NO 7.2

1. AMBIENT TEMPERATURE 30 to 31°C
2. MAXIMUM PERMISSIBLE TEMPERATURE - 70°C

S. NO.	PARTICULARS	INITIALLY UNLOADED CABLE			INITIALLY PARTIALLY LOADED CABLE					
					50% OF RATED VALUE			75% OF RATED VALUE		
		1/2 hour Loading	1 hour Loading	2 hours Loading	1/2 hour Loading	1 hour Loading	2 hour Loading	1/2 hour Loading	1 hour Loading	2 hours Loading
1.	Short time Loading Factors	1.515	1.234	1.058	1.367	1.167	1.023	1.134	1.046	1.01
2.	Short time Loading Capacities	310A	253A	217A	280A	239A	210	232A	215A	207A
3.	Measured Temperature of the conductor	68.9°C	68.6°C	68.2°C	68.5°C	68.6°C	68.4°C	68.2°C	68°C	68.6°C
4.	Ambient Temperature	31°C	30°C	30°C	30°C	30°C	30°C	31°C	31°C	31°C

Initially cable was loaded upto its rated value 205A and waited till saturation is reached. N_ow the current was raised to 300A and temperature of the conductor was noted at various time interval upto 15 minutes. The maximum temperature recorded was 77.1°C. The current then reduced to 205A and the temperature decay was noted for various times till it cooled down to the value of the initial temperature corresponding rated current.

The above experiment was repeated for currents of 320A (165%), 350A (175%). and 400A (200%). The results are given in table no..7.3. The temperature as function of time for these emergency loadings are shown in fig.(7.2) for both temperature rise and decay.

7.4.4.2 Cable Buried Directly

To evaluate the emergency loading of the cable under test when buried directly in ground the same experiment was performed as in case of air, with a modification that maximum duration is increased from 15 minutes to 30 minutes.

The observations were recorded in table no.7.4 and 7.5 the plot temperature rise/decay Vs time is shown in fig.(7.3).

It is quite evident from these experiments that the permissible emergency loading when cable laid is air are small and for smaller duration as compared with when the cable buried directly.

TABLE NO 7.3

1. SATURATION TEMPERATURE = 68.6^{o}C
2. AMBIENT TEMPERATURE = 30^{o}C

3. CABLE LAID IN AIR ABOVE FLOOR

S. No.	CURR-ENT	CONDUCTOR TEMPERATURE RISE ^{o}C										CONDUCTOR TEMPERATURE DECAY ^{o}C						
		t=0 min ^{o}C	t=1 min ^{o}C	t=2 min ^{o}C	t=3 min ^{o}C	t=4 min ^{o}C	t=5 min ^{o}C	t=6 min ^{o}C	t=8 min ^{o}C	t=10 min ^{o}C	t=15 min ^{o}C	t=0 min ^{o}C	t=5 min ^{o}C	t=10 min ^{o}C	t=15 min ^{o}C	t=20 min ^{o}C	t=25 min ^{o}C	t=30 min ^{o}C
1	300A	68.6	-	-	-	-	72	-	-	75	77.1	77.1	72.5	70.6	68.9	-	-	-
2	320A	68.9	-	-	-	-	74	-	-	77.9	80.9	80.9	76.6	73.5	71.6	70.1	68.9	-
3	350A	68.9	-	72	-	75.3	-	78	80.5	-	-	80.5	77.5	72.6	70.7	69.4	68.6	-
4	400	68.6	71.8	75.3	78.3	80.6	-	-	-	-	-	80.6	75.3	72.3	70.6	69.8	68.9	68.6

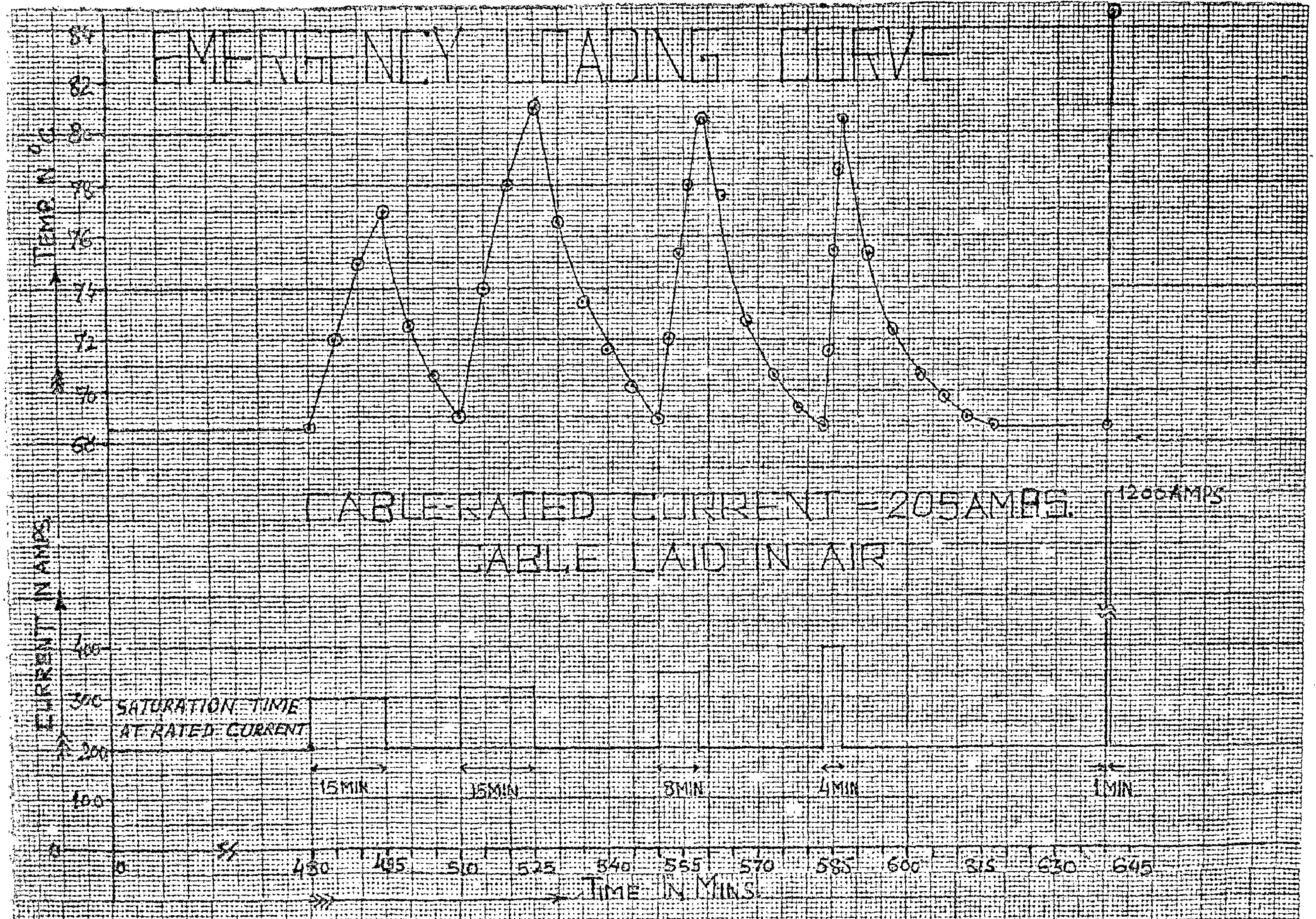

EMERGENCY LOADING CURVE
TEMP. IN °C
84
82
80
78
76
74
72
70
68
CABLE-RATED CURRENT = 205AMPS.
CABLE LAID IN AIR
1200AMPS
CURRENT IN AMPS
400
300
200
100
0
SATURATION TIME
AT RATED CURRENT
15MIN
15MIN
8MIN
4MIN
1MIN
0
430
495
510
525
540
555
570
585
600
615
630
645
TIME IN MINS

FIG. 7.2

TABLE NO 7.4

1. SATURATATION TEMPERATURE - 55.5°C
2. AMBIENT TEMPERATURE - 29°C
3. CABLE DIRECTLY BURIED IN GROUND AT 2.0 METER DEPTH

S. No.	CURRENT IN AMPS	CONDUCTOR TEMPERATURE RISE IN °C						
		t = 0 min	t = 5 min	t = 10 min	t = 15 min	t =20 min	t =25 min	t=30 min
1	342	55.5	60.2	64.3	67.8	70.9	73.6	76.2
2	400	55.5	63.1	70.5	76.2	80.0	-	-
3	460	55.5	68.5	80	-	-	-	-

TABLE NO 7·5

1. SATURATION TEMPERATURE - 55.5°C
2. AMBIENT TEMPERATURE -29°C
3. CABLE DIRECTLY BURIED IN GROUND AT 2.0 METER DEPTH

S. No.	CURR-ENT IN AMPS	CONDUCTOR TEMPERATURE DECAY IN °C															
		t=0	t=5	t=10	t=15	t=20	t=25	t=30	t=35	t=40	t=45	t=50	t=55	t=60	t=65	t=70	t=75
1	342	76.2	73.4	70.6	68.1	65.7	64	62.5	61.1	59.8	58.6	57.5	56.5	55.6	55.5	55.5	55.5
2	400	80	74.1	69.2	65.5	64	62.2	60.7	59.6	58.7	57.5	56.4	56	55.8	55.5	55.5	55.5
3	460	80	72.5	69.2	65.5	64.1	62.3	60.8	60	59	57.9	56.4	56	55.9	55.7	55.5	55.5

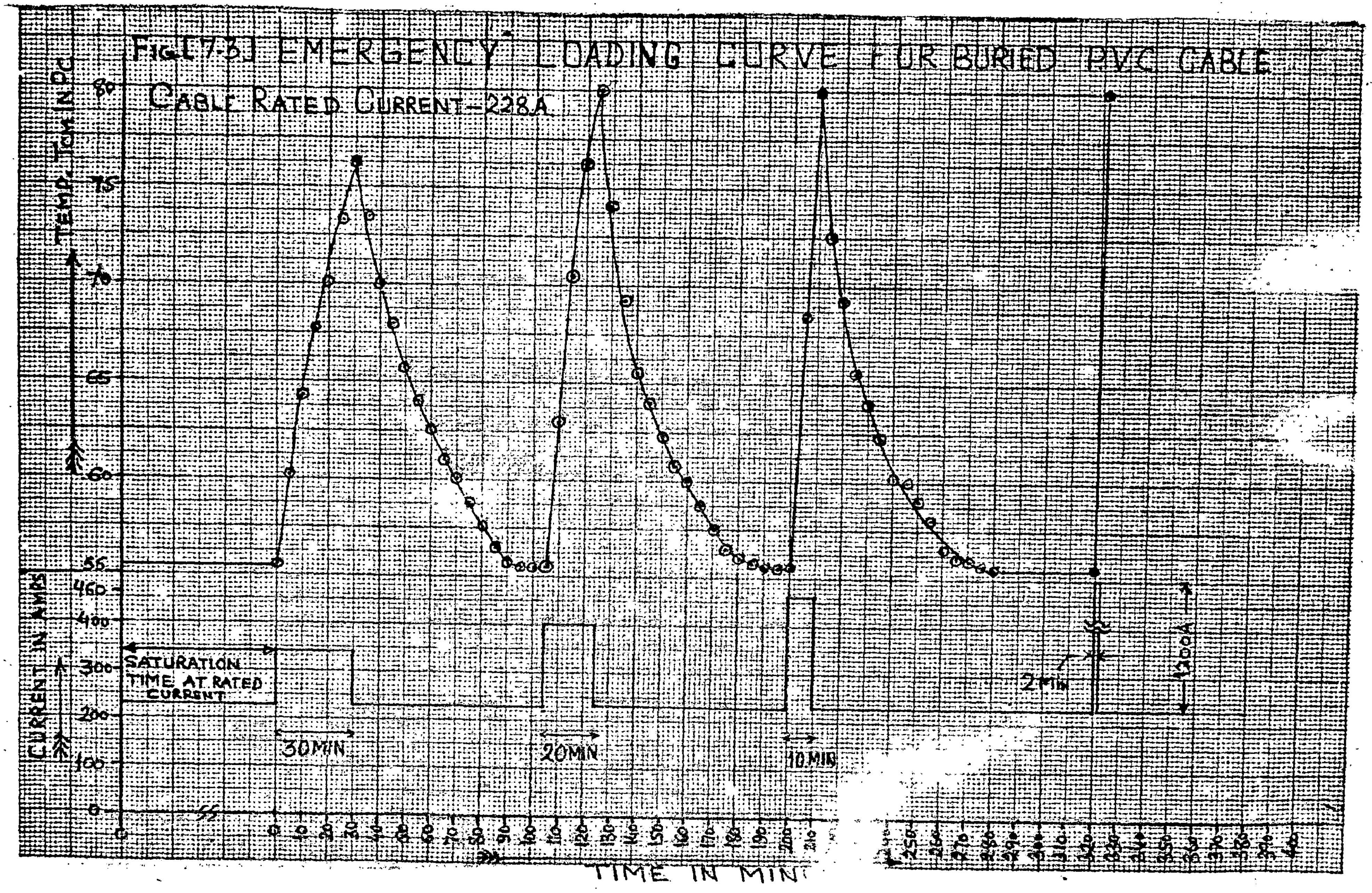


FIG.[7.3] EMERGENCY LOADING CURVE FOR BURIED PVC CABLE

CABLE RATED CURRENT – 228A

7.4.5 Verification of Short Circuit Ratings

To verify the short circuit current rating of the cable under test in both the cases of installation, an experiment was performed.

Initially cable was loaded with its rated value till the saturation is reached and then suddenly the current was raised to 1200A and the time was noted for increase in the temperature of the conductor upto 80°C.

In air this time was observed as 1 minute and in case of buried cable the time was approximate (110 secs) 2 minutes.

As per the formula : $I_{sc} = 0.0751A/\sqrt{t}$ Kilo Amps, this time for temperature rise upto 160°C is 88 secs.

CHAPTER-8

RESULTS AND DISCUSSIONS

8.1 Cable in Air

1. From the results of the experiments performed when cable was laid in air, it is quite evident that the steady state conductor temperature values (measured and estimated) have a very good agreement. The maximum error in estimated values is only ± 3 %, which is within tolerable limits.

All the possible parameters were considered to minimise this error but we could only succeceed in reducing it to ± 3%.

Another very interesting fact was observed during estimation of conductor temperature that the difference between T_{CM} and T_C is more for higher current and very very small for lower currents.

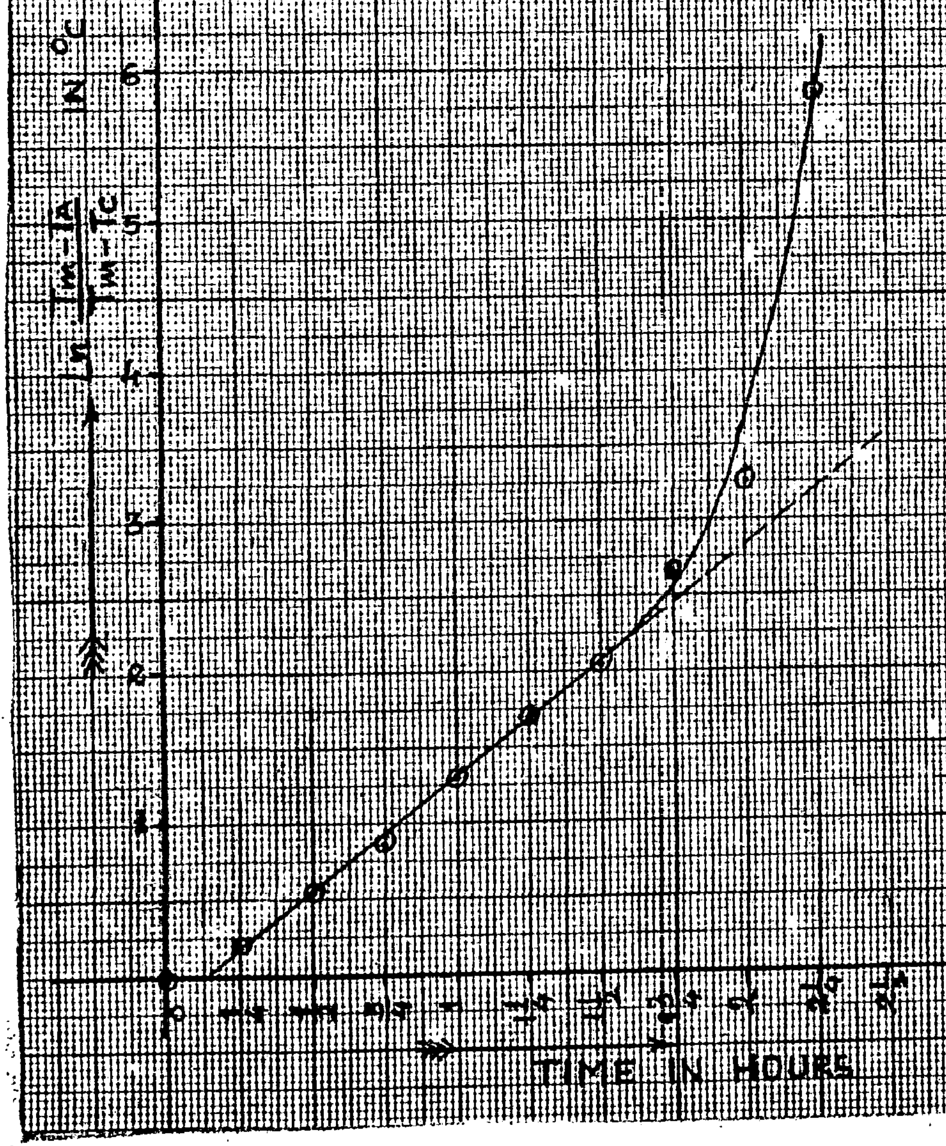
We do not find any reasonable answer to explain this error but in our opinion one of the reasons for this error may be that the saturation curves obtained donot fully follows the exponential law as given by the expression :

$$T_c = T_m \left(1-e^{-t/\lambda} \right)$$

Though these curves seem to be exponential, but on re-plotting on log-linear scale, the plot is not a straight line. This curve should have been a straight line as we

FIG. 8.11 SATURATION CURVE TRANSFORMED TO LOG. FORM FOR CABLE LAID IN AIR

150 AMPS.



2. Now coming to the transient thermal performance of the cable , the thermal circuit was solved using the method as discussed in section no.3.5 and it was noticed that the time constant of cable between conductor insulation and surface is coming out to be only 16 minutes. Detailed solution of the circuit is given in appendix..I.. This value is somewhat less the value of time constant calculated from the measured data. From the measured data the time constant is approximately 36 minutes. The above mentioned fact may also be responsible for this difference.

3. The short time loading , emergency loading and S.C. loading were estimated and verified by experimental results and its was observed that experimental results confirms the estimated value (table no..7.2.). Due to restricted facility we could only conduct the short circuit test for a maximum 1200 Amp.

8.2 Cable Buried Directly in Ground

1. From the results of the experiments performed when cable was directly buried in ground at different depths the following points were noticed:

(a) The estimated steady state conductor temperature, taking cable surface temperature as reference, show a very good agreement with the measured values of conductor temperature in all cases.

(b) The estimated conductor temperature T_c, taking earth surface as reference, had shown some disagreement. In same cases it is coming very close to the measured values. For verification please see the results for 200A current when cable was buried at 0.5 meter depth and soil condition was dry, table no..6:1, whereas in other cases the values are quite different from the measured values.

One of the reasons for this is that the soil resistivity decreases with increase in % moisture contents in the soil and hence the soil thermal resistance also decreases. If we take the new decreased value of R_{soil} we are sure that we will be getting the results within ± 5% error of the measured values. One set of calculation has been done for for confirmation (Please see section 3.3.4 and appendix ...F.... for details).

Another reason may be that the back filling of earth after laying the cable was not done in a packed way; it was loose soil which was filled in the trench, which could have formed some air pockets in the back-fill. The air in these air pockets would have moved upward after warming due to heating of cable surface and its place would have been taken by moist earth. This phenomenon would have a cooling effect on the cable surface. The fact was evident after a few days without rain by the collaps of the top surface of the pit by about 20-30 cms.

This face is responsible to produce considerable error in the measured value of conductor temperature, and in the saturation time as evidenced by the result of fig. (6·3) and (6·4).

2. The thermal circuit for cable buried directly in ground was also solved and it was observed that there is huge difference between estimated value and measured value of time constant. The estimated λ for 0.5 meter depth is coming out to be 142 hours , while the measured value is only 90 minutes. Inspite of our best efforts we were not able to explain this difference.

3. The short time loading capacities of buried cable will be the same as that of the cable in air because it is to be decided by the portion of the cable which is in the air, at both end of the cable [B10] and hence it was not verified in the case of buried cable.

The emergency loading test was performed and it was observed fig(7·2) and (7·3) that the duration and emergency loading capacity of the cable in air is less as compared to that of the cable buried directly due to the fact that the thermal capacity of the soil is very large as compared with the air. This fact is also evident during decay of conductor temperature(when loading is brought to its normal rated value).

CHAPTER-9

SUGGESTIONS FOR FUTURE WORK

1. From the experimental results obtained fig(5.3) it it clear that the error in calculated value of conductor temperature vary with cable loading. To explain this fact further investigations are needed.

2. The fluctuations in readings when cable was directly buried in ground, possibly due to the effect of loose back filling, also require further investigations.

3. The effect of exposed portion of the buried cable on the final temperature also needs to be studied.

REFERENCES

PAPERS

1. BAILEY,N.P. "Heat flow from underground electric power cables", AIEE Transactions, Vol.48(PAS) Jan. 1929, p.156-65.

2. KIRKE W.B. "The calculations of cable temperature in subway ducts" AIEE Journal, Vol.49, Part II. 1930, p. 855-59.

3. ELWOOD.A. CHURCH."Temperatures in electric power cables under variable loadings", AIEE Transactions, Sept.1931, p.982.

4. ELWOOD A.CHURCH, "Economical loading of underground cables", AIEE Transactions, 1935, pa 1166.

5. SHANKLIN G.B. AND BULLER F.H. " The Theory of oil filled cables", General Electric Review, Vol.34,Sept.1931, p.523.

6. MILLER K.W. AND WOLLSTON F.O. " Thermal transients and oil demands on cables", AIEE Transaction, Vol.52,(1933), p.98-113.

7. KIDDER,A.H. "Economical loading of underground cables" (Discussion),AIEE Transactions, 1936, p.398.

8. KIDDER,A.H. "Notes on emergency loading", AIEE Transactions, Vol.58 (1939),p.599-610.

9. BULLER,F.H. "Thermal transients on buried cables", AIEE Tranactions, Vol.70, Part I, 1951, p.45-55.

10. NEHER,J.H."A Simplified mathematical procedure for determining the transient temperature rise of cable systems", AIEE Transactions (PAS), Vol.72,Part III, (1953),p. 712-718.

11. VAN ,WORMER,F.C. "An Improved approximate technique for calculating cable temperature transients", AIEE Trans. (PAS), Part III, Vol.74,p.277-281(1955).

12 SIMONS,D.M. "Cable geometry and the calculation of current carrying capacity", AIEE Transaction (PAS), Vol.42, 1923, p.600-620.

13. SINGH,VIKRAM,"Measurement of temperature of underground cables", M.E.Project Report, 1985-86. Electrical Department, U.O.R.Roorkee (India).

BOOKS

B1 "STANDARD HANDBOOK FOR ELECTRICAL ENGINEERS" By
Fink, D.G. and Beaty, H.W.
Eleventh Edition, 1978, p.14.120.

B2 "ELECTRICAL CABLES HANDBOOK By
Mcallister,
Granada-1982, p.104.

B3 "THE PRINCIPLES OF ELECTRIC POWER TRANSMISSION" By
Waddicor,H.
Asia Publishing House, Bombay

B4 "PLASTICS TECHNOLOGY" By
Robert V.Milby
McGraw-Hill Book Co, New York,1973,p.460-514

B5 "PLASTICS MATERIALS HANDBOOK" By
Athalye, A.S.
Multi-Tech Publishing Co, Bombay, P.58

B6 "UNIFIED CONCEPTS IN APPLIED PHYSICS" By
Edward,J., Court, James E.
Prentice-Hall , Inc. Eng.

B7 "THE NATURE AND PROPERTIES OF SOIL" By
Buckman,Harry,O , Brady,Nyle,C.
Seventh Edition, p.260-61.

B8 "GLOSTER CABLES"

Published by M/S Fort Gloster Industries Ltd.,

Calcutta
Publication No. 204.

B9 IEEE RECOMMONDED PRACTICE FOR ELECTRIC POWER DISTRIBUTION FOR INDUSTRIAL PLANTS

Distribution in Coorporation with
Wiley-Interscience, 1976

B10 "POWER CABLES " t THEIR DESIGN AND INSTALLATION", By

Barnes,C.C,

Second Edition, 1966

Chapman and Hall Ltd. London

B11 "MARK'S STANDARD HANDBOOK FOR MECHANICAL ENGINEERS"

Seventh Edition, Banmeister, P.6.8

B12 "ENGINEERING MANUAL" By

Perry
Third Edition, p.3.18.

13. "ELECTRIC POWER SYSTEMS" By

Weedy, B.M.,
Third Edition.

BIBLIOGRAPHY

1. PHILIP, T. " Permissible operating temperatures of impregnated paper insulation in which dielectric stress is low, AIEE Transaction,(1921),Vol.40, p.107-203.
2. NEHER,J.H. "The temperature rise of cables in duct bank", AIEE Trans. (PAS),Vol.68, Part I (1949), p.540-49.
3. NEHER,J.H. "The temperature rise of buries cables and pipes",AIEE, Transactions, Vol.68, Part 2,1949, p.9-21.
4. NEHER,J.H. "The determination of temperature transient in cable systems by means of an analogue computer", AIEE Transactions, Vol.70, Part II, 1951,p.1361-71.
5. "Symposium on Temperature Rise of Cables", AIEE Committee Report, AIEE Transactions, Vol.72,1953, p. 530-561.
6. ROBERT,J.WISEMAN "An Empirical method for determ ning Transient Temperatures of buried cable system, AIEE Transactions, Vol.72, Pt.III, June 1953,p.545-51.
7. FINK,L.H. "Control of the thermal environment of buried cable system", AIEE Transactions, Vol.73,Part III, April, 1954, p.406-12.

8. E.deHAAS,SANDIFORD, P.J.,CAMERON, A.W.W."An Analogue solution of cable heat flow problems",AIEE Transaction (PAS), Part III, Vol.74, p.315-318,(1955).

9. NEHER,J.H. and McGRATH "The calculation of the temperature rise and load capability of cable systems", IEEE Transaction (PAS), Vol.76, P-752-772,Oct.1957.

10. NEHER,J.H. "The Transient temperature rise of buried cable system", IEEE Transation (PAS), Vol.83,p.102-114, Feb.1964.

11. KIMURA,S AND TSURU,M "Temperature calculation of conductors in underground power cables", Elect. Engineering Japan (USA),Vol.68,No.11,p.24-31. (Nov.1966).

12. THAPAR,B., RAM,S.K. "Soil thermal resistivity for directly buried cables", J.Instn.Engineers(India), Elect.Engineering Div.,Vol.49,no.10 (pt EL5),p.283-6 (June 1969).

13. GOHAR,M.K.," Effect of moisture migration on temperature rise in underground cable" Proceeding IEEE(USA), Vol.59,no.10,p.1540-1 (Oct.1971)

14. PECH,H. "Temp. difference between cables buried at different depth", Cables and Transmission(France), Vol.25, no.3,p. 261-7, July 1971 (IN FRENCH).

15. PRIME,J.B. AND VALDES,J.G. " System to monitor the conductor temperature of the underground cables", IEEE Transaction (PAS), Vol.100, 1981, p.143-151.

16. KELLOW,M.A. "Numerical method for the calculation of temperature rise and ampicity of U.G.Cable, IEEE Gransactions,(PAS), Vol. PAS-100, no.7,p.3322-30 ((July 81).

17. PRIME,J.B., VALDES, Jr.J.G. "System to monitor the conductor of U.G.cable", IEEE Transaction (PAS),Vol. PAS-100, no.1, p.143-53 (Jan.83).

18. BLACK,W.Z.,SANG-IL-PARK " Emergency ampacities of direct buried three core underground cable system", IEEE Trans. PAS(USA), Vol. PAS-102,no.7, p.2124-32 July 1983).

19. Conference record 'Industrial and Commercial Power System Technical Conference 1984 (Cat No.84 CH 2040-4) ATLANTA,G.A.,U.S.A. (May 1984) ,p.172-5.

20. BRAKELMANN,H."Consideration of temperature dependent thermal resistance of power cable insulation", ETZ Arch. (Germany), Vol.7, no.8,p.279-81(Aug 1985) (IN GERMAN).

APPENDIX---- A_1

SPECIFICATION OF AUTO TRANSFORMER

"DIMMERSTAT"

Continously Adjustable Auto transfermer

Three phase, Oil cooled.

Type ... 200D-6T

S.No... T 374/2324

Connection for maximum out put equal to input voltage:-

Input at A_1 A_2 A_3 ... 415 Volt, 3 Ø , 50 c/s

Output at E_1 , E_2 E_2 ..415 Volts

Connection for output voltage 13% higher than maximum input voltage :-

Input at B_1 B_2 B_3 ... 415 Vo,ts , 3 Ø , 50 c/s

Output at E_1 E_2 E_3 ... 0-470 Volts

Output Current ... 200 A/phase

Manufactured by

M/S Automatic Electric Pvt. Ltd., Bombay.

APPENDIX... A_2

SPECIFICATIONS OF 3-PHASE STEP DOWN TRANSFORMERS

Confirms to B.S S 171/1959

S.NO... 703 Type NO...

KVA. = 53 FREQUENCY -50 c/s

VOLTS : H.V = 400
L.V. = 9

AMPS : H.V. = 76
L.V. = 3400

PHASE : H.V. = 3
L.V. = 3

Manufactured by : POWER ENGINEERS CALCUTTA.

Supplied by : M/S Scientific Supplies and Services,
P-39, Princep- Street, Calcutta.

APPENDIX...A_3

SPECIFICATION OF R.T.D.

These sensers are made of platinum

R.T.D. confirm to IS 2848: 1965 and B.S.S. 1904:1964.

Fundamental interval : 38.50 Ohms

: Length - 150 mm
Dimensions : Width - 8 mm
: Thickness - 2 mm

Termination : Direct leads are taken out. PTFE coated silver plated copper leads

Maximum Temperature : 0 - 180°C

Resistance accuracy : 0.1 Ohm at °C and 0.25 Ohms at 100°C as per DIN 43760

Insulation Resistance : More than 50 M - Ohms

Lead Length : As desired

H.V. Strength : More than 2KV r.ms

Other test specifications: confirm to IS 2848

Element : Single

Bridge configration : Three wire

APPENDIX - A

CABLE SPECIFICATIONS

Type : $3 \frac{1}{2}$ Core P.V.C. Insulated and sheathed armoured cable

Nominal Area of the Conductor = 150 mm^2

Nominal Diameter of the Conductor = 15.68 mm

Thickness of conductor insulation 'T' = 1.8 mm

Thickness of belt insulation t = 0.3 mm

Thickness of the outer sheath 'T_1 = 3.0 mm

D.C.Resistance of the Conductor

(Maximum allowable at 20°C), R_{20} = 0.2090 Ohms/Km

Approximate overall diameter of the cable = 44.7 mm

Outer Radius of the sheath r_2 = $\frac{44.7}{2}$ mm

= 22.35 mm

Inner Radius of the sheath r_1 = 22.35 - 3.0

= 19.35 mm

Thickness of the armouring i.e. 'T_2' = 3 mm

APPENDIX B

CALCULATION OF THERMAL RESISTANCE OF CONDUCTOR INSULATION IN A MULTI CORE BELTED CABLE

The emprical formula for calculating thermal resistance of the conductor insulation in a multi core belted cable is given below :

$$R_{ins} = \frac{g}{2\pi}\left[0.85 + \frac{0.2t}{T}\right]\ln\left[\left(4.15 - \frac{1.1t}{T}\right)\left(\frac{T+t}{r}\right)+1\right]$$

As per cable specifications.

g = 6.5 ^{o}C -m/Watt.

t = Thickness of belt insulation = 0.3 mm

T = Thickness of conductor insulation = 1.8 mm

r = Radius of the conductor = 7.84 mm

putting these values in above formula we get,

$$R_{ins} = \frac{6.5}{2\pi}\left[0.85 + \frac{0.2 \times 0.3}{1.8}\right]\ln\left[\left(4.15 - \frac{1.1\times0.3}{1.8}\right)\left(\frac{1.8+0.3}{7.84}\right) + 1.0\right]$$

$$= \frac{6.5}{2\pi} \quad 0.8833 \quad \ln \quad (3.967\times0.2678) + 1.0$$

$$= \frac{0.5}{2\pi} \times 0.8833 \times 0.7239$$

= 0.662 Thermal Ohms/m .

Effective value of the R_{ins} from the mechanism of heat flow Fig.(3·1) will be 1.5 time of the calculated value

$$R_{ins} = 1.5 \times 0.662$$

$$\equiv 0.993 \text{ Thermal Ohms/m}$$

APPENDIX - C

CALCULATION OF THERMAL RESISTANCE OF OUTER SHEATH AND BELT INSULATION

(1) The thermal resistance of outer sheath 'R_{OS}' is given by

$$R_{OS} = \frac{g_1}{2} \ln \frac{r_2}{r_1} \qquad \ldots(1)$$

As per cable specification in Appendix.

r_2 = 22.35 mm

r_1 = 19.35 mm

g_1 = 6.5°C-m/Watt (Assumed) putting these values in (1) we get

$$R_{OS} = \frac{6.5}{2} \ln. \frac{22.35}{19.35}$$

$$= \underline{0.1492 \text{ Thermal Ohms/mt}} .$$

Similarly, thermal resistance of belt insulation will be:

$$R_{is} = \frac{6.5}{2} \ln \frac{r_3}{r_4} \qquad \ldots(2)$$

Where, r_3 = Outer radius of the belt =19.35-3.00 =16.35 mm

r_4 = Inner radius of the belt=16.35-0.3 =16.05 mm

$$\therefore R_{is} = \frac{6.5}{2} \ln. \frac{16.35}{16.05}$$

$$= 0.01917 \text{ thermal Ohms/ mt}$$

APPENDIX - D

(a) CALCULATION OF EFFECTIVE A.C. RESISTANCE OF THE CONDUCTOR :

As PER ISS 1554 (Part I) the d.c. resistance of the conductor for our cable dimensions, R_{20} = 0.2090 ohm/km at 20°C. Now this value of R_{20} must be multiplied by correction factor due to temperature rise (F_t), correction factor due to skin effect (F_s) , correction factor due to proximity effect (F_p) and correction factor for lay of the cable (Fe). So the effective a.c. resistance at θ°C will be

$$R\theta = R_{dc} \times F_s \times F_p \times Fe \times F_t \quad \text{ohm/Km}$$

For our case,

$F_s = 1.1$, $F_l = 1.02$ and F_p = Small can be neglected

$$\therefore \quad R\theta = R_{20} \times 1.1 \times 1.02 \times Ft$$

$$= 0.2090 \times 1.1 \times 1.02\ Ft\ \text{Ohm/Km}$$

$$= 0.2345 \times Ft\ \ \text{Ohm/Km}$$

The value of Ft for various temperature can be selected from ISS 1554(Pt.1) and effective a.c. resistance can be found

(b) ESTIMATION OF CONDUCTOR TEMPERATURE T_c :

Case I : When cable was laid on lab floor.

The phase current = 100 Amps.

From saturation curve the maximum conductor temperature (measured) = $48.2^\circ C$

$\therefore R_{48} = 0.2345 \times 1.112 = 0.261$ Ohm/Km

$\therefore$ The heat produced by each conductor

$$H = I^2 R = 2.877 \text{ Watts}$$

$$\therefore 3H = \text{Total heat} = 8.631 \text{ Watts.}$$

Now,

$$\theta_{m_1} = T_s - T_1 = 3H \times R_{os}$$

$$= 8.631 \times 0.1493 = 1.29^\circ C$$

$$\theta_{m_2} = T_2 - T_1 = 3H \times R_{is}$$

$$= 8.631 \times 0.01917 = 0.165^\circ C$$

$$\theta_{m_3} = T_c - T_2 = H \times R_{ins}$$

$$= 2.877 \times 0.993 = 2.857^\circ C$$

$\therefore$ Estimated conductor temperature

$$T_c = 42.5 + 1.29 + 0.165 + 2.857$$

$$(\text{as } T_s = 42.5^\circ)$$

$$\therefore T_c = 46.81^\circ C$$

But measured value of conductor temperature

$T_{CM} = 48.2^{o}C$

$\therefore \quad T_{CM} - T_{C} = 48.2 - 46.81 = 1.38^{o}C$

Case II :- When cable was laid above the floor (approximate 15 cms above)

For I = 100A, $T_{max} = 48^{o}C$

$\therefore \quad R_{48} = 0.2345 \times 1.112$ Ohm/Km

$= 0.261$ Ohm/Km

Heat as calculated in case I

$H = 2.877$ Watts

$\therefore \quad 3H = 8.631$ Watts

$\therefore \quad \theta_{m_1} = 8.631 \times 0.1493 = 1.29^{o}C$

$\theta_{m_2} = 8.631 \times 0.01917 = 0.165^{o}C$

$\theta_{m_3} = 2.877 \times 0.993 = 2.857^{o}C$

$\therefore$ Eastimated conductor temperature

$T_{C} = 43.2 + 1.29 + 0.165 + 2.857$

(as from table $T_{S} = 43.2^{o}C$)

$\therefore \quad T_{C} = 47.51^{o}C$

and $T_{CM} = 48^{o}C$

$\therefore \quad T_{CM} - T_{C} = 0.49^{o}C$

APPENDIX - E

CALCULATION FOR THERMAL RESISTANCE OF SOIL (R_{soil})

Assuming thermal resistivity of soil in our case,

$g = 1.1$ °C-m/Watt

know that

$$R_{soil} = \frac{g}{2\pi} \ln \frac{2h}{r_2}$$

I :- Depth of Burial = 0.5 meter

$\therefore$ h = 50 + overall radius of the cable

$= 50 + 2.235 = 52.235$ cms

$r_2 = 2.235$ cms

$$R_{soil} = \frac{1.1}{2\pi} \ln \frac{2 \times 52.235}{2.235}$$

$= 0.673$ Th. Ohms/m

II :- Depth of Burial = 1.0 meter

$h = 100 + 2.235 = 102.235$ cms

$$soil = \frac{1.1}{2\pi} \ln \frac{102.235}{2.235}$$

$= 0.791$ Th. Ohms/m

CALCULATION FOR CONDUCTOR TEMP. FOR BURIED CABLES:-

<u>Case I</u> :- Depth of burial = 0.5 meter

(i) considering cable surface as ref :

$R_{cond} = R_{50} = 0.26$ Ohm/Km

$I = 150$ AMP

$\therefore$ Heat $= I^2R = 5.85$ W

$\therefore \theta_{m_1} = 3\text{x } 5.85 \times 0.1493 = 2.62\ ^{\circ}C$

$\theta_{m_2} = 3\text{x } 5.85 \times 0.01917 = 0.336\ ^{\circ}C$

$\theta_{m_3} = 5.85 \times 0.993 = 5.809\ ^{\circ}C$

Measured $T_s = 40.8^{\circ}C$

$\therefore$ Estimated conductor temperature T_c

$= 40.8 + 2.62 + 0.336 + 5.809$

$= 49.56\ ^{\circ}C$

$T_{CM} - T_C = 49.8 - 49.56 = 0.235^{\circ}C$

(ii) Considering the earth surface as ref:

Temp. drop in the soil $= 3H \times R_{soil}$

$= 0.673 \times 3 \times 5.85$

$= 11.81\ ^{\circ}C$

$\therefore$ Estimated conductor Temperature

$T_C = T_A + 11.81 + 2.62 + 0.336 + 5.809$

$= 29.5 + 20.576$

$= 50.076\ ^{\circ}C$

$\therefore T_{CM} - T_C = -50.076 + 49.8 = -0.276\ ^{\circ}C$

APPENDIX-F

EFFECT OF MOISTURE ON SOIL RESISTIVITY :-

After calculation, the conductor temperature (taking earth surface as reference for the observations taking after rain) it was found that the estimated conductor temperature is 64.781°C as compared to the measured value of 60.2°C. This difference is due to heavy rain, the moisture contents in the soil has increased and hence the thermal resistivity decreases.

The value selected as 1.1 °C-m/Watt was for dry soil. The new value can be obtained as under :

$$T_C = T_A + \theta_e + \theta_{m_1} + \theta_{m_2} + \theta_{m_3}$$

$$\therefore 60.68 = 27.5 + \theta_e + 4.747 + 0.609 + 10.525$$

$$= 43.381 + \theta_e$$

$$\therefore \theta_e = \theta_{soil} = 60.68 - 43.381$$

$$= 17.3\ ^\circ C$$

$$\therefore 3H \times R_{soil} = 17.3$$

$$= \frac{17.3}{31.8} = 0.544 \text{ Th. Ohm/m}$$

$$\therefore \frac{g}{2} \ln \frac{2 \times 52.235}{2.235} = 0.544$$

$$\therefore g = 0.88\ ^\circ C\text{-m/Watt}$$

APPENDIX - G

(a) ESTIMATION OF CONDUCTOR INSULATION THERMAL CAPACITANCE:-

From Appendix ' A ' We have

D_i = Diameter of the conductor

= Inner Diameter of the insulation

= 1.568 cms.

D_e = D_i + 2 Thickness of the insulation

= 1.568 + 2 x 0.18 = 1.928 cms.

$\therefore D_e^2 - D_i^2 = 1.928^2 - 1.568^2 = 1.25856$

Putting this value in equation (3.12) we get.

$C_{ins} = 0.04744 \times 1.25856$

$= 0.0597$ WH/°C -m

$- 0.06$ WH/°C-m

(b) THERMAL CAPACITANCE OF CONDUCTOR

From Appendix ' A ' we have

$D_e = 1.568$ cms

$\therefore D_e^2 = 2.458624$ cm^2

Putting this value in equation no (3.13) we have

$C_{cond} = 0.05345 \times 2.4586$

$= 0.1314$ WH/ °C -m

(c) THERMAL CAPACITANCE OF NEUTRAL COND.

$$\therefore\ C_N = \frac{1}{2}\ C_{cond}$$

$$= \frac{1}{2} \times 0.1314 = 0.0657 \text{ WH/}^oC\text{-m}$$

(d) THERMAL CAPACITANCE OF ARMOURING

From appendix (A) we have,

Inner Diameter of the armouring

= Inner Dia of outer sheath -2 Thickness of armouring

$D_i = 4.47 - 0.6 - 0.6 = 3.27$ cm.

Outer diameter of armouring

$D_e = 3.27 + 0.6 = 3.87$ cm

$\therefore\ D_e^2 - D_i^2 = 4.284 \text{ cm}^2$

From ref [B6]

Specific heat for steel = 0.113 Cal/gm- °C

Specific density for steel = 7.8

$$\therefore\ C_a = \frac{\pi}{4}(D_e^2 - D_i^2) \times 7.8 \times 0.113 \text{ Cal/}^oC\text{-cm}$$

$$= \frac{\pi}{4} \times 4.284 \times 7.8 \times 0.113 \times 110 \text{ Cal/}^oC\text{-m}$$

$$= 296.41 \text{ Cal/ }^oC\text{-m}$$

$$= \frac{296.41}{0.239 \times 3600} = 0.3445 \text{ WH/}^oC\text{-m}$$

$$= 0.3445 \text{ WH/}^oC\text{-m}$$

(e) THERMAL CAPACITANCE OF INNER SHEATH

From appendix 'A' We have

Inner diameter of the inner sheath

$D_i = 1.568$ cm

Outer Diameter of the inner sheath = D_e

D_i + 2 thickness of the belt insulation

$\therefore D_e = 1.568 + 0.06 = 1.628$ cm

$\therefore D_e^2 - D_i^2 = 1.3982$

Putting this value of $(D_e^2 - D_i^2)$ in equation (3.12) we get

$$C_{is} = 0.04744 \times 1.3982$$
$$= 0.06633 \quad \text{WH}/\ {}^{\circ}\text{C-m}$$

(f) THERMAL CAPACITANCE OF OUTER SHEATH

From appendix A We have

Outer diameter of the sheath = D_e = 4.47 cms

Inner diameter of the sheath = D_i = 4.47 - 0.6

D_i = 3.87 cms

$\therefore D_e^2 - D_i^2 = 5.004$

Putting this value of $(D_e^2 - D_i^2)$ in equation (3.12) we have

$$C_{os} = 0.04744 \times 5.004$$
$$= 0.2374 \quad \text{WH}/\ {}^{\circ}\text{C-m}$$

APPENDIX- H

CALCULATION OF EARTH THERMAL CAPACITY

Depth of Burial = one meter

From equation (3.14) we have

Thermal capacity of Soil

$$Q = 0.039 (D_e^2 - D_i^2) \text{ WH/ } ^{o}\text{C-m}$$

D_e = 204.47 cms

D_i = 4.47 cms

$Q == 0.039 (204.47^2 - 4.4^2)$

$= 1930 \text{ WH/ } ^{o}\text{C-m}$

The actual thermal capacity which is effecting the heat flow lines will be [from fig. (3.1), heat flow mechanism] equal to 1/3 Q approximately, So,

$$Q = \frac{1}{3} \times 1930 = 643.33 \text{ WH/ } ^{o}\text{C-m}$$

APPENDIX --- I

SOLUTION OF THERMAL CIRCUIT

From Appendix B, C, G, E, & H We have

R_{ins} = 0.22 Thermal Ohm/m

R_{os} = 0.1493 Thermal Ohm/m

R_{is} = 0.01917 Thermal Ohm/m

C_{ins} = 0.06 x 3 = 0.18 WH/°C-m

C_{cond} = 0.1314 x 3 = 0.3942 WH/°C-m

C_N = 0.0657 WH/°C-m

C_a = 0.3445 WH/°C-m

C_{is} = 0.06633 WH/°C-m

C_{os} = 0.2374 WH/°C-m

For solving the thermal circuit of fig.(3.2) let us first findouout the value of P. We know that

$$P = \frac{1}{2 \ln {}^{R}/_{r}} - \frac{1}{R^2/r^2 - 1}$$

$$= \frac{1}{2 \ln \frac{22.35}{7.84}} + \frac{1}{\left(\frac{22.35}{7.84}\right)^2 - 1}$$

$$= 0.34$$

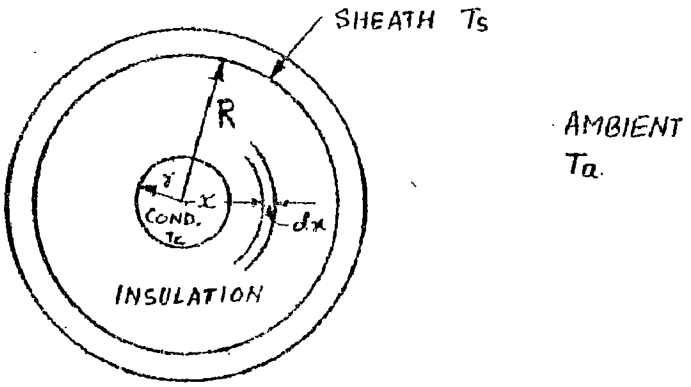


FIG.[A-1] GEOMETRY OF SINGLE CORE CABLE

Now lumping the parameters of the circuit to get the circuit shown in fig. (2·5)

$$C_1 = C_{cond} + C_N + P\,(C_{ins} + C_{is})$$
$$= 0.3942 + 0.0657 + 0.34(0.06633 + 0.18)$$
$$= 0.5436 \text{ WH/}^{\circ}\text{C-m}$$

$$C_2 = C_a + C_{os} + (1 - P)(C_{is} + C_{ins})$$
$$== 0.3445 + 0.2374 + 0.66(0.06633 + 0.18)$$
$$= 0.744 \text{ WH/}^{\circ}\text{C-m}$$

S_{12} = 4.164 (as $R_{12} = R_{ins} + R_{is}$) mho/m

S_2 = 6.698 (as $R_2 = R_{os}$) mho/m

Now putting these values in equation

$$a = \frac{1}{2}\left[\frac{S_{12}}{C_1} + \frac{S_{12}+S_2}{C_2}\right]\left[\frac{1}{4}\sqrt{\left(\frac{S_{12}}{C_1} + \frac{S_{12}+S_2}{C_2}\right)^2 - \frac{S_{12}\,S_2}{C_1\,C_2}}\right]$$

$$= \frac{1}{2}\left[\frac{4.164}{0.5436} + \frac{4.164+6.698}{0.744}\right] + \left[\sqrt{\frac{1}{4}\left(\frac{4.164}{0.5436} + \frac{4.164+6.698}{0.744}\right)^2 - \frac{4.164 \times 6.698}{0.744 \times 0.5436}}\right]$$

$$= \frac{1}{2}\left(7.66 + 14.599\right) + \sqrt{\frac{1}{4}\left(7.66 + 14.599\right)^2 - 68.96}$$

$$= 11{,}13 + 7.41 \qquad = 18.54$$

Similary,

$$b = \frac{1}{2}\left[\frac{S_{12}}{C_1} + \frac{S_{12}+S_2}{C_2}\right] + \sqrt{\frac{1}{4}\left(\frac{S_{12}}{C_1} + \frac{S_{12}+S_2}{C_2}\right)^2 - \frac{S_{12}\,S_2}{C_1\,C_2}}$$

$$= 11.13 - 7.41 = 3.72$$

and

$$A = \left(\frac{1}{a-b}\right)\left[\frac{1}{C_1} - b\left(\frac{1}{S_{12}} + \frac{1}{S_2}\right)\right]$$

$$= \frac{1}{18.54 - 3.72} \times \left[\frac{1}{0.5436} - 3.72\ (0.24 + 0.1493)\right]$$

$$= 0.067\ (1.8396 - 1.448)$$

$$= 0.026$$

$$B = \frac{1}{(a-b)} \times \left[\frac{1}{C_1} - a\left(\frac{1}{S_{12}} + \frac{1}{S_2}\right)\right]$$

$$= -0.067\ (1.8396 - 7.217)$$

$$= 0.36$$

So, the solution of the circuit will be

$$\theta = HA)(1-e^{-at}) + HB(1-e^{-bt})$$

$$\theta = 0.026H(1-e^{-18.54t}) + 0.36H(1-e^{-3.72\,t})$$

So, the time constant of the cable

$$= \frac{1}{b} = \frac{1}{3.72} = 16 \text{ minutes}$$

APPENDIX -J

CALCULATIONS OF SHORT TIME LOADING FACTORS AND SHORT TIME CAPACITIES

Case I :- Cable is at no load

From the temperature rise Vs time curve for rated current we have , fig (5.4)

(i) for t = 1 hr $T = 25^{\circ}C$, $T_m = 38.1^{\circ}C$

$$\therefore \quad n = \sqrt{\frac{T_m}{T}} = \sqrt{\frac{38.1}{25}} = 1.234$$

$\therefore$ Short time current rating = 253 Amps

(ii) for t = 2 hrs, $T = 36^{\circ}C$

$$n = \sqrt{\frac{38.1}{36}} = 1.058$$

$\therefore$ Short time current rating = 217 Amps

(iii) for t = 3 hrs $T = 37.6^{\circ}C$

$$n = \sqrt{\frac{38.1}{37.6}} = 1.0066$$

$\therefore$ Short time current rating = 206 Amps

(iv) $t = \frac{1}{2}$ hrs $T = 16.6^{\circ}C$

$$n = \sqrt{\frac{38.1}{16.6}} = 1.515$$

$\therefore$ Short time current rating = 310 Amps.

Case- II

Cable is initially loaded to 75% of the rated value

(i) $t = \frac{1}{2}$ hrs $T = 29.6\ ^{\circ}C$ $T_m = 38.1\ ^{\circ}C$

$$n = \sqrt{\frac{38.1}{29.6}} = 1.1345$$

Short time current rating = 232.58 Amps

(ii) $t = 1$ hrs $T = 34.8^{\circ}C$ $T_m = 38.1^{\circ}C$

$$n = \sqrt{\left(\frac{38.1}{34.8}\right)} = 1.046$$

Short time current rating = 214.5 Amps

(iii) $t = 2$ hrs , $T = 37.4^{\circ}C$ $T_m = 38.1^{\circ}C$

$$n = \sqrt{\frac{38.1}{37.4}} = 1.0093$$

Short time rating = 207 Amps

(iv) $t = 3$ hrs $T = 37.9^{\circ}C$ $T_m = 38.1\ ^{\circ}C$

$$n = \sqrt{\frac{(38.1)}{(37.9)}} = 1.0026$$

Short time current rating = 205.5 Amps

Case--III

Cable is initially loaded to 50% of the rated value

(i) $t = \frac{1}{2}$ hrs $T = 20.4\ ^{\circ}C$ $T_m = 38.1^{\circ}C$

$$n = \sqrt{\frac{38.1}{20.4}} = 1.367$$

Short time current rating = 280 Amps.

(ii) $t = 1$ hrs $T = 28^{\circ}C$ $T_m = 38.1$

$$n = \sqrt{\left(\frac{38.1}{28}\right)} = 1.167$$

Short time current rating = 239 Amps

(iii) $t = 2$ hrs $T = 36.4$ $T_m = 38.1^{\circ}C$

$$n = \sqrt{\frac{38.1}{36.4}} = 1.023$$

Short time current rating = 210 Amps

(iv) $t = 3$ hrs $T = 37.7\ ^{\circ}C$ $T_m = 38.1$

$$n = \sqrt{\frac{38.1}{37.7}} = 1.0053$$

Short time current rating = 206 A