# PRE-DETERMINATION OF TEMPERATURE RISE IN DC MACHINES BY HEAT TRANSFER CALCULATIONS

A DISSERTATION
*submitted in partial fulfilment of the requirements*
*for the award of the degree*
*of*
MASTER OF ENGINEERING
*(Power Apparatus and Electric Drives)*

*By*
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# CERTIFICATE

Certified that the dissertation entitled 'PRE-DETERMINATION OF TEMPERATURE RISE IN D.C.MACHINES BY HEAT TRANSFER CALCULATIONS' which is being submitted by Shri ANUP SINGH in partial fulfilment for the award of the Degree of Master of Engineering in 'POWER APPARATUS AND ELECTRIC DRIVES' of Electrical Engineering of the University of Roorkee is a record of the student's own work carried out by him under our supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked ~~for a period of......16.....months from.....January, 1977 to ...May, 1978... for preparing the dissertation for~~ Master of Engineering Degree.

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# SYNOPSIS

The present work deals with the calculation of temperature rise of different parts of a large d.c. machine. From the design details aerodynamic resistances of different parts are determined using which an equivalent circuit has been developed. This equivalent circuit has been solved using network techniques and air distribution in the machine is determined. On the basis of the ventilation calculations, heat calculations are carried out and temperature rise of different parts of a d.c. machine are predetermined. This method has been compared with conventional methods and actual test results.

Page

CHAPTER-I

CHAPTER-II

CHAPTER-III

Page

CHAPTER-IV

CHAPTER -V

CHAPTER-VI

# NOMENCLATURE

$As$ : Linear electrical loading

$bz_2$ : Width at middle of tooth

$Bz_2$ : Flux density at middle portion of the tooth

$b_b$ : brush width

$b_n$ : Slot width

$B_a$ : Armature core flux density

$D_a$ : Armature diameter

$D_i$ : Armature core inner diameter

$D_K$ : Commutator diameter

$D_z$ : Armature diameter at bottom of slot

$d_f$ : depth of shunt coil

$F_b$ : brush area in contact with the commutator

$F_n$ : area under consideration

$F_{n-1}$ : area occuring prior to $F_n$

$f$ : frequency

$GF_{\ell a}$ : weight of steel in armature core

$GF_{\ell z}$ : weight of steel in armature teeth

$h_f$ : height of shunt coil

$h_n$ : height of slot

$I_a$ : armature current

$I_e$ : excitation current

$j_a$ : armature winding current density

$j_s$ : shunt winding current

$K$ : number of commutator segments

$k$ : constant

$k_t$ : heating coefficient

$\ell_t = \ell$ : armature core length

$\ell_s$ : end part of armature winding

$\ell_b = \ell_e$ : extension of armature winding at both ends

$L_p$ : length of pole core

$\ell_k$ : length of commutator

$n_d$ : number of radial ventilating ducts

$P$ : output of the machine

$p$ : pair of poles

$p'$ : dissipation

$Q$ : total inlet air

$Q_1$ : quantity of air through the magnetic system

$Q_2$ : quantity of air through the armature

$QF_{\ell a}$ : iron losses in armature core

$QF_{\ell z}$ : iron losses in armature teeth

$Q_M$ : mechanical losses

$r_{a\,75}$ : resistance of armature winding at 75°C

$r_{w\,75}$ : resistance of interpole winding at 75°C

$r_{c\,75}$ : resistance of compensating winding at 75°C

$t_1$ : slot pitch at top

$U_n$ : armature voltage

$U_e$ : exitation voltage

$\Delta U_b$ : brush drop

$v_a$ : armature peripheral velocity

$v_K$ : commutator peripheral velocity

$Z$ : number of armature slots

$\tau$ : pole pitch

$\beta_K$ : commutator pitch

# CHAPTER - I

## INTRODUCTION

The study on pre-determination of temperature rise in d.c. machine has been carried out with the objective that at design stage itself one should knew the temperature of various parts of the machine. The loss in various parts of a d.c. motor is converted into heat, which produces a temperature rise above that of the ambient air. The value of final temperature rise depends upon the heat capacity of various insulating materials used and also upon the rate at which heat is conducted through materials to cooling medium. The final temperature is achieved when heat is dissipated as fast as it is generated.

## 1.1 Different parts of a large d.c. machine

A d.c. machine consists essentially of a stationary magnetic system called the stator and a rotating armature carrying conductors which are connected to the commutator mounted on the same shaft as the armature. The different parts of a large d.c. machine shown in Fig.1(i) are described below:-

a) Stator: It consists of a frame or yoke and poles which support the field winding also. The yoke serves as a mechanical support for the entire assembly. Earlier, cast iron was used for the yoke and subsequently it has been replaced by cast steel. This has helped in reduction in weight of the machine as cast steel saturates at 1.5 $Wb/m^2$ as compared to cast iron which saturates at 0.8 $Wb/m^2$. Now-a-days, we have laminated yoke construction. Lamination of electro-technical sheet steel, 1.0 mm thick are stacked together to form the yoke. This has helped in reduction of eddy current losses and also enables the machine to sustain higher rate of rise of currents.

b) Poles: Poles were formerly cast integral with the frame or yoke, the practice still continuing for small machines. But these days, it is usual to use completely laminated pole construction. The laminations are generally 1.0 mm thick, and the material used is electro-technical sheet steel. The poles are fixed to the yoke by means of bolts. In case of machines having compensating windings, the poleshoe is slotted to accommodate the compensating bars or coils.

c) Interpoles: The interpoles lie in between the main poles and are fixed to the yoke by means of bolts. Interpoles too are of laminated construction for large machines. For smaller ones, however, solid low carbon steel poles may be used. Interpoles may be parallel sided or tapered.

d) Main field winding: This winding is accomodated on the main poles of the machine. Generally, rectangular glass covered conductors are used for large machines. The complete coil is taped and baked and then impregnated with epoxy varnish to avoid air space between conductors as such space obstructs the flow of heat from the inner coil side to its surface. The coil is mounted on the main pole core and impregnation is carried out again.

e) Interpole winding: Bare copper conductors are used for interpole winding for large machines. The conductors are insulated from each other by means of asbestos spacers. The top and bottom layers are insulated with flexible polyster varnish bonded glass mica paper tape. Over this one layer of glass fibre woven tape is used. The interpole winding is mounted on the core and the complete assembly is impregnated in epoxy varnish.

f) Compensating windings : This winding is housed in the main pole slots of the machine. It is normally in the form of a coil or bar type. Compensating bars are used for large machines and consist of bar~~s~~e copper conductors and these are suitably insulated by means of samica therm insulation. This winding is connected in series with the main armature circuit.

g) Armature: The armature of d.c. machines is built up of thin laminations of low silicon steel, generally termed as electro-technical sheet steel. The laminations are 0.5 mm thick and are insulated from each other by varnish.

In small machines, the armature laminations are fitted directly on to the shaft and are clamped tightly between end flanges which also act as support for the armature winding. The laminations are punched in one piece and provision is made for axial ventilation holes.

In large machines, the armature core is divided into a number of packets by radial ventilating spacers. These spacers are I Sections and welded to the steel lamination. Depending upon the armature diameter of the machine, it is sometimes not possible to punch the laminations in one piece. In such cases, the laminations are punched in segments. The segments are attached to the spider arms by means of matching dove tail grooves.

h) Armature windings : Depending upon the current to be carried by the armature, the d.c. machine may be designed for simple lap, simple wave, double lap, double wave or frog leg winding. The armature coils are generally former wound and then after appropriate insulation (samica therm) are laid in the armature slots. For medium sized machines, bandaging of the armature is done to prevent the coils from leaving the slots due to centrifugal action while the machine is rotating. For large machines glass textolite wedges are used.

i) Commutator: The electromotive force generated in the armature coils is alternating in nature and the commutator with brushes is used for rectifying the alternating emf. The segments of a commutator are made from hard drawn copper or silver bearing copper and are separated by thin sheets of micanite. The segments are connected to the armature conductors through risers, made of copper strip.

j) Brush gear: This assembly consists of brush rockers, brush holders and brushes. The brush rocker is arranged concentrically round the commutator. The brush holders are fixed to the brush rocker by means of bolts. Brush holders are generally made of bronze casting and accomodate a carbon brush, complete or split type. The brush comes in contact with the commutator surface and appropriate pressure is provided by means of a spring. These days, use of constant pressure brush holders has been envisaged. The brushes are at times staggered along the commutator surface. Axial staggering helps in uniform wear of the commutator surface whereas circumferential staggering increases the width of the commutating zone.

## 1.2 Conventional methods of temperature rise calculations

Temperature rise limitations are strictly imposed on all windings of the machine. As mentioned earlier, steady state temperature conditions are achieved when heat is dissipated at the same rate at which it is developed. However, under certain conditions of overloading, the machine is incapable of getting rid of heat rapidly enough, in which case, the temperature may rise sufficiently to cause the insulating materials to carbonise and become brittle. In such cases, the insulation fails to keep the winding from touching the iron or maintaining complete electrical separation between individual conductors. This leads to ground and short circuit faults and eventual break down. The life of such insulating material depends not only upon temperature but also upon electric stresses, vibrations, repeated expansion and contractions, exposure to moisture, air and fumes.

As such, to ensure the performance of the machines, it is essential to determine the temperature rise values of its windings and to ensure that the temperature values are well within the permissible allowable values. The conventional methods as laid down by various authors have been discussed below and finally compared with the values obtained by the equivalent circuit method and the results obtained from actual tests. The conventional methods used for calculating the temperature rise are briefly described below:-

### 1.2.1 Method given by Clayton and Hancock

Temperature rise of armature :

For precise calculations, it is necessary to take into consideration the number and width of ventilating ducts, the external and internal surfaces of the armature core and surfaces of free portion of the windings. Accurate enough results are also obtained by basing the calculations on the external surface of the armature winding.

The following formula has been used by the author:

$$\text{Temp. rise in } {}^{\circ}\text{C} = \frac{250 \text{ to } 300 \times p'}{1 + 0.09\, v_a^{1.3}}$$

The cooling surface is obtained by multiplying the overall axial length of the complete winding by the external circumference of the armature. The power wasted includes the iron loss, the copper loss and the additional losses.

For armature peripheral velocity ranging from 15 to 25 m/sec, the formula suggested is

$$\text{Temp. rise in } {}^{\circ}\text{C} = \frac{150 \text{ to } 200 \times p'}{1 + 0.1\, v_a}$$

<u>Temperature rise of field windings</u>: For the field windings, the manner in which permissible losses vary with surface speed of the armature is dependent very largely upon the type of field coil employed.

Calculations for field coil temperature rise have been based taking into account the total surface of the coil. For coils having winding depth not more than 4 or 5 cm, temperature rise is calculated as

$$\frac{(1400 \text{ to } 1600) \times p'}{1 + 0.07\ v_a}$$

Temperature rise of commutator: Temperature rise of commutator is greatly affected by the fanning action of the risers. For a machine in which risers provide good fanning action,

$$\text{Temp. rise in } ^{\circ}\text{C} = \frac{120 \times p'}{1 + 0.1\ v_k}$$

This formula takes into account the cylindrical surface of the commutator and the commutator peripheral velocity.

## 1.2.2 Method given by Kuhlmann

Armature temperature rise :

For large diameters, the cooling surface per watt loss is

$$\frac{S_a}{W_a} = \frac{\left\{\left[\pi D_a (l_g + 4\ l_o) + \pi D_i\ l_g + \frac{\pi}{4} (D_a^2 - D_i^2)(2 + n_d)\right] \times 1 + 0.00051\ v_a\right\}}{W_a}$$

Where, $W_a$ = sum of armature copper losses, iron losses and frictional and additional losses.

All dimensions in the above formula are in inches and peripheral velocity in feet/min. Radiating surface is indicated by the dotted lines in figure 1(ii). The factor $(1+0.00051\ v_a)$ accounts for the increased radiating capacity of the armature due to rotation.

Temperature rise of the armature

$$T_a = \frac{C_{ca}}{S_a / W_a}\ {}^{\circ}C\ ,$$

where $C_{ca}$ = Cooling coefficient

= 45 to 65.

Field winding temperature rise:

Radiating surface of the shunt winding

$$S_{\not{f}} = 2(d_f + h_f)\ L_p$$

Surface per watt loss

$$\frac{S_f}{W_f} = \frac{2\ (d_f + h_f)\ \ L_p}{W_f}$$

Cooling coefficient $C_{cf}$ for the shunt coil can be determined as follows:

$C_{cf}$ = $C_c + 70\ (1 - f_s)\ d_f$ where

$C_c$ = Cooling coefficient which varies with armature velocity

$$f_s = \text{Space factor}$$

$$= \frac{\text{Copper cross-sectional area}}{(\text{Insulated cond. area})^2}$$

$W_f$ = Excitation circuit losses.

Temperature rise

$$T_f = \frac{C_{cf}}{S_f / W_f} \ {}^{o}C$$

### Commutator temperature rise

The cooling surface of the commutator per watt loss

$$\frac{S_c}{W_c} = \frac{\pi D_K l_K (1 + 0.00051 v_K)}{W_b + W_{bf}}$$

Where, $W_b$ = Losses due to brush drop

$W_{bf}$ = Frictional losses.

Commutator temperature rise

$$T_c = \frac{C_{cc}}{S_c / W_c}$$

$C_{cc}$ = 15 to 20 for commutating pole machines with no sparking at the brushes. When there is sparking at the brushes, it is not possible to calculate the commutator losses and commutator temperature rise.

### 1.2.3 The following method is given by Greenwood

Temperature rise of armature

In this method as suggested by Greenwood, iron and copper losses are dissipated by not only the armature core, but also the overhangs. The effective radiating surface is determined as

$$\frac{\pi \; D_a \; ( \lambda_t + 0.6 \; \tau + 18 \text{ cm})}{100} \text{ sq dm}$$

The specific dissipation is then calculated as

$$\frac{\text{Total armature loss}}{\text{Surface area (sq dm)}}$$

In the formula for determination of temperature rise, armature velocity is taken into account and also a coefficient derived from test on similar machines. Thus temperature rise in $^{o}C$

$$= \frac{\text{Specific dissipation}}{1 + 0.1 \; v_a} \times K_t$$

The heating coefficient $K_t$ varies for a fan ventilated machine or a self ventilated machine and also the armature peripheral velocity. This value can be obtained from a graph.

## Temperature rise of field coils

The heat produced in the coil is dissipated partly through the body of the spool to the pole, and partly by the scrubbing of the outside surface of the coil to the cooling air. Final steady state temperature will be achieved when the heat is dissipated at the rate at which it is generated. The maximum internal temperature depends on the construction and insulation treatment of the coils, whilst the difference between the internal and external surface temperature will increase with the winding depth.

The dissipation surface for the field coils is taken as the outside surface of the coils.

Surface area = N Shunt OLT $W_h$

This method has been given for 40 °C rise in temperature and the dissipation expected is determined from graph for either fan ventilated machine or self ventilated machine as the case may be.

Commutator temperature rise

The radiating surface in case of a commutator is taken as the barrel surface x $D_K \ell_K$. Cooling action due to the risers is also considered using a different heating coefficient. The total losses to be dissipated are the contact losses and frictional losses, which when divided by the surface area of the commutator, give the specific loss, in watts/$dm^2$

Temperature rise in °C is given by

$$\frac{\text{Watts / Sq dm x } K_e}{1+0.1\ v_K}$$

The commutator heating coefficient $K_c$ varies with the length of the commutator, height and width of the risers, and whether the bars are extended at the bearing end. This value is obtained from a graph.

### 1.2.4 Method given by Still and Siskind

Armature temperature rise

Method of calculation for armature temperature rise has been given for a self ventilated machine.

Outside cooling surface

$$S_o = \pi D_a \ell_t$$

Inside cylindrical surface

$$S_i = \pi D_i \ell_t$$

Velocity at the inside surface $v_i$ is calculated proportional to inside and outside diameter of the machine. Cooling surface of the axial canals is also taken into consideration. Velocity of air in axial canals is taken approximately 1/3 of armature peripheral velocity, $v_a$. Watts dissipated by the cylindrical cooling surface is calculated as

$$W = t\ S\ \left(\frac{1500 + v_a}{100000}\right)$$

Where, W = Watts dissipated

t = temperature rise in °C

S = Cooling surface in square inches

$v_a$ = peripheral velocity in ft/min.

Cooling coefficient $C = \left( \frac{1500 + v_a}{100000} \right)$

Cooling coefficient for inside surface is calculated as

$$C_i = \left( \frac{1500 + v_i}{100000} \right)$$

Cooling coefficient for ducts

$$C_{ad} = \frac{v_d}{100000}$$

The watts that can be dissipated per degree rise in temperature is calculated for the outside cylindrical surface, the inside cylindrical surface and for the ducts. The temperature rise is then determined by substitution in the above formula.

Temperature rise of Commutator

The watts that can be dissipated per square inch of commutator surface will depend on many factors. The peripheral velocity of commutator surface will undoubtedly have an effect upon the cooling coefficient, but the influence of high speeds on the cooling of revolving cylindrical surfaces is not so great as might be expected. The design of risers has much to do with effective cooling of commutators.

In the formula proposed, the risers add to effective cooling surface up to a limiting radial distance of 2". That is, if the risers are longer than 2", the area beyond this distance will be considered ineffective in dissipating heat losses occuring at commutator surface.

The cooling area of the commutator (Fig.1(iii)) will consist of the cylindrical surface $\pi D_K \ell_K$, the surface of risers $\pi/4\ (D_r^2 - D_c^2)$, the surface of exposed ends (if any), of copper bars of value $\pi/4\ (D_c^2 - D_e^2)$ and allowance of $2\ell_c b$ for brush holders, where

$\ell_c$ = total width of one brush set

b = total number of sets.

Cooling coefficient of commutator

$$C = \frac{W}{ts} = \left(0.025 + \frac{v_K}{100000}\right)$$

Where, W = total loss to be dissipated

s = cooling surface computed as above in square inches.

$v_K$ = peripheral velocity of cylindrical surface of commutator in ft/min.

t = temperature rise in °C

## 1.3 Brief description of the present method.

For keeping the machine within prescribed temperature rise limits, cooling air is forced into the machine for dissipation of the various losses. The amount of air required is a pre-determined quantity.

When air enters the machine, it encounters obstruction due to the various machine parts in the path which resist the flow of air. In other words, these machine parts are said to offer resistance to the flow of air. These resistances due to change in cross-sectional area are identified in a machine and a circuit is formed depicting the split of the mainstream into sub-streams and the various resistances encountered along each path. Once the complete equivalent circuit is formed, it is solved employing network techniques and the equivalent resistance or impedance of the complete machine is determined. This in brief is the equivalent circuit method and will be applied to the machine D100/255 in a subsequent chapter for determination of temperature rise of different parts of the machine.

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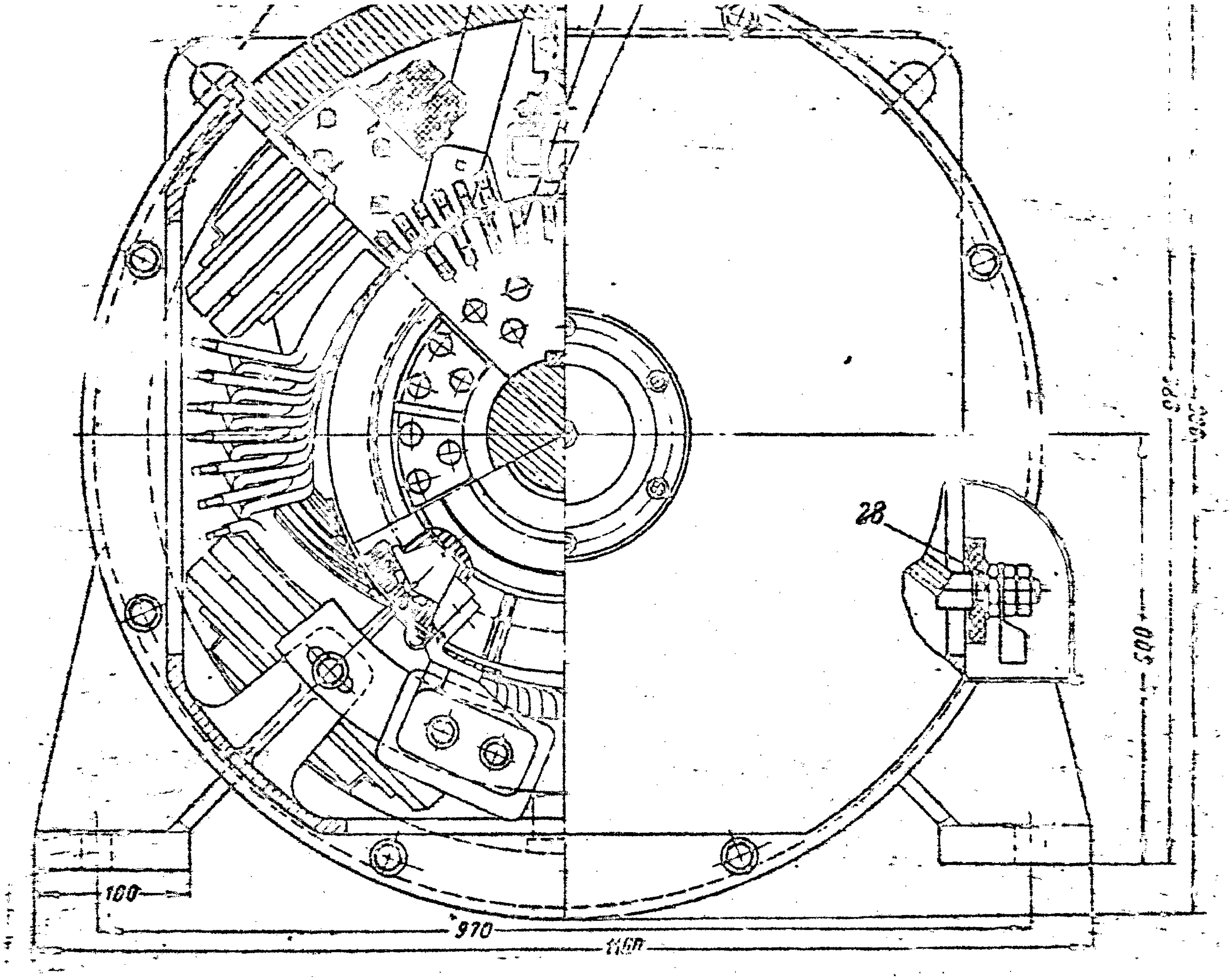

Fig 1(i)

SHEET

1

1

SIGN & DATE

DUPLICATE INVENTORY NO.

SUPERSEDES INVENTORY NO.

SIGN & DATE

NTORY NO.

# CHAPTER - II

## DESIGN DETAILS AND LOSS CALCULATION OF A LARGE D.C.MACHINE

In this chapter, the design details of the large d.c.machine under consideration are given. The losses at different parts have been calculated.

### 2.1 Design features of the d.c.machine considered

This machine is being manufactured at BHEL Hardwar for Bhilai Steel Plant. D100/255 implies that it is a 100 Kw machine and 255 is the fixed rpm at which it will operate. This machine has been designed for 440 v operation.

The armature diameter of this machine is 493 mm, with 45 slots and (5x2) conductors per slot. As this machine is having a low armature current, it has been designed for a simple wave winding. All machines in 493 mm armature diameter are having 4 poles. Machines in this range are all having provision for axial ventilation. No provision is kept for radial ventilation, as this type of ventilation is restricted only to larger frame sizes. As such, D100/255 is also axially ventilated and has 20 holes of diameter 30 mm and 10 holes of diameter 30 mm on two different pitch circle diameter of the armature stamping.

Once the armature diameter of the machine is decided, it is our tendency to keep certain internal parameter of the machine fixed as far as possible. For example, parameters like armature core inner diameter, yoke inner diameter, yoke outer diameter, number of poles, main pole width, inter pole width are some of the parameters which should be kept same for all machines being manufactured for a particular frame size. This is to reduce variety in designs. All such details for D100/255 are available in the data sheets.

At the design stage it is ensured that reactance emf of the machine is well within permissible limits so as to ensure the commutating ability of the machine. Another important factor is that of the heat load, which is the product of the electrical loading per cm and the current density of the conductors of the armature circuit. Too high a value of heat load will mean greater heat generation within the machine. Other important checks include limiting the commutator segment pitch, voltage drop between adjacent commutator segments and last, but not the least, limiting the values of flux densities in different parts of the machine. The electrical data sheet for D100/255 is given in figure 2(1).

## 2.2 Calculation of losses

All losses occuring within the machine are calculated at the design stages. Calculation of losses become essential for the efficiency calculation of the machine and also to determine the quantity of air required for effective dissipation of these losses.

The losses occuring in d.c.machines can be broadly characterised as below:-

1. Losses due to changing magnetisation, i.e., iron losses.
2. Electrical losses, i.e., copper losses.
3. Mechanical losses.
4. Friction and additional losses.

Iron losses occur mainly in the armature core and armature teeth portion of the machine. However, iron losses occuring in the main pole core and teet~~c~~h portion are negligibly small and hence neglected for all calculation purposes.

Iron losses for D100/255 have been calculated as follows:-

Weight of steel in armature core

$$GF_{\ell a} = \frac{x\ (D_a^2 - D_i^2)}{4} \ell_e \times 7.8 \times 10^{-6}$$

$$= 393 \text{ Kg.}$$

Weight of steel in armature teeth

$$GF_{\ell s} = z\ \ell_e\ bz_2\ hn \times 7.8 \times 10^{-6}$$

$$= 114 \text{ Kg.}$$

Iron losses in armature core at flux density corresponding to flux at rated load is given by

$$QF_{\ell a} = \frac{f(f+70)}{500} \left(\frac{B_a}{10000}\right)^2 GF_{\ell a}$$

$= 0.46$ Kw.

Losses in iron of armature teeth at flux density corresponding to flux at rated load

$$QF_{\ell z} = \frac{f(f+30)}{350} \left(\frac{BZ_2}{10000}\right)^2 GF_{\ell z}$$

$= 0.28$ Kw.

Armature copper loss $= I^2a \; r_{a\,75}$

$= 7.1$ Kw.

Losses in interpole winding $= I^2a \; r_{w\,75}$

$= 1.21$ Kw.

Losses in compensating winding $= I^2a \; r_{c\,75}$

$= 3.56$ Kw.

Additional losses for compensated machines

$= 0.005$ Ia Un

$= 0.572$ Kw.

Losses in the commutator are

a) Contact losses

$= Ia \, \Delta Ub$

$= 0.52$ Kw.

b) Frictional losses

$= 0.35 \, F_b \, v_K$

$= 0.21$ Kw.

Mechanical losses

$$Q_M = K \left(\frac{V_a}{10}\right)^{1.6} P_N$$

$$= 0.05 \text{ Kw.}$$

Losses of the excitation circuit

$$= U_e \; I_e$$

$$= 1.65 \text{ Kw.}$$

The losses of the excitation circuit are not added to the total losses in the case of a separately excited machine for efficiency calculation. Instead of using the emperical relations, specific iron loss curves can also be used for calculation of iron losses.

-00-

32[illegible] [illegible]100 [illegible]

B[illegible] STEEL PLANT 4 [illegible] EXPANSION

100 [illegible] 255

CONT[illegible]OUS

PROTECTED TYPE
FORCED [illegible]
IN OPEN [illegible]

FIG 2(i)

# CHAPTER - III

## VENTILATION SCHEMES

In this chapter, some basic ventilation schemes generally employed are discussed alongwith some aerodynamic principles.

### 3.1 Ventilation of d.c.machines

Ventilation schemes for d.c. machines have certain peculiarities because of design feature of machine of this type. Presence of pole windows of complicated geometrical shapes, winding holders working as forcing elements, overhang parts, commutator risers, radial canals of rotors make ventilation systems multistream and complicated for calculation.

D.C.machines are air ventilated and the following systems are generally adopted.

1. Self ventilation
2. Forced ventilation
3. a) In open cycle
   b) In closed cycle.

In case of latter, there may be either a built in blower or a separate blower. Smaller machines are self ventilated whereas larger ones are forced ventilated. Self ventilated d.c.machines have a shaft mounted fan and are employed where a constant speed run is required.

In some cases, the projecting coils on the winding holder contribute to the fanning action and thus produce enough discharge for cooling the machine in open cycle.

The aremature core ventilation consists of

a) Radial
b) Axial

In large d.c.machines, it is almost a general practice to have a radial ventilation circuit for armature. The aerodynamic and thermal basis for providing radial ventilation is that more copper and iron losses are dissipated and the temperature lies within the permissible limits. Heat transfer improves substantially because:-

a) Air stream passes through the radial ducts
b) Armature behaves as a fan and thus contributes enough additional discharge stream for the machine circuit in parallel.

The discharge of air which comes out in this case comes under pressure and cools the pole shoe face and the compensating winding. This is beneficial and essential, keeping in view the high temperature of the pole shoe because of the compensating winding.

In the case of axial ventilation of armatures, circular holes are provided at a certain p.c.d depending upon the armature diameter. While deciding the number and diameter of axial holes or canals the following considerations are taken into account:-

a) Sufficient area for armature flux

b) Sufficient area for carrying armature copper and iron losses

c) Sufficient area for cooling ducts.

For optimum design, these factors are considered and minimum distance and area between ducts, and ducts and slots is taken into account for flux density.

The axial canals are circular in shape through which the circulating air enters from one side and leaves through the other. In machines having axial canals, the coefficient of frictional resistance for the canals cover an important feature for the ventilation calculations.

## 3.2 Aerodynamics of flow

Two types of flow are generally encountered

a) Laminar

b) Turbulant

Laminar flow : If for any uniform flow, the Reynold's Number is less than 2300, the flow is termed laminar. In this case, the velocity and cross-section of the flow tube are relatively small. The larger the kinetic viscosity of the fluid, the greater the chances of a laminar flow.

Turbulent flow : In this case, the Reynolds Number is always greater than 2300. In case of d.c.machines, flow within the machine is always turbulent. In case of turbulent flow, the adjacent fluid layers mix continuously, so that the flow pattern is unsteady, full of eddies and without any mathematical expressible regularity.

Reynolds number is given by the following expression.

$$Re = \frac{V.d}{\nu}$$

where, $V$ = velocity of flow (m/sec)

$d$ = hydraulic diameter of flow path/m

$\nu$ = coefficient of kinematic viscosity ($m^2$/sec)

Reynold number is a dimensionless quantity which characterises the nature of flow.

Hydraulic diameter is given by the following expression

$$d = \frac{4 \times \text{cross-sectional area of path}}{\text{perimeter of the path}}$$

## 3.9 Hydraulic loss coefficients

In both laminar and turbulent flow, a number of coefficients of hydraulic losses come in picture. These are

a) Coefficient of resistance due to a change in section ($\varepsilon_1$)

b) Coefficient of resistance due to change in direction ($\varepsilon_2$)

c) Coefficient of resistance due to friction ($\varepsilon_3$)

## 3.3.1 Coefficient of resistance due to change in section

Depending upon the geometry of the available flow section, the ratio of areas is determined for which $\varepsilon$, is evaluated depending upon contraction or expansion as the case may be, either graphically or analytically.

a) In case of contraction and expansion....fig.3(i),

$$\varepsilon = K\left(1 - \frac{f}{F}\right) \text{ where}$$

K = coefficient which depends upon the geometry of entry.

b) In case of contraction with inside projection.... fig. 3(ii)

$$\varepsilon = \left(1 - \frac{f}{F}\right) \text{ i.e, } K = 1$$

c) In case of sudden expansion and contraction....fig. 3(iii)

$$\varepsilon = \left(1+0.707\, f_1 + \frac{f_1}{F} - \frac{f_1}{f_2}\right)^2$$

d) In case of hole in a wall...fig.3(iv)

$$\varepsilon = \left(1.707 - \frac{f}{F}\right)\left(\frac{f}{F}\right)^2$$

For more than one hole, $f = nf_1$

e) For sudden contraction, $\varepsilon = 0.5$

f) For sudden expansion, $\varepsilon = 1.0$

### 3.3.2 Coefficient of resistance due to change in direction

In this case for the respective bend, $\varepsilon_2$ is evaluated by the values given

| S. No. | Bend | $\varepsilon_2$ |
|---|---|---|
| 1. | 90° | 1.1 to 0.9 |
| 2. | 135° | 0.5 |
| 3. | 135° | 0.35 |

### 3.3.3 Coefficient of resistance due to friction

Consider both laminar and turbulent flow. In case of laminar flow, the various layers take the shape of the surface and hence the coefficient of friction is not affected by shape and surface.

For circular pipes:

$$\lambda = \text{Coefficient of friction} = \frac{100}{Re}$$

In the above expression, the factor 100 is not constant but depends upon the condition and shape of entry section.

Also $\lambda = 64/Re$ applicable for constant boundary layer of the flow. This is achieved at a distance of 50 times the internal diameter from the entry section.

In case of a turbulent flow, coefficient of friction depends upon the following factors.

1. Reynold's number
2. Shape and condition of surface roughness

## 3.4 Ventilation Scheme

Ventilation calculations for d.c. machines with any ventilation system involve:

(i) Calculation of aerodynamic resistances of separate branches of scheme.

(ii) Plotting on this basis the aerodynamic resistance curves for whole machine.

(iii) Selection of forcing elements i.e., whether shaft mounted or external fans.

(iv) Air velocity and air discharge in separate branches are determined for thermal calculations.

(v) Aero-dynamic resistance of machine is calculated according to equivalent scheme of ventilation system.

Equivalent scheme reflects all characteristic elements of ventilation system consisting of cooling air circulation paths; presence of branch zones of streams, presence of forcing (developing head) elements of scheme. In those cases where equivalent scheme does not have forcing elements mounted inside the machine at all (e.g., in machines with forced axial ventilation or in slow speed machines) calculation of aerodynamic resistance is made by the method of equilisation of pressure drops in the parallel branches of the scheme at arbitrary discharge.

If there are no parallel branches, resistance of machine is determined by method of simple summing up of separate parts connected in the scheme in series. Hydraulic constant of separate parts is determined by the relationships

$$Z = \frac{\varepsilon \rho}{F^2} \quad [\text{Kg-sec}^2/\text{m}^8]$$

Where, $\rho = \frac{\gamma}{2g} [\text{Kg-sec}^2/\text{m}^4]$

density of air at corresponding temperature.

$F(m^2)$ = section of ventilation path for which coefficient of hydraulic resistance $\varepsilon$ is determined.

As an example, consider the simple ventilation scheme shown in Fig.3(v).

Equivalent scheme of this machine is as shown in fig.3(vi).

Following resistances have been taken into account.

$Z_{bx}$ = inlet of machine

$Z_1$ = inlet into interpole window and air gap

$Z_2$ = friction of interpole canals

$Z_3$ = outlet from interpole space

$Z_4$ = resistance at inlet to the fan.

Sectional area of interpole space and hydraulic diameter are determined by planometric method.

Interpole window and part of the air gap are drawn to scale on a millimeter graph sheet. Area and perimeter are calculated from the graph.

Coefficient of hydraulic resistances are determined by the ratio of areas.

After determination of hydraulic constants, pressure drops depending upon discharge is determined by

$$\Delta H = Z_m Q^2$$

Where,

$H$ = static pressure drop of the machine (MMWC)

$Z_m$ = aerodynamic resistance of the machine $Kg\text{-}sec^2/m^8$

$Q$ = rated discharge of the machine ($m^3/sec$)

Also,

$$Q = \frac{P}{C_p . V . \Delta t}$$

Where,

$P$ = total loss in the machine in Kw.

$C_p$ = specific heat at constant pressure for air

$V$ = mass density ($kg/m^3$)

$t$ = permissible temperature rise of the machine in °C. This value lies between 18-20 °C.

Scheme of air flow in various parts, together with the quantity of air flowing through the individual parts of the machine, viz. poles, pole windows, armature canals etc. are also evaluated once the ventilation calculations are completed.

Some of the basic principles employed for conversion are given in figure 3(vii).

## 3.5 EQUIVALENT CIRCUIT METHOD AND ITS APPLICATION TO A LARGE D.C.MACHINE

Equivalent circuit method as employed to D100/255 can be explained as follows:

Air is forced through the inlet area by means of a blower. The air will encounter some impedance at inlet. It then expands around the periphery of the machine before it takes a sharp 90° bend and contracts at the entry to the baffle. Again it encounters a sudden expansion within the baffle. The air now divides into two streams, one part coming in contact with the winding holder on the drive end side whereas another part comes in contact with the yoke area. The further break up is clearly represented by the equivalent circuit.

All the areas marked on the equivalent circuit have been calculated from the part-drawings of the motor. Most of the areas have been determined by calculation whereas some have been drawn on a scale and calculated from a graph.

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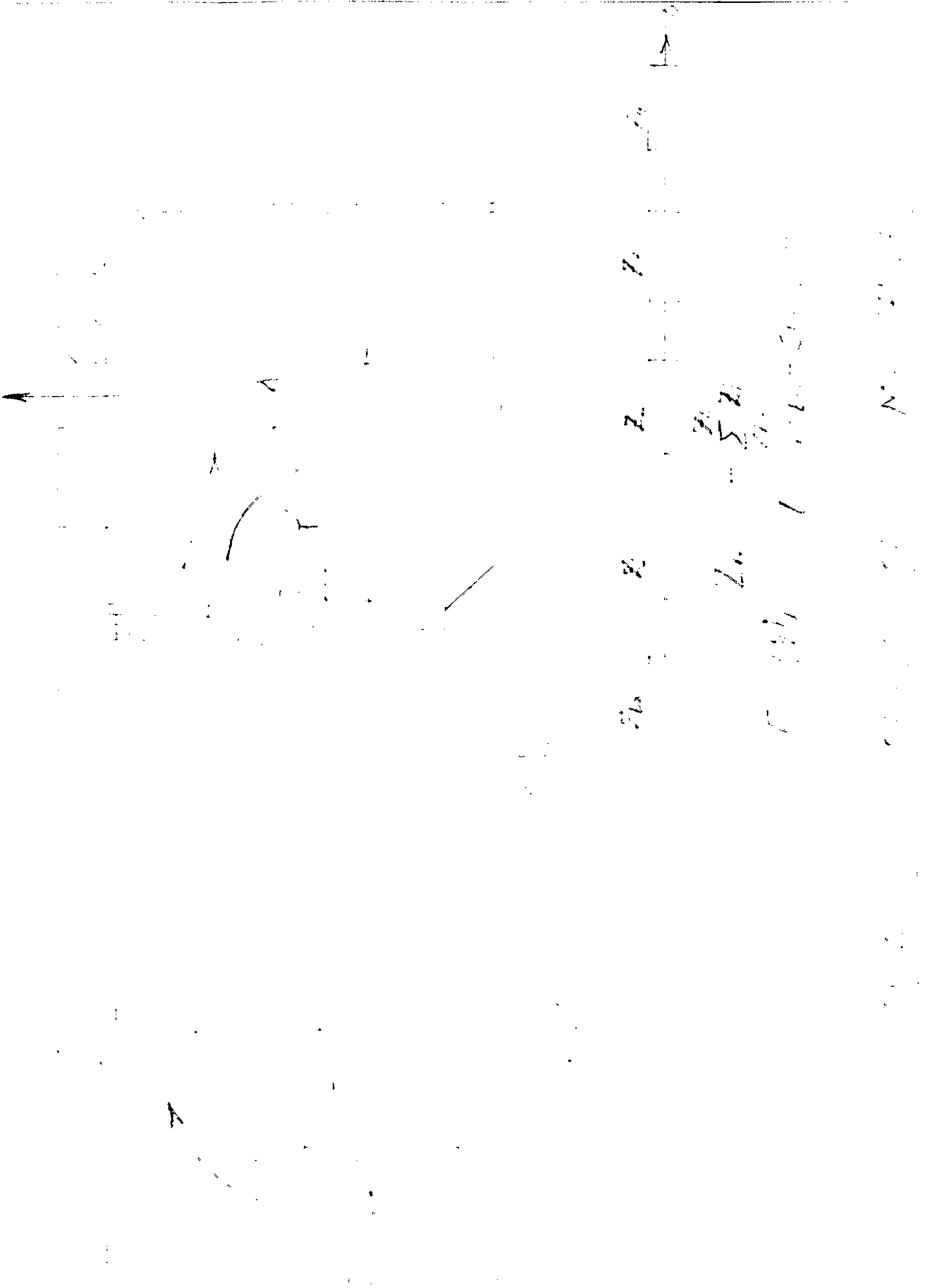

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# CHAPTER - IV

## EVALUATION OF AREAS AND AIR DISTRIBUTION

In this chapter, areas have been calculated whenever a change in section is encountered by the flowing air. Part drawings of the machine have been referred for determination of these areas. The areodynamic resistances have been defined and the equivalent circuit developed. This circuit has been solved employing network techniques and the distribution of air between the armature and the magnetic system is determined.

### 4.1 Evaluation of areas

Area at inlet = $0.0752\ m^2$

Area along periphery after expansion within the machine

= $0.692\ m^2$

Area within baffle at contraction point

= $0.273\ m^2$

Area after expansion within baffle

= $0.56\ m^2$

Area at inner diameter of yoke

= $0.37\ m^2$

Area at inlet to winding holder, drive end side

= $0.037\ m^2$

Area at outlet of winding holder-drive end side

$= 0.0655\ m^2$

Area of all the axial canals

$= 0.0212\ m^2$

Area at inlet to winding holder commutator end

$= 0.0655\ m^2$

Area between winding in overhang

$= 0.0715\ m^2$

Area at inlet to poles

$= 0.114\ m^2$

Area at outlet from poles

$= 0.114\ m^2$

Area at inlet to bush

$= 0.00681\ m^2$

Area within bush $= 0.00681\ m^2$

Area at outlet of bush

= area at inlet to pressing ring

= area within pressing ring

= area at outlet of pressing ring

$= 0.0175\ m^2$

Resistance encountered by the combined stream in the vicinity of brush rocker assembly

$= 0.49\ m^2$

Area encountered after circumferential expansion and 90° bend

$= 0.08\ m^2$

Area at outlet $= 0.08\ m^2$

Area at inlet to commutator risers

$= 0.0329\ m^2$

Area at outlet from commutator risers

$= 0.0329 \ m^2$

All the areas evaluated above are represented in fig.4(1).

## 4.2 Evaluation of aerodynamic resistances

The various symbols shown in the equivalent circuit are explained as follows:

$Z_{in}$ = Aerodynamic resistance encountered at inlet to the machine

$Z_{ph}$ = Aerodynamic resistance encountered after peripheral expansion within the machine

$Z_1$ = Aerodynamic resistance encountered after sharp 90° bend and contraction within the machine

$Z_2$ = Aerodynamic resistance encountered on expansion within baffle

$Z_3$ = Aerodynamic resistance after contraction at inner diameter of yoke

$Z_{in, WH, DE}$ = Aerodynamic resistance encountered at inlet to winding holder, drive end side

$Z_{WH, DE}$ = Fanning action of winding holder, drive end side

$Z_{out, WH, DE}$ = Aerodynamic resistance at outlet of winding holder, drive end side

$Z_{rotor}$ = Equivalent resistance of axial canals while in rotation for the armature

$Z_{in}$, WH, CE = Aerodynamic resistance encountered at inlet to winding holder, commutator end.

$Z_{in}$ poles = Aerodynamic resistance at inlet to poles

$Z_{out}$ poles = Aerodynamic resistance at outlet of poles

ZWH, CE = Fanning action of winding holders - commutator end

$Z_{out}$, WH, CE = Aerodynamic resistance encountered at outlet of winding holder, commutator end

$Z_{in}$, $R_1$ = Aerodynamic resistance encountered at inlet to risers

$Z_{out}$ $R_1$ = Aerodynamic resistance encountered at outlet of risers

$Z_4$ = Aerodynamic resistance encountered at entry to bush

$Z_5$ = Aerodynamic resistance within bush

$Z_6$ = Aerodynamic resistance at exit from bush

$Z_7$ = Aerodynamic resistance at entry to pressing ring

$Z_8$ = Aerodynamic resistance within pressing ring

$Z_9$ = Aerodynamic resistance at outlet from pressing ring

$Z_{10}$ = Aerodynamic resistance after equivalent contraction within the brush rocker zone

$Z_{11}$ = Aerodynamic resistance after equivalent peripheral expansion within the machine and after $90^\circ$ bend

$Z_{out}$ = Aerodynamic resistance at outlet from machines.

## Evaluation of Impedances

$\underline{Z_{in}} = \frac{0.0612 \times 0.5}{(0.0752)^2}$ At inlet to the machine

$= 5.41 \text{ Kg sec}^2/\text{m}^8$

$\underline{Z_{ph}}$ = After peripheral expansion

$F_n = 0.692$

$F_{n-1} = 0.0752$

$\frac{F_n}{F_{n-1}} = \frac{0.692}{0.0752} = 9.2$

$\varepsilon = 65$

$Z_{ph} = \frac{0.0612 \times 65}{(0.692)^2} = 8.31 \text{ Kg sec}^2/\text{m}^8$

$\underline{Z_1}$ = After sharp $90^\circ$ bend and contraction within machine

$F_n = 0.273$

$F_{n-1} = 0.692$

$\frac{F_n}{F_{n-1}} = \frac{0.273}{0.692} = 0.3945$

$\varepsilon_1 = 0.38$

and $\varepsilon_2 = 1.1$ [due to sharp 90° bend]

$\therefore \varepsilon = \varepsilon_1 + \varepsilon_2 = .38 + 1.1$

$= 1.48$

$$z_1 = \frac{0.0612 \times 1.48}{(0.273)^2}$$

$= 1.215$

$\underline{z_2}$ : On expansion within baffle

$F_n = 0.56$

$F_{n-1} = 0.273$

$$\frac{F_n}{F_{n-1}} = \frac{0.56}{0.273} = 2.05$$

$\varepsilon = 0.98$

$$z_2 = \frac{0.0612 \times 0.98}{(0.56)^2}$$

$z_2 = 0.191$ Kg-sec$^2$/m$^8$.

$\underline{z_3}$ : After contraction at inner dia of yoke

$F_n = 0.37 + 0.037$

$F_{n-1} = 0.56$

$$\frac{F_n}{F_{n-1}} = 0.727$$

$\varepsilon = 0.18$

$$z_3 = \frac{0.0612 \times 0.18}{(0.37)^2}$$

$= 0.08$ Kg-sec$^2$ /m$^8$

$z_{in}$, WH, DE : Inlet to winding holder, drive end

$$z_{in}\text{, WH, DE} = \frac{0.0612 \times 0.18}{(0.037)^2} = 8.05 \text{ kg sec}^2/\text{m}^8$$

$\underline{Z_{CH,DE}}$ : We are neglecting the framing section due to the winding holder because its effect is going to be negligible. However, presence of winding holder is going to offer some impedance.

$$D_n = 0.0719 + 0.0659$$

$$D_{n-1} = 0.037$$

$$c = D_n / D_{n-1} = 3.7$$

$$c = 7$$

$$Z_{CH,DE} = \frac{0.0612 \times 7}{(0.0719)^2}$$

$$= 83.0 \ Kg\text{-}sec^2/m^8$$

$\underline{Z_{out}, CH, DE}$ : At outlet of winding holder, drive end side

$$\frac{D_n}{D_{n-1}} = \frac{0.0719 + 0.0655}{0.037}$$

$$= 3.7 \ DB$$

$$c = 7$$

$$Z_{out}, CH, DE = \frac{0.0612 \times 7}{(0.0655)^2}$$

$$\underline{Z_{out}, CH, DE = 99.85}$$

$\underline{Z_{in} \text{ poles}}$ : Aerodynamic resistance at inlet to poles:

$$D_n = 0.114$$

$$D_{n-1} = 0.37 + 0.0719$$

$$\frac{D_n}{D_{n-1}} = \frac{0.114}{0.4419} = 0.26 , \quad c = 0.49$$

$Z_{in}$ poles $= \dfrac{0.0612 \times 0.43}{(0.114)^2} = \underline{2.02}$

**$Z_{out}$ poles** : Aerodynamic resistance at outlet from poles

$D_n = 0.114$

$D_{n-1} = 0.114$

$\zeta = 0.$

$\therefore$ $Z_{out}$ poles $= 0$ Kg sec$^2$/m$^8$

**$Z_{in}$. W.H.C.E** : Aerodynamic resistance at inlet to winding holder commutator end.

$D_n = 0.0655$

$D_{n-1} = 0.021$

$D_n/D_{n-1} = \dfrac{0.0655}{0.021} = 3.12$

$\zeta = 4.$

$Z_{in}$. W.H.C.E $= \dfrac{0.0612 \times 4}{(0.0655)^2}$

$= 57.06$ Kg sec$^2$/m$^8$

**$Z_{out}$. W.H.C.E** : Aerodynamic resistance at outlet of winding holder, commutator end.

$\dfrac{F_n}{F_{n-1}} = \dfrac{0.0655 + 0.0715}{0.0655} = \dfrac{0.137}{0.0655}$

$= 2.09$

$\zeta = 1.2$

$Z_{out}$. W.H.C.E $= \dfrac{0.0612 \times 1.2}{(0.0655)^2}$

$= 17.12$ Kg sec$^2$/m$^8$

**$Z_7$** = $F_n = 0.0175$

$F_{n-1} = 0.0175$

$\varepsilon = 0$

$Z_7 = 0$

**$Z_8$** = Within pressing rings

= 0

**$Z_9$** = At outlet of pressing ring

= 0.

**$Z_{10}$** = After equivalent contraction within brush rocker zone

$F_n = 0.49$

$F_{n-1} = \overset{0.0715}{\cancel{0.0175}} + 0.0329 + 0.0175$

$= 0.122$

$$\frac{F_n}{F_{n-1}} = \frac{0.49}{0.122} = 4.0$$

$\varepsilon = 8.5$

$$Z_{10} = \frac{0.0612 \times 8.5}{(0.49)^2}$$

$\underline{Z_{10} = 2.2 \quad Kg\ sec^2/m^8}$

**$Z_{11}$** = $F_n = 0.712$

$F_{n-1} = 0.49$

$$F_n / F_{n-1} = \frac{0.712}{0.49} = 1.45$$

$\varepsilon = 0.19$

$$Z_{11} = \frac{0.0612 \times 0.19}{(0.712)^2} = 0.023$$

**ZWH,CE**

$F_n = 0.0655 + 0.0715$

$= 0.137$

$F_{n-1} = 0.0655$

$\frac{F_n}{F_{n-1}} = 2.09$

$\varepsilon = 1.2$

$$ZWH,CE = \frac{0.0612 \times 1.2}{(0.0715)^2}$$

$$ZWH,CE = \underline{14.37}$$

**$Z_{in} R_1$**

At inlet to risers

$F_n = 0.0329 + 0.00681$

$= 0.0397$

$F_{n-1} = 0.0655$

$$\frac{F_n}{F_{n-1}} = \frac{0.0397}{0.0655} = 0.61$$

$\varepsilon = 0.26$

$$Z_{in}R_1 = \frac{0.0612 \times 0.26}{(0.03297)^2}$$

$$= 14.7 \text{ Kg sec}^2/\text{m}^8$$

**$Z_{out}R_2$**

$F_n = 0.0329$

$F_{n-1} = 0.0329$

$\varepsilon = 0$

$$\therefore \underline{Z_{out}R_2 = 0}$$

$\underline{Z_4}$ : At entry to bush

$F_n = 0.00681 + 0.0329$

$= 0.0397$

$F_{n-1} = 0.0655$

$F_n / F_{n-1} = 0.61$

$c = 0.26$

$$Z_4 = \frac{0.0612 \times 0.26}{(0.00681)^2}$$

$\underline{Z_4 = 343.1}$

$\underline{Z_5}$ : $F_n = 0.00681$

$F_{n-1} = 0.00681$

$c = 0$

$\underline{Z_5 = 0}$

$\underline{Z_6}$ : $F_n = 0.0175$

$F_{n-1} = 0.00681$

$$\frac{F_n}{F_{n-1}} = 2.57$$

$c = 2.5$

$$Z_6 = \frac{0.0612 \times 2.5}{(0.0175)^2}$$

$= 499.6$

$\underline{Z_7}$ = $F_n = 0.0175$

$F_{n-1} = 0.0175$

$\varepsilon = 0$

$Z_7 = 0$

$\underline{Z_8}$ = Within pressing rings

= 0

$\underline{Z_9}$ = At outlet of pressing ring

= 0.

$\underline{Z_{10}}$ = After equivalent contraction within brush rocker zone

$F_n = 0.49$

$F_{n-1} = \overset{0.0715}{\cancel{0.0175}} + 0.0329 + 0.0175$

$= 0.122$

$$\frac{F_n}{F_{n-1}} = \frac{0.49}{0.122} = 4.0$$

$\varepsilon = 8.5$

$$Z_{10} = \frac{0.0612 \times 8.5}{(0.49)^2}$$

$$\underline{Z_{10} = 2.2 \quad \text{Kg sec}^2/\text{m}^8}$$

$\underline{Z_{11}}$ = $F_n = 0.712$

$F_{n-1} = 0.49$

$$F_n / F_{n-1} = \frac{0.712}{0.49} = 1.45$$

$\varepsilon = 0.19$

$$Z_{11} = \frac{0.0612 \times 0.19}{(0.712)^2} = 0.023$$

## Calculation of frictional resistance in axial canals for D100/255

**Method of calculation:**

1. Static axial canals:

Coefficient of frictional resistance

$$c_f = \frac{\lambda \cdot \ell}{d}$$

Where $\lambda$ = coefficient of frictional resistance

$= f\,[Re, \Delta, d]$

$$= \frac{1}{[1.8 \log Re - 1.64]^2}$$

and $Re = \dfrac{V . d}{\nu}$

Where $V$ = Velocity of air $\simeq$ 20 m/sec

$d$ = Hydraulic diameter

$$= \frac{4 \times \text{cross-sectional area of canal}}{\text{perimeter } (\pi D)}$$

$$= \frac{4 \times 0.000707}{\pi \times 0.030}$$

$= 0.02966$

$\simeq 0.03$ for one canal.

$\nu = 17.5 \times 10^{-6}$ m$^2$/sec

$$\therefore Re = \frac{20 \times 0.03}{17.5 \times 10^{-6}}$$

$= 34286$

∴ Coefficient of frictional resistance

$$= \frac{1}{(1.8 \log 34286 - 1.64)^2}$$

$$= 0.0235$$

$$c_f = \lambda . \frac{l}{d} .$$

$$= 0.0235 \times \frac{0.45}{0.03}$$

= 0.35 for one canal.

Coefficient of hydraulic resistance of axial canals considering entry and outlet

$$c_1 = c_1 + c_f + c_2$$

Where $c_1$ = coefficient of resistance at entry

$c_2$ = coefficient of resistance at outlet

Now, coefficient of resistance at inlet and outlet will not be same

$$c_1' = 0.495 \left[ \frac{F_n}{F_{n-1}} = \frac{0.000707}{0.0655} = 0.012 \right]$$

from graph 4

$c_1'$ = 0.495 for one canal at p.c.d. 290.

There are 10 such axial canals in this p.c.d.

$$c_1'' = 0.495 \left[ \frac{F_n}{F_{n-1}} = \frac{0.000707}{0.0655} = 0.012 \right]$$

from graph

$c_1''$ = 0.495 for one canal at p.c.d 310.

There are 20 such canals in this p.c.d.

At outlet,

$$\varepsilon_2' \quad = \quad 1 \text{ from graph } \left[ \frac{F_n}{F_{n-1}} = \frac{0.0655}{0.000707} \right]$$

$$= 93.57$$

for one canal at p.c.d. 230

$$\varepsilon_2'' \quad = \quad 1 \text{ feom graph } \left[ \frac{F_n}{F_{n-1}} = \frac{0.0655}{0.000707} \right]$$

for one canal at p.c.d. 310.

2. Axial canals in rotation :

(i) Coefficient of frictional resistance for rotating canals

$$\varepsilon_{fr} \quad = \quad \varepsilon_f \left[1 - 0.037 \left(\frac{U}{V}\right)^{2.772}\right]$$

Where $\varepsilon_f$ = coefficient of friction in static conditions

$\mu$ = peripheral velocity at the diameter of location of the canals.

D100/255 armature stamping has two p.c.d's

p.c.d. 230 : 10 nos. canals dia.30mm each

p.c.d. 310 : 20 nos. canals dia.30mm each

$$\text{Peripheral velocity} \quad \mu_1 = \frac{\pi \times 23 \times 255}{6000} = 3.07 \text{ m/sec}$$

$$\text{Peripheral velocity} \quad \mu_2 = \frac{\pi \times 31 \times 255}{6000} = 4.14 \text{ m/sec}$$

V = Velocity of air in the canals = 20 m/sec.

$$\therefore \quad \varepsilon_{fr} = 0.35 \left[1 - 0.037 \left(\frac{3.06}{20}\right)^{2.772}\right]$$

for p.c.d. at 230

$$= 0.35 \left[1 - 0.000203\right]$$

$$= 0.35 \times 0.99979$$

$$= 0.3499.$$

$c_{fr}$ for p.c.d at 310

$= 0.35 \left[1-0.037 \left(\frac{4.14}{20}\right)^{2.772}\right]$

$= 0.35 \times 0.99953$

$= 0.3498.$

Coefficient of hydraulic resistance at canal entry.

$c'_{1r} = c_1 \left[1 + 0.3 \left(\frac{U}{V}\right) - 0.04 \left(\frac{U}{V}\right)^2\right]^2$

$= 0.495 \left[1+0.3 \times \frac{3.06}{20} - 0.04 \left(\frac{3.06}{20}\right)^2\right]^2$

at p.c.d. 230 for one canal

$= 0.495 \times 1.093$

$= 0.541$

$c''_1 = 0.495 \left[1 + 0.3 \left(\frac{4.14}{20}\right) - 0.04 \left(\frac{4.14}{20}\right)^2\right]^2$

at pcd 310 for one canal.

$= 0.495 \times 1.124$

$= 0.557.$

Coefficient of friction at outlet from axial canals:

$c_{2r} = c_2 \left[1+0.3 \left(\frac{U}{V}\right) - 0.04 \left(\frac{U}{V}\right)^2\right]^2$

for one canal

$c'_{2r} = 1\left[1+0.3 \times \frac{3.06}{20} - 0.04 \left(\frac{3.06}{20}\right)^2\right]^2$

for one canal at pcd 230

$= 1.093.$

$c''_{2r} = 1 \left[1 + 0.3 \times \frac{4.14}{20} - 0.04 \left(\frac{4.14}{20}\right)^2\right]^2$

for one canal at pcd 310

$= 1.124.$

Now, for p.c.d 230,

Now, for p.o.d 230,

$$\epsilon T_{r1} = \epsilon'_{1r} + \epsilon_{fr} + \epsilon'_{2r}$$

$$= 0.541 + 0.356 + 1.093$$

$$= 1.984$$

.˙. Constant of hydraulic resistance of axial canals in rotation

$$ZT_{r1} = \frac{0.0612 \times \epsilon T_{r1}}{F_n^2}$$

$$= \frac{0.0612 \times 1.984}{(0.000707)^2}$$

$$= 247755$$

Now, for n axial canals,

$$Z_1 = \frac{ZT_{r1}}{n_1^2}$$

$$= \frac{247755}{(10)^2} = 247755 \text{ at pod } 230.$$

For p.o.d 310,

$$\epsilon T_{r2} = \epsilon''_{1r} + \epsilon_{fr} + \epsilon''_{2r}$$

$$= 0.557 + 0.35 + 1.124$$

$$= 1.981$$

.˙. $ZTR_2 = \frac{0.0612 \times 1.981}{(0.000707)^2}$

$$= 247347$$

.˙. $Z_2$ for $n_2$ axial canals.

$$Z_2 = \frac{ZTR_2}{(n_2)^2}$$

$$= \frac{247347}{(20)^2}$$

$$= 618.4.$$

Now, the equivalent impedance offered by these canals in parallel.

$$Z_{eq} = \frac{Z_1 \; Z_2}{(\sqrt{Z_1} + \sqrt{Z_2})^2}$$

$$= \frac{2477.6 \times 618.4}{(\sqrt{2477.6} + \sqrt{618.4})^2}$$

$$= \frac{1532148}{(49.8 + 24.9)^2}$$

$$= \frac{1532148}{5580.1}$$

$$\therefore \underline{Z_{eq} = 274.6}$$

## 4.3 Evaluation of equivalent impedances

Fig.4(ii) depicts all the impedance values calculated in the preceding article. This circuit has now been solved in several steps for the equivalent impedance. Refer Figs.4(iii) to 4 (xi).

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## 4.4 Distribution of air

Refer figure 4(ix). The inlet air stream is divided into two distinct paths, one for the armature and the other for the magnetic system. let,

$Q_1$ ($m^3$/sec) = quantity of air through the magnetic system

$Q_2$ ($m^3$/sec) = quantity of air through the armature

$$\therefore \quad Q_1^2 \, [40.08] = Q_2^2 \, [428.19]$$

$$\text{or} \quad \left[ \frac{Q_1}{Q_2} \right]^2 = \frac{428.19}{40.08}$$

$$= 10.683$$

$$\text{or} \quad Q_1 = 3.6282 \qquad \ldots \text{(i)}$$

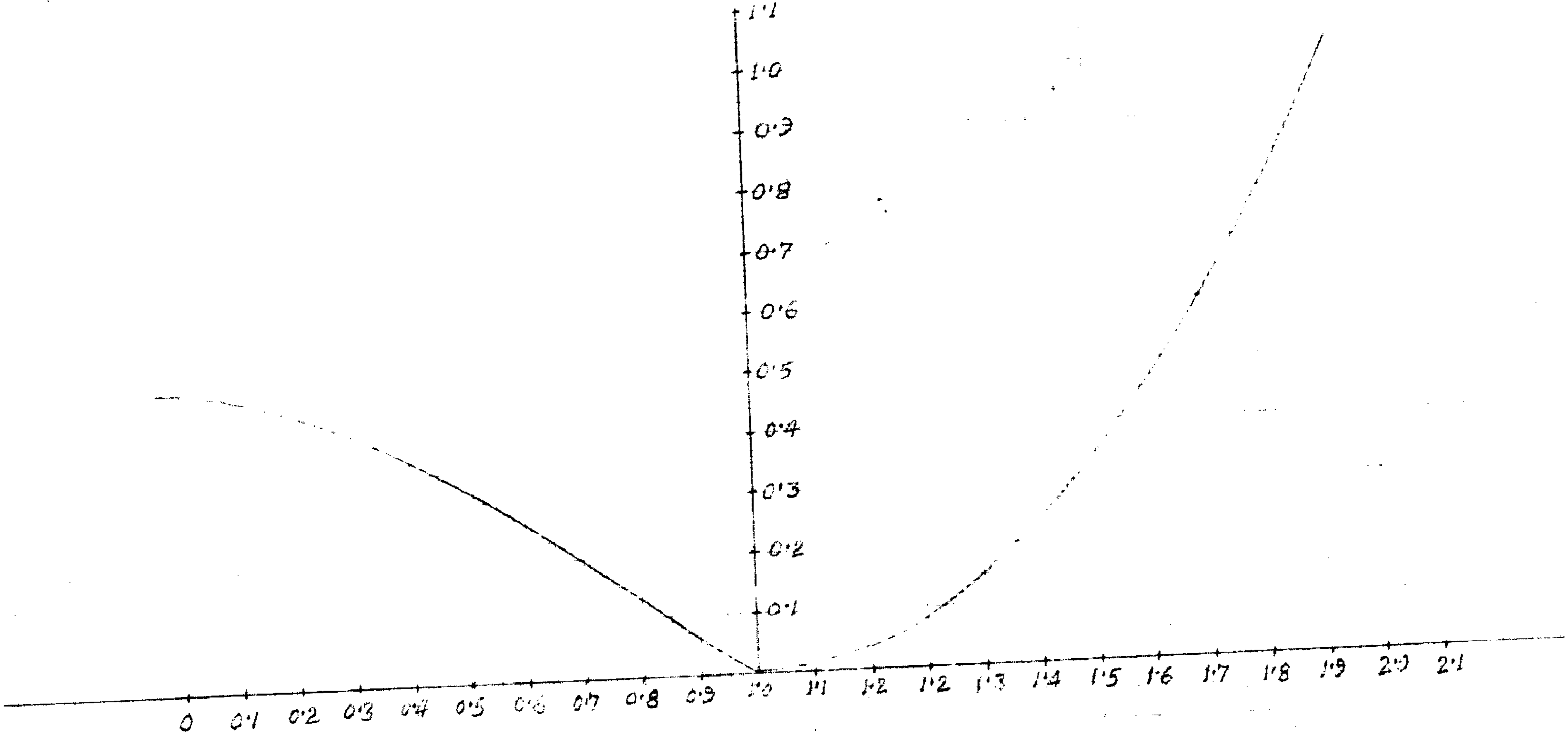
$$\text{Also,} \quad Q = Q_1 + Q_2 = 1 \text{ m}^3/\text{sec} \qquad \ldots \text{(ii)}$$

Solving equations (i) and (ii), we get

$$Q_1 = 0.765 \, ; \, Q_2 = 0.235.$$

This implies that 76.5 % of the total inlet air passes through the magnetic system and the remaining i.e. 23.5 % passes through the armature.

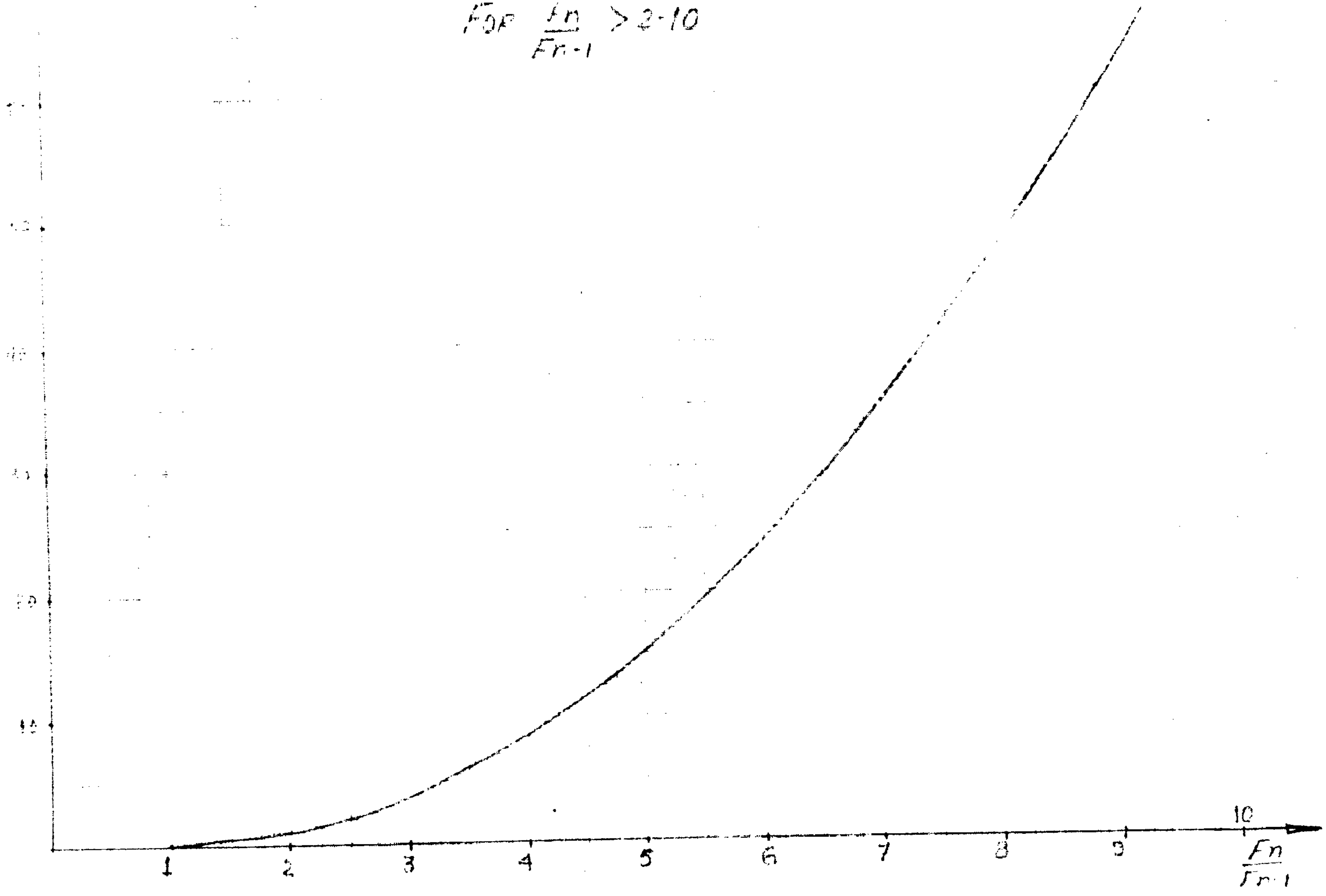
Fig-1



GRAPH FOR THE COEFFICIENT OF RESISTANCE ($\xi_1$)

DUE TO CHANGE IN SECTION

For $\frac{F_n}{F_{n-1}} > 2 \cdot 10$



# EQUIVALENT VIBRATION SCHEME

→ [illegible] AHEAD

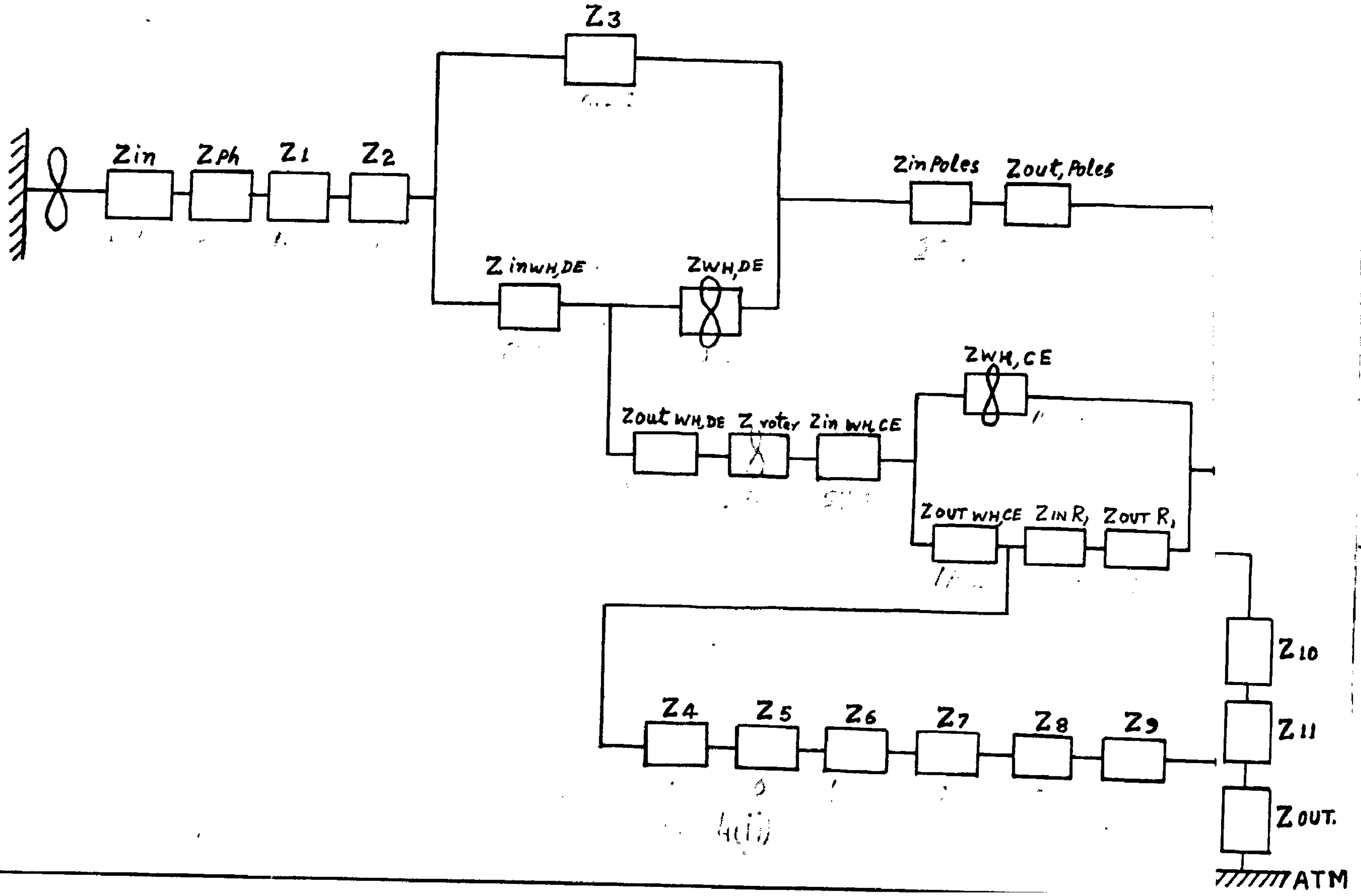
SHEET

DRAWN / TRACED

SIZE 11

FORM 01.05 2

# EQUIVALENT VENTILATION SCHEME



4(ii)

SHEET

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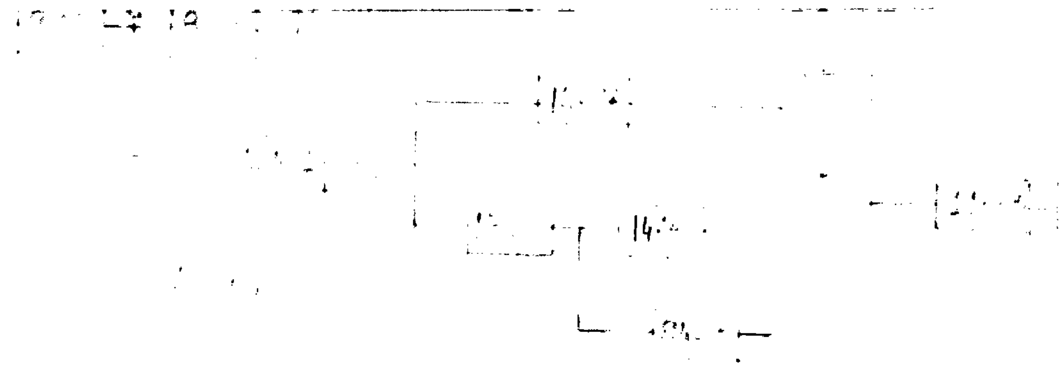

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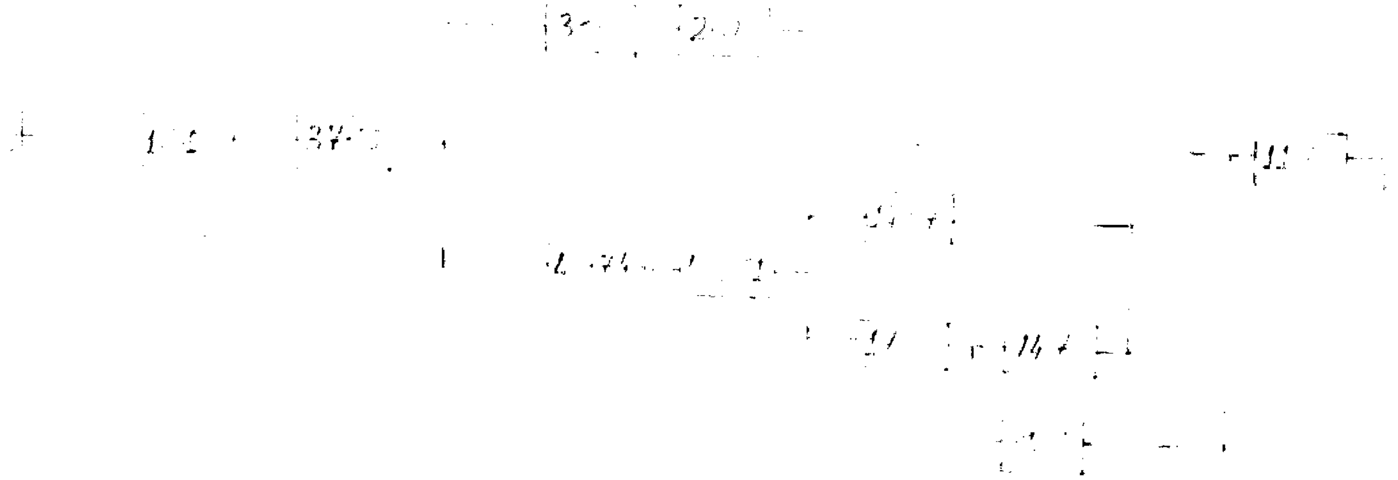

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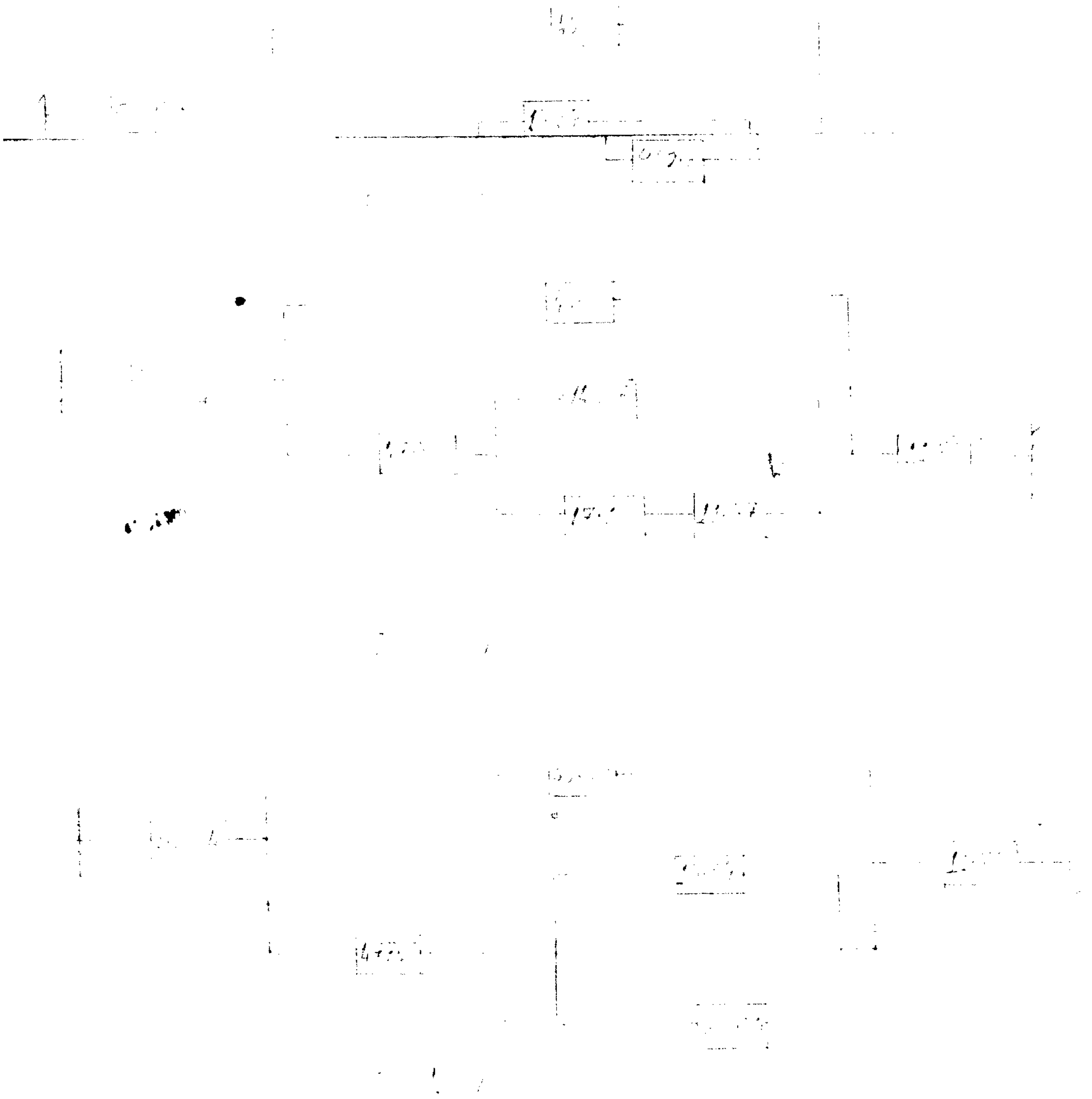
SHEET



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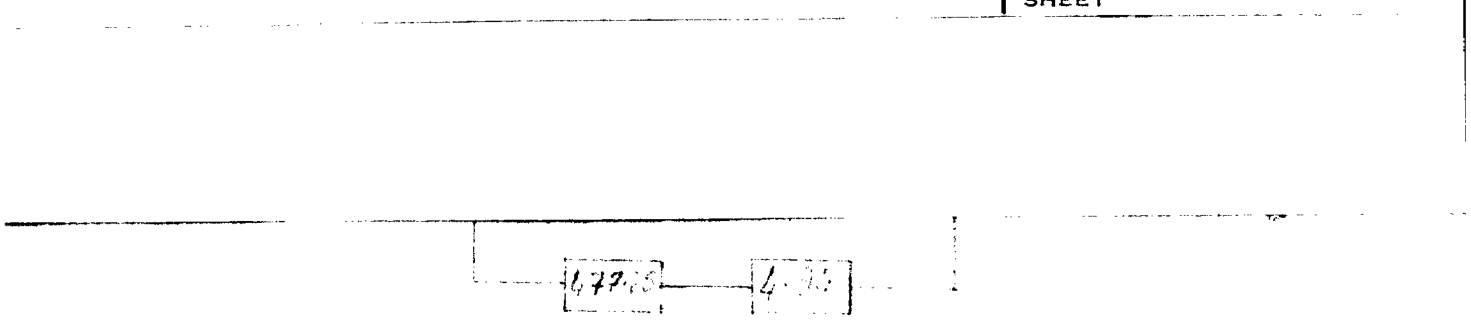
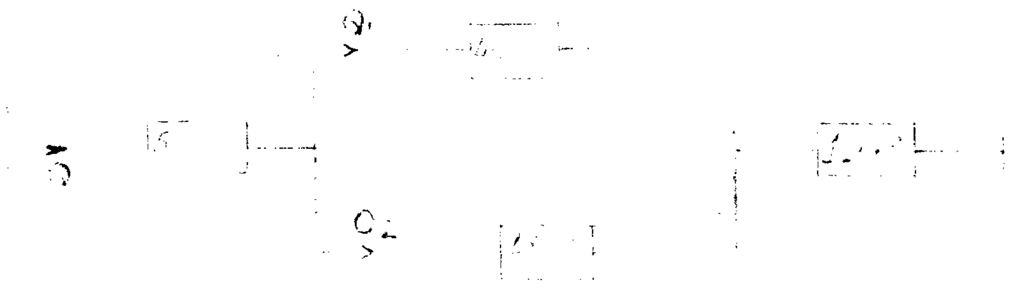
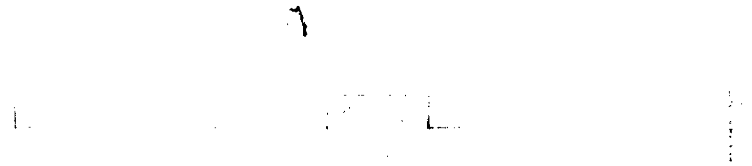


Fig 4(viii)





# CHAPTER - V

## HEAT CALCULATIONS

This method of calculation helps us in determining the temperature of active parts of the machine. This helps us in selecting the parameters of the d.c.motor more judiciously. The temperature rise of active parts is determined by the value of resistance in the path of the heat flux. The more effective the heat transfer, higher will be the electromagnetic loading and higher will be the utilisation of the machine.

Some essential data which will be useful at the time of heat calculation is listed on the pages to follow. This data is collected from the drawings and some of the variants have also been calculated.

### 5.1 Data for heat calculation of d.c. machines

FOR MAIN POLE :

| Sl.No. | Designation | Particulars | Units | Value |
|---|---|---|---|---|
| 1 | $\delta_m$ | Current density in winding of mainpole | $A/mm^2$ | 1.70 |
| 2 | $Q_p$ | Losses in the shunt winding | Kw | 1.65 |
| 3 | $\delta_{ip}$ | Thickness of outer insulation of shunt coil. | mm | 0 |

| | | | | |
|---|---|---|---|---|
| 4 | 2p | Number of poles in the m/c | - | 4 |
| 5 | $l_p = l_m$ | Length of pole core | mm | 450 |
| 6 | $b_m$ | Width of pole core | mm | 210 |
| 7 | $b_{kn}$ | Thickness of coil side of main pole | mm | 56 |
| 8 | $h_{kn}$ | Height of coil of main pole | mm | 91 |
| 9 | N | Number of layers in the coil | - | 31 |
| 10 | $n_{total}$ | Total number of turns | - | 684x4 |
| 11 | n | Number of turns in each layer | - | 24 |
| 12 | - | Number of coils on each pole | - | 1 |
| 13 | $l_{mt}$ | Length of mean turn of the winding conductor of the main pole | mm | 1525 |
| 14 | $b_p x a_p$ | Cross-section of bare conductor of main pole coil | $mm^2$ | 1.35x3.2<br>= 4.22 |
| 15 | $b_p' x a_p'$ | Cross-section of insulated conductor of main pole coil. | $mm^2$ | 1.62x3.5 |

INTERPOLE :

| | | | | |
|---|---|---|---|---|
| 1 | $j_w$ | Current density in interpole winding | $A/mm^2$ | 2.89 |
| 2 | $Q_{pw}$ | Losses in interpole winding | Kw | 1.21 |
| 3 | $\delta_{iw}$ | Thickness of outer insulation of interpole coil | mm | Bare |
| 4 | - | Number of turns of interpole winding | - | 18 |
| 5 | $l_m$ | Length of interpole winding | mm | 450 |

| | | | | |
|---|---|---|---|---|
| 6 | $b_m$ | Width of interpole winding | mm | 40 |
| 7 | - | Cross-section of bare conductor of interpole coil | mm$^2$ | 3x30 |
| 8 | $\ell_{mt}$ | Length of mean turn of interpole winding | mm | 1150 |
| 9 | $b_w'$ | Width of insulated conductor | mm | Bare |
| | $b_w$ = | bare conductor width | mm | 30 |
| | $b_{kw}$ = | width of coil or layer of interpole coil | mm | 56 |

**ARMATURE :**

| | | | | |
|---|---|---|---|---|
| 1 | $D_a$ | Armature diameter | mm | 493 |
| 2 | $\delta$ | Air gap under main pole | mm | 4 |
| 3 | $D_i$ | Internal diameter of armature | mm | 140 |
| 4 | $\ell_t$ | Total length of armature core | mm | 450 |
| 5 | $n_r$ | Number of radial ventilating ducts | - | 0 |
| 6 | b | Width of radial canals | - | 0 |
| 7 | $b_n$ | Width of armature slot | mm | 12.9 |
| 8 | u | Number of conductors width wise in the armature slots | - | 5 |
| 9 | $b_a$ | Width of bare conductor | mm | 1.56 |
| 10 | $b_a'$ | Width of insulated conductor | mm | 1.83 |
| 11 | $Q_{fla}$ | Iron losses in core of the armature | Kw | 0.46 |

| | | | | |
|---|---|---|---|---|
| 12 | $Q_{fez}$ | Iron losses in teeth of armature | Kw | 0.28 |
| 13 | As | ~~Inner~~ Linear electric loading of armature | Amp/cm | 380 |
| 14 | $J_a$ | Current density in armature conductors | $A/mm^2$ | 5.75 |
| 15 | $h_n$ | Height of armature slot | mm | 40.6 |
| 16 | Z | Number of armature slots | | -45 |
| 17 | - | Number of packets in the armature | - | 1 |
| 18 | $QC_{ua}$ | Copper losses in the armature | Kw | 7.1 Kw |
| 19 | P | Total losses in the machine | Kw | 13.96 |
| 20 | Q | Discharge of air in the machine | $m^3/sec$ | 1.0 |

COMPENSATING WINDING :

| | | | | |
|---|---|---|---|---|
| 1 | $J_c$ | Current density in winding bar | $A/mm^2$ | 4.33 |
| 2 | $b_p$ | Pole arc | mm | 267 |
| 3 | $\ell_p$ | Length of pole shoe | mm | 450 |
| 4 | $t_{1p}$ | Slot pitch of compensating winding | mm | 44.5 |
| 5 | $Z_c$ | Number of slots in pole shoe arc of compensating winding | - | 6 |
| 6 | - | Cross-section of bare conductor of compensating winding | $mm^2$ | 2.1x7.6 |

| | | | | |
|---|---|---|---|---|
| 7 | - | Cross-section of insulated conductor of compensating winding | $mm^2$ | Bare |
| 8 | $\tau$ | Pole pitch of the machine | mm | 387.5 |
| 9 | $Q_{wo}$ | Losses in the compensating winding | Kw | 3.62 |
| 10 | $\ell_{mt}$ | Length of mean turn of compensating winding | mm | 2050 |
| 11 | $h_{ne}$ | Height of compensating slot | mm | 36.4 |
| 12 | $b_{no}$ | Width of compensating slot | mm | 17.8 |

COMMUTATOR :

| | | | | |
|---|---|---|---|---|
| 1 | $Q_1$ | Electrical losses on Commutator bar | Kw | 0.52 |
| 2 | $Q_f$ | Frictional losses of the commutator | Kw | 0.22 |
| 3 | $D_K$ | Diameter of commutator | mm | 350 |
| 4 | $\ell_K$ | Length of commutator bar | mm | 168 |
| 5 | $n_b$ | Number of brushes on the commutator | $mm^2$ | 16 |
| 6 | | Area of one brush | $mm^2$ | 25x32x40 |
| 7 | N | Speed of the machine | RPM | 255 |

## 5.2 Specific heat loads

A. For armature with axial ventilating ducts

Specific heat load due to losses in iron core and armature teeth, referred to cooling surface of the armature

$$W_1 = \frac{QF_{\ell a} + QF_{\ell a} \times 10^2}{\pi D_a \ell_t (1 + K_b)}$$

Where $K_b = \sum \frac{n_a d_a}{D_a}$

$= (20 \times 30 + 10 \times 30)/493$

$= 1.825$

$$\therefore \quad W_1 = \frac{0.46 + 0.28}{\pi \times 493 \times 450 \; (1+1.825)} \times 10^2$$

$= 0.0376 \quad W/cm^2$

Specific heat load due to losses in armature winding referred to cooling surface of the armature

$$W_2 = \frac{K_{fn}' \;\; As \; j_a}{3800(1 + K_b)}$$

$K_{fn}'$ = field coefficient considering increase of losses in slot part of conductor for section of armature winding with split conductors along height.

$$= 1 + \frac{K_{fn} - 1}{n^2} + \left(\frac{n^2-1}{n^2}\right) (K_{fn-1}) \frac{\ell_a}{\ell_a}$$

Where $K_{fn} = 1 + \frac{0.76 \, m^2 \, \varepsilon^2}{2 + \gamma}$

and, $\gamma = \frac{31n}{\varepsilon^2} \cdot \frac{m_b + j-1}{K}$

$m_b$ = number of horizontal conductors along width of slot

= 5

$\beta$ = brush width/commutator pitch

= 5.12

Referred height of conductor

$$\xi = \frac{b_{cu}}{10} \sqrt{\frac{f}{50} \cdot \frac{a_{cu}}{b_n} \cdot \frac{\lambda}{50}}$$

Where $a_{cu}$ = dimension of active conductor along the height of the slot

= (7.4x2) 2 = 29.6 mm

$b_{cu}$ = total thickness of copper of conductors along the width of the slot

= 1.56 x 5

= 7.8 mm

$\lambda$ = conductivity of copper

= 46 at temperature 75 °C

= 42.5 at temperature 100 °C

= 40 at temperature 115 °C

Take $\lambda$ = 46.

$$\therefore \quad \xi = \frac{7.8}{10} \sqrt{\frac{8.5}{50} \times \frac{29.6}{12.9} \times \frac{46}{50}}$$

$$= 0.47$$

$$\therefore \quad \gamma = \frac{(31 \times 2)\,(5 + 5.12 - 1)}{(0.47)^2 \times 225}$$

$$= 11.38$$

Also,

$m$ = number of active conductors along height of the slot

$= 2$

$n$ = number of active conductors along height of the slot in one active conductor

$= 2$

$$\therefore \quad K_{fn} = 1 + \frac{0.76\ (2)^2 \times (0.47)^2}{2 + 11.38}$$

$$= 1.05$$

$$K_{fn} = 1 + \frac{1.05-1}{2^2} + \left(\frac{2^2-1}{2^2}\right)(1.05-1)$$

$$= 1.05$$

$$\therefore \quad W_2 = \frac{1.05 \times 378 \times 5.75}{3800(1+1.825)}$$

$$= 0.213$$

Specified heat load due to losses in armature winding, referred to the surface of slot part of coil

$$W_3 = W_2 \cdot t_1 (1 + K_{\bar{b}}) / \Gamma$$

Where $\Gamma = 2\ (h_n + b_n)$

$$= 2\ (40.6 + 12.9)$$

$$= 107 \text{ mm}$$

$$\therefore \quad W_3 = \frac{0.213 \times 34.4\ (1 + 1.825)}{107}$$

$$= 0.193 \text{ W/cm}^2$$

Specific heat load referred to cylindrical surface of end part of armature winding (over hang)

$$W_4 = \frac{As \cdot J_a}{3800} \times \frac{\ell_a}{\ell_b}$$

$$= \frac{378 \times 5.75}{3800} \times \frac{1.4 \times 387}{320}$$

$$= 0.97 \ W/cm^2$$

## 5.3 To determine the temperature rise of winding of the motor

5.3.1 Temperature rise of axially cooled armature is determined as follows.

$v_L$ = component of speed of air along the axis of the machine

= $Q_2/F$

$F$ = Cross-sectional area in $m^2$ for the passage of air along the active iron of armature and ducts

= $(0.697 + 1.27)\ m^2$

= $1.97\ m^2$

$\therefore\ v_L$ = $0.235 / 1.97$

= $0.12$ m/sec

$OF_{ea}$ = temperature rise of armature iron above temperature of inlet air

$$= \frac{(W_1 + W_2)\ C' F_e}{1 + v_b}$$

Where, $C'F_e$ = Constant characterising the heat transfer of armature iron at axial ventilation

450

$$v_b = \sqrt{\left(\frac{v_a}{2}\right)^2 + v_L}$$

$$= 3.314 \text{ m/sec}$$

$$\theta F_{ea} = \frac{(0.0376 + 0.213) \times 450}{1 + 3.314}$$

$$= 26.2\ ^{\circ}C$$

$\theta_{ia}$ = Temperature drop in insulation

$$= W_3 \times \frac{\delta_i}{0.016}$$

Where $\delta_i$ = thickness of slot insulation

$$= \frac{b_n - (m_b - 1)\, b_a' - b_a}{2} \text{ mm}$$

$b_a'$ = Width of insulated conductor

= 1.83 mm

$b_a$ = Width of uninsulated conductor

= 1.56

$\therefore$ $\delta_i$ = 2.01

$$\theta_{ia} = \frac{0.193 \times 2.01}{0.016}$$

$$= 24.24\ ^{\circ}C$$

$\theta_{sa}$ = Temperature of over hang part of armature winding above inlet air

$$= \frac{W_4 \times C_{sa}}{1 + \left( \frac{W_a}{2} + W_b \right)}$$

Where,

$C_{sa}$ = coefficient characterising the heat transfer of copper of end parts of winding It is chosen, depending upon the voltage of the machine.

$C_{sa}$ = 300-350 for windings with voltage up to 1000V

D100/255 is a 440 V machine.

$\therefore$ $C_{sa}$ = 300

$$\therefore \quad \theta_{sa} = \frac{0.97 \times 300}{1 + \left( \frac{6.6}{2} + 0.12 \right)}$$

$$= 76.8\ ^{\circ}C$$

$\theta C_{ua}$ = Average temperature rise of copper of armature winding over temperature of inlet air

$$= \frac{(\theta F_{sa} + \theta_{ia}) \frac{l}{10} + \theta_{sa} \left( l_a - \frac{l}{10} \right)}{l_a}$$

Where $l_a$ = $l_t + l_s$ = 985 mm

$l$ = $l_t$ = 450 mm for machines without radial ducts.

$$\therefore \quad \theta C_{ua} = \frac{(26.2 + 24.24)\frac{450}{10} + 76.8\left(98.5 - \frac{450}{10}\right)}{98.5}$$

$$= 64.7\ ^\circ C$$

## 5.3.2 Temperature rise of shunt winding

Temperature rise of shunt coil over temperature of inlet air

$$\theta_{on} = W_n \cdot \frac{C_n}{1 + v_{in}}$$

Where $C_n$ = constant characterising the heat transfer of shunt coil

$= 300$

$$W_n = \frac{j_s^2 \times b_{kn} \times 10}{3800} \times K_{bs}$$

$K_{bs}$ = 1, since coils are laid close to each other

$b_{kn}$ = Width of coil = 56 mm

$$\therefore \quad W_n = \frac{(1.78)^2 \cdot 56 \cdot 10}{3800} \times 1$$

$$= 0.467$$

Velocity of air through shunt coil,

$$v_{in} = \sqrt{(v_a/2)^2 + (v_L')^2}$$

where, $v_L' = \dfrac{Q_1}{F'}$

where $F'$ = window area of shunt coil

$$= [2(\ell_m + b_m) + 2\pi b_{kn}]\, h_{kn} \times 2p \times 10^{-2}$$

$= [\ 2\ (450 + 210) + 2\pi \times 56\ ]\ 91 \times 4 \times 10^{-2}$

$= 0.6085\ m^2$

$\therefore\ v_L' = 0.765 / 0.6085\ m/sec$

$= 1.26\ m/sec.$

$\therefore\ v_{in} = 3.53\ m/sec.$

$$\therefore\ \theta_{on} = \frac{0.467 \times 300}{(1+3.53)}$$

$= 30.93$

$\theta_{in}$ = average temperature rise of copper of coil over the temperature of its outer surface

$$= W_n \times \frac{\delta_{ip}}{0.016}$$

Where,

$\delta_{in}$ = thickness of outer insulation of shunt coil

$= 0$

$\therefore\ \theta_{in} = 0$

$\therefore$ Temperature rise of shunt coil

$= \theta_{on} + \theta_{in}$

$= 30.9\ ^{\circ}C$

### 5.3.3 Temperature rise of interpole winding

Specific heat load of interpole winding referred to cooling surface of interpole winding

$$W_w = \frac{J_w^2\ b_w \times 10 \times K_{bw}}{3800}$$

Where, $K_{bw}$ = 1, since coils are laid close to each other

$$= \frac{(2.89)^2 \times 30 \times 10 \times 1}{3800}$$

$= 0.66 \ W/cm^2$

Average temperature of copper of interpole winding above outer surface

$$\theta_{iw} = W_w \left( \frac{b_{kw}}{8K_w} + \frac{\delta_{iw}}{K_j} \right)$$

Where,

$\delta_{iw}$ = thickness of outer insulation of interpole coil

$= 0$

$K_j$ = 0.01 for impregnated coils, W/mm °C

$K_w$ = average coefficient of heat conductivity along the width of the coil

$$= K_j \cdot \frac{b_w'}{b_w' - b_w}$$

Where, $b_w'$ and $b_w$ are the sizes of insulated and bare conductors along the width of the coil.

The interpole coils for D100/#255 are bare

$$\therefore \ \theta_{iw} = 0$$

Rise of temperature of outer surface of interpole coils over the temperature of inlet air

$$\theta_{ow} = W_w \times \frac{C_w}{1 + v_{1w}}$$

Where, $C_w$ = constant characterising the heat transfer of cooling surface of coil

$= 300.$

$v_{Lw} = Q_1 / F_w$

Where, $F_w$ = Cooling surface of interpole coil

$= [2(\ell_w + b_w) + 2x\ b_{kw}]\ h_{kn} \times 2p \times 10^{-2}\ cm^2$

Where, $h_{kn}$ = height of interpole coil

$= 44$ mm.

$\therefore \quad F_w = 0.20895\ m^2$

$$v_{Lw} = \sqrt{\left(\frac{6.6}{2}\right)^2 + (3.7)^2}$$

$= 4.96$

$$\theta_{ow} = \frac{0.66 \times 300}{1 + 4.96}$$

$= 33.22\ ^oC$

$\therefore \quad \theta_w = \theta_{iw} + \theta_{ow}$

$= 0 + 33.22$

$= 33.22\ ^oC.$

### 5.3.4 Compensating winding temperature rise

Specific heat load due to losses in pole shoe referred to surface of pole shoe

$$q_p' = \frac{Q_{po} + Q_{pd}}{2p\ b_p\ l_p} \times 10^2$$

Where $Q_{po}$ = additional losses on the surface of pole shoe caused by the teeth of the armature

$$= \Delta\ [\ \frac{(K_{C_1} - 1)\ B_\delta\ t_1}{10000}\ ]^2 \times \frac{2p\ F_p}{1000} (\frac{Z.n}{10000})^{1.5}$$

$\Delta$ = thickness of sheet of pole shoe = 1 mm

$K_{C_1}$ = Carter's coefficient considering the pressure of slots in the armature

= 1.21

$F_p$ = surface of pole shoe

= 46.0 x 26.7 $cm^2$

= 1228.2 $cm^2$

$$\therefore Q_{po} = 1\ [\frac{(1.21-1)\ 8290 \times 34.4}{10000}\ ]^2 \times \frac{4 \times 1228.2}{1000}\ (\frac{45 \times 255}{10000})^{1.5}$$

= 217 W.

Additional losses on the surface of pole shoe due to tooth harmonics of mmf of armature

$$Q_{pd} = Q_{po}\ (\ \frac{\Delta a\ \tau}{\Delta a_\delta} \cdot \frac{2p}{Z} \cdot \frac{1}{K_{C_1} - 1})^2$$

Where,

$AW_\delta$ = ampere-turns required for air gap

$= 1.6\ K_c\ B_\delta \times \delta$

$= 1.6 \times 1.54 \times 8298 \times 0.5$

$= 10,223$

$$\therefore\ Q_{pd} = 217\ \left(\frac{378 \times 38.7}{10223} \times \frac{4}{45}\ \ \frac{1}{1.21-1}\right)^2$$

$= 79.61\ W$

$$\therefore\ W_p' = \frac{217 + 79.61}{4 \times 460 \times 267} \times 10^2$$

$= 0.06\ W / cm^2$

Specific heat load due to losses in copper of compensating winding referred to surface of pole shoe

$$W_p'' = \frac{As_c\ J_c}{3800}$$

Where,

$As_c$ = compensating conductors / cm of compensating winding $= \dfrac{J_c\ Z_c}{b_p}$

and $J_c = \dfrac{S_c\ I_{an}}{a_c}$

$S_c$ = Conductor in a slot

$= 6$

$a_c$ = number of parallel branches of the winding

$= 1$

$$J_c = \frac{6 \times 260}{1}$$

$= 1560$

$$\therefore \quad As_c = \frac{1560 \times 6}{267}$$

$$= 35.06 \text{ A/mm}$$

$$= 350.6 \text{ A/cm}$$

$$W_p'' = \frac{350.6 \times 4.33}{3800}$$

$$= 0.4 \quad \text{W/cm}^2$$

Rise of temperature of pole shoe iron over the temperature of inlet air

$$\theta F_{ep} = \frac{(W_p' + W_p'')\ \mathrm{xx}_x^x \quad C'' F_e}{1 + v_b}$$

$C'' F_e$ = Constant characterising the heat transfer of pole shoes

= 450.

$$\therefore \quad \theta F_{ep} = \frac{(0.06 \;\; + 0.4\;) \times 450}{1+3.53}$$

$$= 45.7 \ ^\circ C$$

Thickness of insulation from copper of compensating winding up to wall of the slot

$\delta_{ic}$ = 1.5 mm (from drawing)

Drop in temperature in insulation of compensating winding

$$\theta_{ic} = W_c \cdot \frac{\delta_{ic}}{0.016}$$

Where $W_c$ = specific heat loads due to losses in copper of compensating winding referred to surface of slot part of coil of compensating winding

$$= \frac{W_p'' \times t_{1p}}{P_c}$$

Where $t_{1p}$ = tooth pitch along surface of pole shoe

$= 267 / (6-1)$

$= 53.4$ mm

$P_c$ = Perimeter of cooling surface of slot part of compensating winding

$= 2\ (b_{nc} + h_{nc})$

$= 2\ (17.8 + 36.4)$

$= 108.4$ mm.

$$\therefore W_c = 0.4 \times \frac{53.4}{108.4}$$

$$= 0.197$$

$$\therefore \theta_{ic} = 0.197 \times \frac{1.5}{0.016}$$

$$= 18.5\ ^{\circ}C$$

Rise of temperature of copper of end parts of compensating windings over temperature of inlet air

$$\theta_{ac} = W_c' \times \frac{C_{ac}}{1 + (\frac{v_a}{2} + v_b)}$$

Where $W_c'$ = Specific heat load referred to outer surface of connecting bus bar of compensating winding

$= 0$

$C_{so}$ = Constant characterising the heat transfer of end parts of compensating winding

= 750

$\therefore\ \theta_{so}$ = 0.

Average rise of temperature of compensating winding over the temperature of inlet air

$$\theta C_{uo} = \frac{(\theta F_{ep} + \theta_{io})\frac{\ell_p}{10} + \theta_{so}\,\ell_o''}{0.1 \times \ell_p + \ell_o''}$$

$$= \frac{(45.7 + 18.5)\frac{450}{10}}{0.1 \times 450}$$

$$= 64.2\ ^{\circ}C.$$

## 5.3.5 Commutator temperature rise

Specific heat load of commutator referred to surface of commutator

$$W_K = \frac{(Q_i + Q_f)}{\pi D_K \ell_K} \times 10^2 \text{ Watts/cm}^2$$

$$= 0.4\ \text{W/cm}^2.$$

Temperature rise of commutator above inlet air

$$\theta_K = \frac{W_K \times 200}{1 + j_K \sqrt{V_K}}$$

Where, $j_K$ = Coefficient depending upon the condition of cooling of commutator

= 0.7

$$\therefore \quad \theta_K = \frac{0.4 \times 200}{1 + 0.7\sqrt{4.67}}$$

$$= 31.8 \ ^\circ C$$

The results obtained by calculation are listed below:

1. Armature temperature rise : 64.7 °C
2. Shunt winding temperature rise :30.9 °C
3. Interpole winding temperature rise : [redacted] 33.22 °C
4. Compensating winding temperature rise : 64.2 °C
5. Commutator temperature rise : 31.8 °C.

-00-

# CHAPTER - VI

## TESTING OF THE MACHINE D100 / 255

A number of tests are carried out on the machine once it reaches the test bed. Some important tests carried out are the determination of cold values of armature resistances, the heat run, the back bend test, high voltage test, insulation resistance, air gap measurement between main pole and the armature circuit and the open circuit characteristics.

Amongst the above tests, carried out, the heat run test is of special interest. The above machines were tested two at a time, connected back to back, one machine running as a motor and the other as a generator. The electrical output of the generator can be fed to the mains or can be used for feeding the motor.

### 6.1 Experimental set up

The experimental set up is as shown in figure 6(i). The generator is put in parallel with the supply system, the excitation being adjusted until V' reads zero. The switch $S_2$ isthen closed. Under this condition, the generator will neither take nor give current to the supply.

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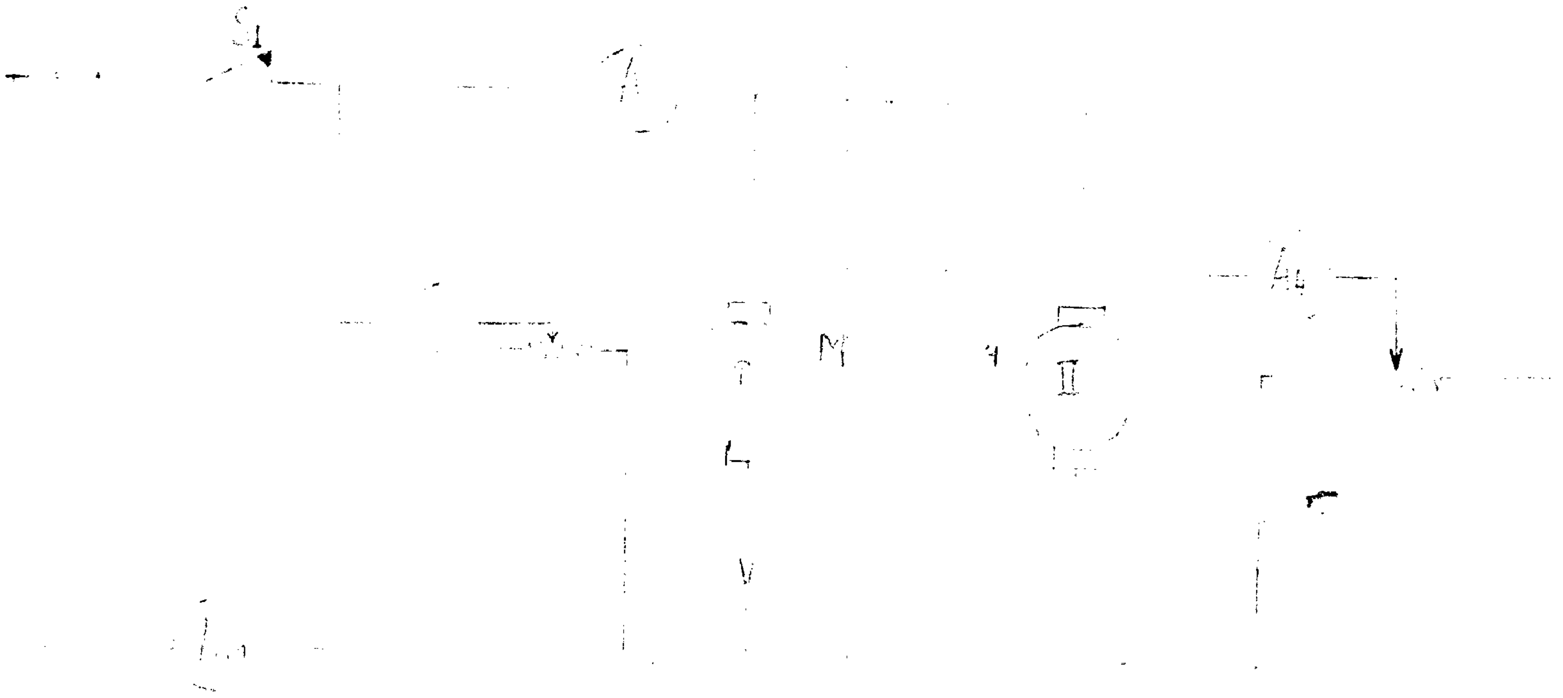

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The generator can be loaded to any desired value by increasing the value of its induced e.m.f. This in turn can be achieved by increasing the generator exciting current or decreasing the motor exciting current. The generated current can thus be utilised to drive the motor and the current taken from the supply system is simply that necessary to supply the losses, i.e. the difference between the motor input and the generator out put.

An alternative method is to connect the machine in parallel at starting and run up to speed through a single starter. For the machine to start, torque for both machines should develop in the same direction. Failure to start can be overcome by reversing the field of one of the machines.

By adjusting the two field rheostats $R_1$ and $R_2$, it can be arranged that each machine takes exactly the same armature current and the set runs at rated speed when supplied at normal working voltage. To put load on the machine, field of current of either machine can be weakened. As a result, this particular machine will speed up the set slightly and will act as a motor whereas the other will be a generator. To maintain normal working speed, it is necessary that the load shall be obtained by both weakening the field of one machine and strengthening that of the other.

The machines are now ready for the heat run. D100 / 255 is ~~a~~ forced ventilated and air is forced in from the bottom, commutator end. An appropriate blower motor is chosen to regulate the required quantity of air. Air exit is from the commutator end. For the heat run, the machine is run for a period of 4 to 5 hours until the temperature stabilises. This is indicated by a voltmeter connected across the terminals of interpole windings. A consistent reading implies that the temperature has stabilised .

The value of hot resistance can then be determined for the interpole and compensating windings. Cold values of resistance of these windings are also known at 20 °C. Total temperature rise is determined as follows

$$\frac{R_{t1}}{R_{t2}} = \frac{235 + t_1}{235 + t_2}$$

Where,

$R_{t1}$ = cold resistance

$t_1$ = temperature at which cold resistance is measured.

$R_{t2}$ = hot resistance

$t_2$ = temperature to be determined.

Shunt winding temperature rise is determined in like manner.

Armature winding temperature rise can be determined only ~~by~~ after the machine comes to rest. A number of readings are taken one after another and the corresponding time is noted. These values are plotted on a graph sheet and extra polated to determine the temperature rise at zero time.

Commutator temperature rise is measured directly by means of a thermometer.

## 6.2 Experimental results and discussion

The temperature rise values of some machines (D100/255) tested at BHEL Hardwar are enclosed in Table-1. It is seen that there is variance in results for machines of ~~its~~ the same design. This can be attributed to various reasons. A few reasons are listed below:

1. No two machines can be exactly similar however ideal the conditions may be.
2. Copper used for windings may vary in section along the length, giving rise to higher values of current density which in turn will ~~measure~~ increase the heat loads and hence the temperature rise.
3. During the process of impregnation of the armature, the axial ventilating holes get blocked. If these holes are not cleared, the passage of air passing throug the armature canals gets blocked, preventing the losses from being dissipated. This accounts for additional temperature rise.
4. Variance in distribution of the cooling air between the armature and the magnetic circuit.

5. The blower motor, should run at the rated rpm to provide the required discharge of air. Thus, variance in speed means variable quantity of air supplied which accounts for the difference in temperature rise values.

## 6.3 Temperature rise calculation by conventional methods

The method of calculation of temperature rise of a d.c. machine by conventional methods was discussed in chapter I. These methods when applied to the machine D100/255 yield the results enclosed in Table-II.

## 6.4 Discussion

All authors have in general given methods for determination of temperature rise of armature and commutator. Temperature rise of interpole and compensating windings have not been determined. Field winding calculation has been restricted to temperature rise values of 40 °C in some cases. There is some difference noted in the temperature rise values obtained when compared with the tested results.

Calculated value of armature temperature rise is within the permissible limits and also compares closely with the tested values. Shunt winding temperature rise obtained by calculation is also well within permissible limits. However, higher values of temperature rise are obtained from the test results. The reason may be attributed to different percentage of air distribution between the armature and the magnetic system. Commutator temperature rise values compare favourably with the tested results. The difference in results can be attributed mainly to the machine hall environments.

### Table-I

TEMPERATURE RISE VALUES OBTAINED FROM TESTS CONDUCTED On D100 / 255.

| P.O.No. | Armature °C | Shunt (°C ) | Compensating and Interpole (°C) | Commutator (°C) |
|---|---|---|---|---|
| 32124100 - 2 | 75 | 57.3 | 69.51 | 28 |
| 32124100 - 4 | 62.5 | 40.5 | 68.0 | 40 |
| 32124100 - 5 | 62 | 49.0 | 66.0 | 43 |
| 32124100 - 8 | 57 | 43.0 | 74.0 | 40 |
| 32124100 - 9 | 50 | 34.0 | 72.5 | 35 |
| 32124100 -14 | 62 | 36.2 | 58 | 40 |
| 32124100 -15 | 60.9 | 33.4 | 45 | 39 |
| 32124100 -21 | 52 | 31 | 62 | 41 |

## Table-II

### TEMPERATURE RISE VALUES OBTAINED BY CONVENTIONAL METHOD CALCULATION.

| | Armature (°C) | Field (°C) | Commutator (°C) |
|---|---|---|---|
| CLAYTON AND HANCOCK | 44.5 | 86.8 | 32.3 |
| KUHLAMANN | 112.5 | 104 | 34.7 |
| GREENWOOD | 82.8 | - | 39.1 |
| STILL AND SISKIND | 176.8 | - | 21.3 |

## 6.5 Conclusion

The present method has been found to yield more accurate results as compared to the conventional methods of calculation of temperature rise. In the conventional methods the temperature rise calculations are based on the peripheral velocity of the armature irrespective of the distribution of air in the machine. In the present method, the quantity of air required by the d.c. motor is determined. An equivalent circuit is then developed depicting the resistance offered by the various machine parts to the flow of air. This circuit is solved and the exact distribution of air between the armature and the magnetic system is determined. The values obtained are used for temperature rise calculations, thus yielding more accurate results.

The results obtained by the present method are compared with the test results in Table-III (Results given to the nearest °C).

Table-III

| Salient Parts | Temperature rise by conventional methods (°C) | Temperature rise by present method (°C) | Experimental results (°C) |
|---|---|---|---|
| 1. Armature | 44 - 177 | 65 | 32 - 75 |
| 2. Shunt | 87 | 31 | 31 - 57.3 |
| 3. Interpole winding | - | 33 | 45 - 74 |
| 4. Compensating winding | - | 64 | |
| 5. Commutator | 21 - 39 | 32 | 28 - 41 |

The values obtained by the equivalent circuit method are found to be more realistic and compare well with the results obtained experimentally. As such, this method proves to be more useful for temperature rise determination of a d.c. machine.

## REFERENCES

1. Clayton and Hancock - Performance and design of d.c. machines.
2. Greenwood - Design of direct current machines.
3. Kuhlmann - Design of electrical apparatus.
4. Still and Siskind - Elements of electrical machine design.
5. Short course on ventilation and heat transfer of electrical machines held at Corporate Research and Development Division, Hyderabad, April 1976 and April 1977.
6. Brown Boveri Review, September 66 - Calculation of cooling air flow.
7. D.B. Houseason, - The cooling of electrical machines Jr., Inst. Elect. Engrs.(London) Jan.1951.

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