OPTIMIZATION OF SERIES OF INDUCTION MOTORS FOR STANDARD FRAMES

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

By

ALOK PRAKASH MITTAL

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE-247672 (INDIA)

November, 1980

CERTIFICATE

Certified that the thesis entitled, "Optimization of Series of Induction Motors for Standard Frames", which is being submitted by Sri Alok Prakash Mittal in partial fulfilment of the requirements for the award of the degree of 'MASTER OF ENGINEERING' in 'Power Apparatus and Electric Drives', is a record of candidate's own work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree.

This is further certified that the candidate has worked for a period of seven months from January 1980 to July 1980 for preparing this thesis.

Saxena
(Dr.R.B.Saxena)
Professor
Department of Electrical Engg.
University of Roorkee,
ROORKEE

Dated November 27 ,1980

****

Acknowledgements

The author wishes to express his deep sense of gratitude to Dr.R.B.Saxena, Professor,Electrical Engineering Department, for his invaluable suggestions and guidance at every stage of the work presented in this thesis.

The author is highly grateful to Dr.S.K.Gupta, Sr.Manager, and Sri R.K.Raheja, Dy.Manager, B.H.E.L., Hardwar for their valuable suggestions during the course of this dissertation.

Sincere thanks are also due to Sri H.O.Gupta, Lecturer, ElectricalEngineering Department for his valuable help in preparing computer programs.

Lastly the author wishes to thank one and all, helped him during the whole tenure of this dissertation in one way or the other.

CONTENTS

*

Page No.

CHAPTER

contd....

******

LIST OF NOTATIONS

B_{av}, BAV	Average air gap flux density
P, POL	No.of poles
ϕ_m, FLUX	Flux per pole
D, DIA	Bore diameter in m.
L, SLTH	Stack length in m.
Q, RKVA	KVA rating of machine
RKW	KW rating of machine
CO	Output coefficient
n_s, SYN	Synchronous speed in r.p.s.
K_w, AKW	Winding factor
$\overline{ac}$, AC	Ampere conductors per metre
I_1, CI1	Current per phase in stator conductors
TS	Number of turns per phase
S1	Number of stator slots
S2	Number of rotor slots
l_g, AGL	Air gap length in mm.
Z_b, BIMP	Impedence of rotor bar at the time of starting
u_o	Permeability of air
ρ, SPRB	Specific resistivity of rotor bars
ψ ,PR,X(I,1)	Pole arc to pole pitch ratio
PF	Rated power factor
EFF,X(I,7)	Rated efficiency
SLTNI	Net iron length in m.
STKF	Stacking factor for laminations
ND	Number of ventillating ducts
WD	Width of ventillating ducts in m.

ES	Rated voltage per phase
QS	Number of stator slots per pole per phase
YSS	Stator slot pitch in m.
ZSS	Stator conductors per slot
CONA	Area of stator conductor in mm^2
DELTA, X(I,3)	Current density in stator conductors in A/mm^2
SLF	Slot factor
ASS	Area of stator slot in mm^2
AX, X(I,2)	Stator slot depth to width ratio
DSS	Depth of stator slot in mm.
WSS	Width of stator slot in mm.
TWS	Stator tooth width in m.
BT1, X(I,5)	Maximum flux density in stator teeth in Wb/m^2
DCS	Depth of stator core in m.
OD	Outer diameter of stator stampings in m.
BCS	Flux density in stator core in Wb/m^2
RDIA	Rotor outer diameter in m.
YRS	Rotor slot pitch in m.
CIB	Rotor bar current
BARA	Area of rotor bar in mm^2
DELB, X(I,4)	Current density in rotor bars and end rings in A/mm^2
WRS	Width of rotor slot in mm.
TWR	Rotor tooth width in mm.
DRB	Depth of rotor bar in mm.
DRS	Depth of rotor slot in mm.
BT2, X(I,6)	Maximum flux density in rotor teeth in Wb/m^2
BLTH	Length of rotor bar in m.
CIE	End ring current
ERAR	Area of end ring in mm^2

DE	Depth of end ring in mm.
TE	Thickness of end ring in mm.
DEO	Outer dia-meter of end rings in m.
DEI	Inner diameter of end rings in m.
DEM	Mean diameter of end rings in m.
RSID	Inner diameter of rotor stampings in m.
WSO	Width of slot opening in mm.
YSS'	The contracted slot pitch in m.
CGCS	Carter's gap coefficient for stator slot
Rgs'	Reluctance of air gap with slotted armature
Rgs	Reluctance of air gap with smooth armature
GCFS	Gap contraction factor for stator slot
CGCR	Carter's gap coefficient for rotor slot
GCFR	Gap contraction factor for rotor slot
CGCD	Carter's gap coefficient for ventillating ducts
GCFD	Gap contraction factor for ventillating ducts
GCFT	Total Gap contraction factor
EAGL	Effective air gap length in m.m.
ATG	Air gap m.m.f.
WTS	Width of stator teeth at 1/3rd height from narrow end in m.
AST	Area of stator tooth at 1/3rd height from narrow end in m^2.
BTSS	Stator tooth flux density considering saturation effect in Wb/m^2
SATST	M.M.F. per metre for stator teeth
ATST	Total m.m.f. for stator teeth
SATSC	M.M.F. per metre for stator and rotor core
SCPATH	Length of flux path through stator core in m.

ATSC	Total m.m.f for stator core
WRT	Width of rotor tooth at $1/3^{rd}$ height from narrow end in m.
ART	Area of rotor tooth at $1/3^{rd}$ height from narrow end in m^2.
BTRS	Flux density in rotor teeth considering saturation in Wb/m^2
SATRT	M.M.F. per metre for rotor teeth
ATRT	Total mmf for rotor teeth
RCPATH	Length of flux path through rotor core in m.
ATRC	Total m.m.f for rotor core.
TAT	Total m.m.f. requirements of motor
CIM	Magnetising component of no load current per phase
TWM	Mean width of stator tooth m.
WTST	Weight of stator teeth in Kgs.
BTSM	Maximum flux density in stator teeth at $1/3^{rd}$ height from narrow end in Wb/m^2.
SPLST	Loss per kg in stator teeth in Watts
LIST	Total iron loss in stator teeth in Watts
WTCI	Weight of iron in stator core in Kgs.
SPLC	Loss per Kg in core in Watts
LIC	Total iron loss in stator core in Watts
TIL	Total iron losses in watts
FWL	Friction and windage losses in Watts
NLL	Total no load losses in Watts
CIL	Loss component of no load current per phase
CINL	No load current per phase

PFNL	Power factor at no load
XM	Magnetising reactance
RM	Resistance due to core losses
SCML	Mean length of stator conductor in m.
SCLP	Length of conductor per phase in m.
RS	Stator resistance per phase
SCLOS	Stator copper losses, in watts
RB	Resistance of each rotor bar
BCLOS	Rotor bar copper losses in Watts
RE	Resistance of each end ring
ECLOS	Copper losses in two end rings in Watts.
RCLOS	Total rotor copper losses in Watts
TCLOS	Total copper losses in Watts
SLIP	Slip at rated speed
RROT	Total rotor resistance
TFR	Transformation ratio
RSR	Stator referred rotor resistance per phase
PSS	Specific slot permeance for stator slot
SSLR	Stator leakage reactance.
PRS	Specific slot permeance for rotor slot
RPRS	Rotor slot specific permeance referred to stator side
RSLR	Stator referred, rotor slot leakage reactance.
OP	Permeance of overhang portion
OLR	Overhang leakage reactance
QR	Number of rotor slots per pole per phase
XZ	Zig-zag leakage reactance
XL	Total leakage reactance per phase

XS	Total stator leakage reactance per phase
XR	Total rotor leakage reactance referred to stator side per phase
ZS	Stator circuit impedence per phase
ZR	Rotor circuit impedence per phase
ZM	Magnetising branch impedence - G1 + jG2
ZRM	Impedence of rotor and magnetising ckt -G3+jG4
Z1	Total series impedence referred to stator, per phase
PFFL, X(I,8)	Full load power factor
BRS	Bar resistance at starting
SRROT	Total rotor resistance at starting
SRSR	Stator referred, starting rotor resistance per phase
C1	Effect of magnetising branch on torque of motor
TFL	Full load torque
TST	Starting torque
TRT1, X(I,9)	p.u. starting torque
Scr	Slip corresponding to maximum torque
TMAX	Pull out torque
TRT2, X(I,10)	p.u. pull out torque
CIFL	Full load current
CIST	Starting current
STCR	p.u. starting current
SSO	Outside cyllindrical surface of stator in m^2
SSI	Inside cyllindrical surface of stator in m^2
SCO	Cooling coefficient for outside stator surface
OHL	Overhang length
SPS	Relative peripherial speed of stator surface
SCI	Cooling coefficient for inner stator surface

SSD	Surface of ventillating ducts in m^2
SCD	Cooling coefficient for ventillating ducts
SLOS	Total stator power loss in Watts
STRISE,X(I,11)	Stator temperature rise
RSO	Outside cyllindrical surface of rotor in m^2
RCO	Cooling coefficient for outside rotor surface
RPS	Relative peripherial speed of rotor surface
RSD	Surface of ventillating ducts in m^2
RCD	Cooling coefficient for ventillating ducts
RTRISE,X(I,12)	Rotor temperature rise
WTRI	Weight of iron in rotor in Kgs
CI	Cost of iron per Kg
TIC	Total cost of iron in Rs.
WTSW	Weight of stator windings in Kgs.
WTRW	Weight of rotor windings in Kgs.
CC	Cost of stator copper per kg.
CR	Cost of rotor copper per Kg.
TCW	Total cost of winding in Rs.
TC,F(I)	Total cost of active material in Rs.

SYNOPSIS

In the present work, the series of induction motors, having different outputs and speeds is being optimized using complex Box algorithm.

Firstly, the general design procedure is presented and the different considerations involved in three phase induction motor design, are discussed. A flow chart for general design procedure using synthesis approach of design has been developed. The different optimization techniques are discussed and the complex Box method is selected for present problem on the basis that only four variables are used for optimizing the series. The objective function is formulated using two approaches, namely the root mean square method and weightage function method.

The results of series optimization are compared with that of individual optimization of motors. The various constraints are selected as per practice adopted by manufacturers.

Introduction

Cage induction motors being robust and economical have captured the leading place in industrial drives. The design of cage induction motors is based on universally accepted physical and mathematical principles which have been verified by the experimental methods. However, with the fast changing developments, the knowledge of these principles is often insufficient to work out the optimal design. Optimization, either of cost or weight, of electrical devices has been approached as a problem in nonlinear programming. Induction motor, in particular, gained special attention from research organisations, in the field of cost optimisation, due to its extensive use.

The tremendous rate of performing calculations at reasonable cost and ability to carry out the logical decisions - are the important qualities of the present generation digital computers. For these reasons digital computer has been employed for many years in the area of electrical machine design. More recently, there has been some progress inthe area of design synthesis, i.e. the determination of machine parameters from a knowledge of the performance requirements.

Induction motor performance was first tested in a synthetic manner by Vienett(1) giving complete details of input output data sheet and computer flow chart. Because of fast and accurate computational facilities, he improved the basic design procedure by including several additional effects and corrections while testing the performance.

Abetti et al.(2), in their paper, have discussed the importance of computers emphasizing the economic considerations. The basis for selecting new computer program applications have been presented. Analysis and synthesis method of design have been discussed and an iterative procedure has been used for designing transformers and rotating machines. Programmes for performance calculations of induction and synchronous motors have been given by Herzog et al.(3) using synthetic approach.

Godwin(4) has used the digital computer for getting an optimum design for an induction motor. He has developed a technique to eliminate unsatisfactory combinations of design parameters and the remaining parameters have been surveyed systematically to locate the optimum design as rapidly as possible. The development of performance chart, outlining the area of satisfactory design, is the original contribution.

Appelbaum and Erlichi(5) have optimized the parameters of conventional three phase induction motor using programming techniques. They have evaluated an unconstrained minimum cost design by suitably forming the objective function, consisting of cost of active and structural material, loss expenditure, constant parameter expenditure, total annual instalments on the invested capital, stator bore diameter, stack length, slot dimensions, specific loadings and stator, rotor winding current densities. The solution sought by them has been found to be impracticable but the results are useful in predicting the trend, in which the minimum cost design would proceed.

For a given specification and class and thickness of insulation, Artanov(6) has derived the design expressions. Calculation of optimum parameters is based on use of maximum slot fullness factor. Maximum slot fullness factor is obtained when the ratio of slot depth to width is equal to the ratio of thickness of insulation along the height to width.

Chalmers and Bennington(7) have developed a digital computer program for design synthesis of large squirrel cage induction motors. Stator outside diameter, rotor inside diameter, number of stator and rotor slots, coil pitch etc., have been taken as independent variables. Several program routines have been developed in their fully automatic program.

The nonlinear programming approach for optimization of polyphase induction motor was first carried out by Ramarathnam and Desai(8). They considered stator bore diameter, stack length, core depth, stator and rotor slot dimensions, airgap flux density, end ring dimensions and air gap length as continuous variables and performance indices as constraints. An initial design and optimization procedure flow charts have been presented and discussed. No details of optimized design have been given.

Bhattacharya and Mukherjee(9) have optimized the stator design of induction motor using steepest descent technique. Design equations are presented in terms of variables selected, i.e. number of ampere conductors, ratio-pole arc to pole pitch, ratio-stator slot depth to width, stator core depth and flux density.

Steepest-descent technique has been discussed mathematically. The flow chart for the optimization procedure is presented.

Optimization program for the design of large induction motors has been presented by Menzies and Neal(10). The cost minimization is approached using nonlinear programming technique. The performance evaluation programs include saturation effects, stray load losses and airflow and temperature rise throughout the machine, while the cost function includes labour as well as material cost. Core length, stator and rotor slot dimensions, stator bore diameter, rotor inside diameter, stator and rotor slot openings and air gap length have been taken as design variable. The objective function chosen is based on p^{th} optimization method which is commonly applied for network problems. Parameter variations during the optimization process have been plotted and discussed. No computer flow chart, details of results and comparision have been included in the work presented.

The work described above is with reference to fresh design of induction motors. The fresh design is the process in which there are no manufacturers constraints and design variables are calculated satisfying the performance requirements with minimum cost of active materials. However, the fresh design approach has not been considered economical, as the manufacturers like to go for manufacturing the motors out of existing standard frame sizes because of their adequate availability in the market. The cost of stamping in the fresh design is also more than that of frame design because there the fresh die has to be made for each design. Frame design is the approach in which the outer diameter of the machine is prefixed and on the basis of this value the design is approached. Standard frames of different outer diameters are readily available to manufacturers. The following authors, in their papers, deal with the frame design approach for optimization of induction motors.

Frame designed conventional three phase induction motor optimization using nonlinear programming penalty function method has been put forth by Rajsekhar et al.(11). They have considered stack length, gap density and air gap length as variables and performance indices as constraints. Objective function and constraint expressions in terms of variables have been given. A general computer flow chart for design and optimization program flow chart have also been incorporated. They have discussed the importance of selecting fewer but effective variables. Results obtained have been discussed in detail. However, the paper does not include the comparision of the optimum design with normal one.

Geometrical approach to the economical design of rotating electrical machines has been discussed by Schwarz(12). For a given stator dimensions (outside diameter, bore diameter and number of slots), other design details have been expressed in terms of tooth width, which has been considered as the only independent variable. The theory is developed assuming a maximum permissible flux density in teeth and core and a constant specific electric loading. He has discussed the variation of all the performance items with tooth width. The terminology "Iron machine' and "Copper machine" has been introduced for the limiting conditions when the tooth width is zero or a maximum. The cost of a motor with different stator bores and tooth widths has also been studied.

Fulton et al.(13), in their paper dealt with optimization of small three phase frame designed induction motors. They have taken stack length, turns per phase and winding wire diameter as the variables. The method of optimization used is an incremental search type where an ordered search is conducted from a given starting point. Design specifications considered by them include motor rating and performance quantities like starting torque, pull out torque, maximum full load temperature rise, slot fullness factor etc. For every small motor below 1 KW it is observed that the temperature rise is approximately proportional to the stator copper loss and so a relationship between temperature rise and copper loss is established. Effect of variables on performance and cost has been studied through graphs.

A comparative study of several optimization techniques for induction motor design optimization has been presented by Ramrathnam et al.(14). The methods considered are steepest-descent, quadratic convergence, Davidson-Flether-Powell, Direct search and random search methods. Best results have been obtained with the help of direct search method. No flow charts, program details or algorithms have been given to support the theory.

Bhardwaj et al.(15) studied the experiences with direct and indirect search methods applied to cage induction motor design optimization. They assigned fix values to some parameters like stator and rotor slots, winding layout scheme, slot fullness factor, slot openings and wedge and lip heights and air gap length etc., while the variables selected are ampere conductor per metre, ratio core length to pole pitch, stator slot depth to width ratio, stator core depth, average air gap flux density and stator and rotor winding current densities. The constraints considered in evaluating the performance of machine are, maximum stator tooth flux density, full load stator temperature rise, p.u. no load current, full load efficiency, full load p.u. slip, p.u. maximum torque, p.u. starting torque, full load power factor and full load rotor temperature rise.

The direct methods they considered are, incremental search method, Rosenbrock's method and Box's complex method. The only indirect method considered is penalty function method. The computer programs and flow charts are also developed for above methods. Among the direct methods, they found Box's complex method suits the problem for the same starting point and within a prescribed range of variables and constraints. Although, the penalty function method resulted in better optimum design than the direct methods, but as direct methods are simple to program and require less computer memory and hence are preferred for general purpose. An optimization program flow chart using two direct methods, namely Box's complex method and incremental search method, is also developed to obtain optimum results and fast convergence in another paper published by same authors(16). The results of all methods along with normal design are compared. Among direct methods best results were obtained by Box's complex method but the variation in this method is continuous If we have to use standard conductor size and standard frame sizes then Box's complex method fails because there the increment is discrete; hence the proposed method by Bhardwaj et al.(16) is best suited for induction motor design optimization.

The frame designed induction motor optimization, although accepted by some manufacturers, the need is still there for improvement in the technique so that a range of induction motor is optimized in one attempt. This will save a lot of computer time as well as the material cost.

If we may able to fix the bore diameter of a series of induction motors with a large range of outputs, by some method, the stamping size for the series may be fixed. It will require single die-punch for stampings which will be common for all the machines in the series. This will considerably reduce the manufacturing cost.

The work presented in this thesis deals with the optimization of series induction motors. Here the induction motors of different outputs and speeds, which are presently designed with single frame by industries, are considered as series for optimization. A single value of bore diameter is estimated for all the machines in series from general design considerations. In this process the other design variables like stack length, stator turns, current densities etc.are taken different for each machine in the series.

For the purpose of optimization, the Box's complex method is used as the results obtained by this method by earlier authors(17), for few number of variables are quite good. Here only four variables are used for the purpose of optimization and hence complex Box method guarantees good results as it is a tested algorithm.

In Chapter 2 of this thesis, the general design procedure is formulated with reference to a flow chart using synthesis approach of design and the considerations involved in the design of three phase cage induction motor are discussed. In chapter 3, the different optimization techniques with special reference to present problem are discussed and the objective function is formulated in chapter 4. In chapter 5, the computed results are discussed in light of different manufacturing constraints and other design problems. Conclusions, design recommendations and scope of further work are given in chapter 6. Listing of programs used have been given in appendix.

Chapter - 2

" GENERAL DESIGN CONSIDERATIONS AND DESIGN PROCEDURE "

****

2.1. Introduction

The chapter firstly deals with the general considerations in the design of three phase induction motors. The discussion includes selection of variables, selection of slot dimensions and shape, Tooth and core flux densities, combination of stator and rotor slots, air gap length, deep bar effect and starting and full load currents and torques. The method of fixing the bore diameter for the series of induction motors is discussed. After discussing these aspects, a general design procedure, on the basis of flow chart using synthesis approach of design, is developed. The flow chart ensures that flux densities and temperature rise in different parts of the machine are kept within limit and the ratio of starting torque to full load torque is adjusted to a specified value.

2.2. Selection of design variables

The induction motor is a highly nonlinear device and there are as many as twenty six parameters which control the design (4). The main task of design engineer is to select fewer but effective and significant variables. Fortunately, it is possible to treat some of the parameters as assigned parameters. For the purpose of getting feasible initial design, the variables selected are specific electric and magnetic loadings, current densities in stator and rotor bars, pole arc to pole pitch ratio, stator slot depth to width ratio and number of stator and rotor slots. The effect of these variables on the performance of machine is discussed in preceding sections. After investigated the eff of these variables, initial values are assigned to these variab for starting the design and these are suitably modified at time to meet the desired performance constraints. The effect of som of these variables on cost of active material and performance i investigated by Bhardwaj(17) in his Ph.D. thesis.

2.3. Selection of specific magnetic and specific electric loadi

2.3.1. Specific magnetic loading:-

Specific magnetic loading is defined as the average magnetic flux density over the whole surface of the air gap and is given by,

$$Bav = p\,\phi m / \pi \,.\, D.L. \qquad \ldots\ldots\ldots \qquad (2.1)$$

The selection of specific magnetic loading depends upo following factors:

(a) Effect on volume :- The output equation of a machine is gi by,

$$Q = C_o\, D^2\, L\, n_s \qquad \ldots\ldots\ldots \qquad (2.2)$$

Where C_o is output coefficient and is given by,

$$C_o = 11 \times Kw \times Bav \times \overline{ac} \times 10^{-3} \qquad \ldots\ldots \qquad (2.3)$$

From equations (2.2) and (2.3) it is clear that for a given output the choice of Bav straight away fixes the volume and hence cost of the machine. A high value of Bav reduces the volume and cost of machine.

(b) Effect on power factor :- Power factor depends upon magnetising current and reactances of the machine. Both, the magnetising current and reactances increases as the specific magnetic loading increases resulting in poor power factor. Therefore, moderate values of specific magnetic loading should be chosen in order to get good power factor.

(c) Effect on losses :- The study of magnetisation curve (Fig.2.3 shows that loss of the steel sheets used depends upon the flux density. The variation is almost linear for the lower densities and the curve turn suddenly and move up for higher densities. The form of the curve indicates that a very high value of flux density will cause more iron losses and hence high value of temperature rise. It is for this reason that value of specific magnetic loading is chosen such that the maximum value of flux density in teeth portion remain in the unsaturated regionof the magnetisation curve.

Keeping in view the above factors, the value of Bav is usually taken between 0.4 and 0.6 Wb/m^2 for a normal 50 c/s machine.

2.3.2. Specific electric loading :-

Specific electric loading is defined as number of r.m.s. ampere-conductors per unit length of gap surface circumference and is given by,

$$\overline{ac} = 3 \times 2 \times I_1 \times T_s / \pi \times D \qquad \text{amp. cond. per m.}$$

The selection of the value of specific electric loading depends on the following factors:

(a) <u>Effect on volume</u> :- As given in equation (2.2) and (2.3) the high value of 'ac' will reduce the volume andhence the cost of machine.

(b) <u>Effect on performance</u> :- The total number of conductors per slot on the armature will increase in a machine with the higher value of 'ac'. This will result in (i) increased depth of slot and its effect (discussed in art.2.4). A deeper slot cannot be avoided for a machine with smaller diameter due to higher values of 'ac'. To accomodate a larger area of copper per slot, the cross-sectional area of slot must be more. To avoid the undue saturation in teeth and to have sufficient mechanical strength, there is lower limit on the width of teeth, and a given value of slot pitch forces the adoption of deeper slots to accomodate the area of copper after allowing for teeth.

(ii) Higher copper losses resulting high temperature rise and low efficiency.

The large number of conductors carrying the load current contained in one slot generate more power loss due to resistance of the winding. The increased power losses must be dissipated by the available surface. As the available surface is limited due to choice of large value of 'ac', to dissipate the excessive losses, the temperature of slot surface will rise. The rise in temperature of slot surface is also transmitted to the windings and insulation. The large number of 'ac' also results in larger number of turns per phase resulting in increase in resistance per phase as the area of the conductor is already fixed with reference to permissible current density in the copper This increase in resistance causes more copper losses. Hence the operating efficiency of the motor lowers with higher value of 'ac

(c) Effect of voltage and speed on selection of 'ac' :- A high voltage machine requires a large space for insulation, and if the space for iron is kept same space for copper becomes small. Therefore, it is better to use lower value of 'ac' for high voltage machine.

A high speed machine has better cooling due to its natural fan action, hence a high value of 'ac' can be taken in high speed machine.

Keeping the above facts in consideration, the general value of 'ac' for normal 50 c/s, machine varies between 5000 and 50000. Taking high values for higher rating machines.

2.4. Selection of slot dimensions and shape

After obtaining the area of the slot, the dimension of the slots should be adjusted. The slot should not be too wide to give a thin tooth. The width of the slot should be so adjusted that the mean flux density in the tooth lies between 1.25 and 1.6 Wb/m^2. The width of tooth should also not to be large as it results in narrow and deep slots. A deeper slot results in large value of leakage reactance. The increased value of leakage reactance gives rise to low operating power factor and high valu of magnetising current. This also leads to reduced starting current and starting torque as,

$$I_{start} = \frac{V}{Z_1} \qquad \ldots\ldots\ldots\ldots \qquad (2.4)$$

In general to ratio of slot depth to slot width is taken between 3.5 and 5.5.

The stator slots used are open type slot due to the fact that in high rating machine it is pretty difficult to insert large coils in the semiclosed type slot although semiclosed type slots result in smaller value of leakage reactance.

The rotor slots are always of partially closed type. The rectangular shaped bar and slot is generally preferred.

2.5. Selection of conductor area and current densities

The stator conductor cross sectional area depends upon the stator current densities. The current density is so adjuste that the temperature rise falls within limit. The area of condu tor cross section should be taken as per I.S.I. specification. For this purpose a special subroutine called "Standard conductor selection" may be added to design program. The rotor conductor current density can be taken higher than stator current density due to the fact that heat dissipation is good in rotor due to its speed. The stator current density, in general, is taken between 4 A/mm^2 to 8 A/mm^2 and rotor current density between 4.5 A/mm^2 to 9 A/mm^2.

2.6. Tooth and core flux densities

For a given total flux, the dimension of slots determine the tooth density and the depth of stator laminations below the slots determines the core flux density. The iron loss in tooth and core depend upon their respective flux densities, and high values of flux densities in these parts will give rise to high iron losses. Also higher values of flux densities require a large number of ampere-turns to send the flux through teeth and yoke. The maximum value of flux densities in teeth and core are taken as 1.65 and 1.4 Wb/m^2 respectively.

2.7. Selection of number of stator and rotor slots

The total number of stator slots should be a multiple of three for a three phase machine. The larger the number of slots for a given diameter, the smaller will be the slot pitch resulting in narrow teeth. Thus the teeth may become mechanicall week and the flux density in teeth may become excessively high. The minimum value of slot pitch for large induction motors is generally taken 20 to 25 mm.

For squirrel cage motors, careful design of the rotor is necessary to avoid vibration and noise, cogging or locking torque and synchronous cusps in the speed torque curve.

Cogging or locking torque is a condition of varying torque at starting for different rotor positions. The cycle of high and low torque repeats as the rotor is moved through a rotor slot pitch. Synchronous cusps are points on the speed torque curve where motor locks into step at low speed and runs as a synchronous motor over a wide range of torque values. The minimum point on the torque curve may be so low that the rotor can not come up to full speed even at no load. These undesirable characteristics are largely due to harmonics in the air gap flux wave. Since the stator and rotor slots produce harmonics in the air-gap flux it is important that a proper number of rotor slots be chosen in relation to the number of stator slots, to avoid these undesirable characteristics. To limit vibration and noise number of rotor slots, S_2, should not exceed 1.25 times number of stator slots S_1. S_1 must not be equal to S_2 to prevent locking torque. Noise, vibration and synchronous cusps can be avoided if the difference $(S_1 - S_2)$ is not taken equal to ± 1, ± 2, $\pm (p\pm 1)$, $\pm (p\pm 2)$, $\pm P$, $\pm 2P$, $\pm 3P$ and $\pm 5P$. Therefore, number of rotor slots are selected, taken into consideration the above factor. The minimum value of S_2 is taken as 20% less than S_1.

2.8. Selection of Air gap length

The airgap is a mere clearance between stator and rotor so that rotor may rotate freely. Considering the performance of machine, the airgap length should be as small as possible, as the large airgap length will cause large magnetising current hence poor power factor. But for mechanical difficulties in large induction motor there should be sufficient clearance between stator and rotor, in order to avoid any contact between stator a rotor surfaces. The general expression used for calculating airgap length is,

$$\ell_g = 0.2 + 2\sqrt{DL} \text{ mm} \quad \ldots\ldots\ldots \quad (2.5)$$

Where D and L are expressed in meters. For overcoming mechanism difficulties 0.1 mm is added to this length as the motor is large sized.

2.9. Fixing of starting torque, maximum or pull out torque and maximum current

The induction motor is inherently a low starting torque motor due to the fact that it draws excessive current during starting. As the starting torque is directly proportional to the square of starting current, the increase in the value of starting torque slightly will result in very high increase in starting current. Hence a balance is obtained between starting current and starting torque. Fixing a high value of maximum permissible current the high starting torque may be obtained. In our design the maximum permissible starting current is taken upto 600% the full load current to obtain at least 100% of full load torque as starting torque.

The maximum or pull out torque of the motor is the value of torque beyond which motor will break down. Pull out torque determines the overload capacity of motor. Pull out torque should be such that motor may take overloads due to fluctuations and other normal reasons but should not be very high as the higher value of pull out torque will result in increased losses and hence less efficiency. In the design the pull out torque is fixed at 200% the full load torque.

2.10. Deep Bar effect

Due to the skin effect, the resistance of thick and deep conductors changes with the change in frequency. The variation of rotor frequency gives a means of changing the effective rotor resistance, since an inductive impedance losses almost all of its reactance at the low frequencies common to induction moto rotors when operating at normal slip. But during starting the slip is very high (Unity at standstill) resulting in high frequency in rotor conductors which in turn results in increased rotor impedance. Hence the rotor impedance may be considered as variable during the course of motor speeding up from standstill to its normal operating value of slip.

For calculating this rotor impedance a formula is given by Adkins(18) as,

$$Z_b = \frac{1}{Y}\sqrt{\frac{w\mu_o}{2}(1+j)\frac{(\sin h\ 2\theta - j\ \sin 2\theta)}{(\cos h\ 2\theta - \cos 2\theta)}} \quad \ldots\ldots. \quad (2.6$$

$$\text{Where } \theta = h\sqrt{\frac{w\mu_o}{2}} \quad \ldots\ldots\ldots \quad (2.7$$

Where y is the constant width of rotor slot

h is depth of slot

w is angular frequency of rotor bars = $2\pi sf$

μ_o is permeability of air

and is specific resistivity of rotor bars.

2.11. Fixing the bore diameter for different sets of No.of poles

The bore diameter is fixed by varying the ratio pole arc to pole pitch,

$$\frac{L}{D/p} = \psi \quad \ldots\ldots\ldots\ldots \quad (2.8)$$

So when P is varied, ψ will vary and so the stack length for fixing the bore diameter. The ratio ψ should not go beyond 3, to ensure good design. If the ratio ψ is beyond 3, it will lead to unbalanced machine and poor power factor.

2.12. General design procedure

The flow chart, using synthesis approach of design, is developed in figure 2.1. The description of the flow chart, blockwise, is as under:

B-1 - In this block the specifications of motor like kilowatt rating, efficiency, power factor, number of poles and constraints values like pull out torque, starting torque, permissible tempera ture rise and flux densities in stator and rotor teeth are fed. Initial values of variables and the values of assigned parameters are set here.

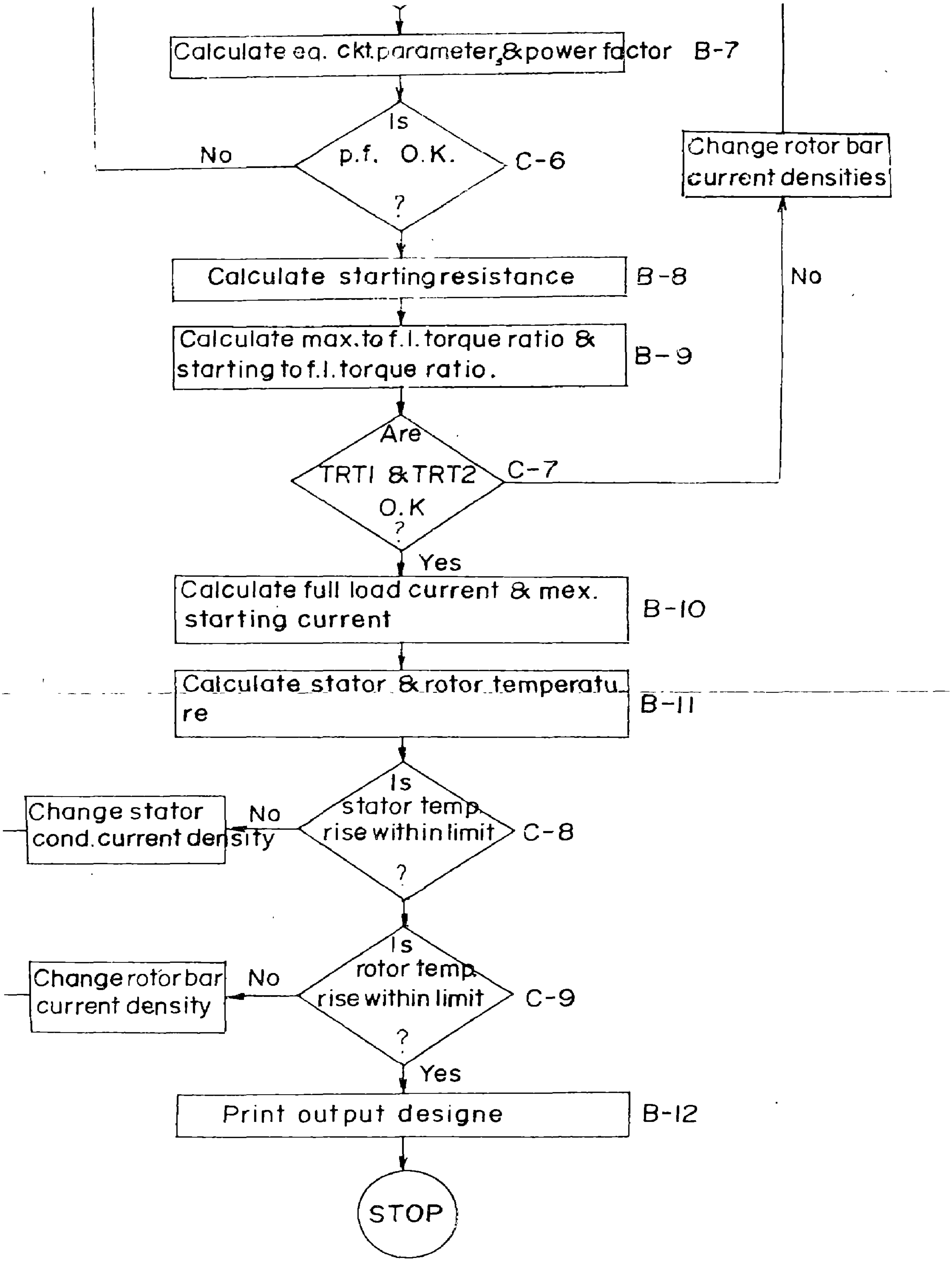
B-2 - In this block the following equations are fed to calculate the values of bore diameter and stack length of the machine.

The output coefficient

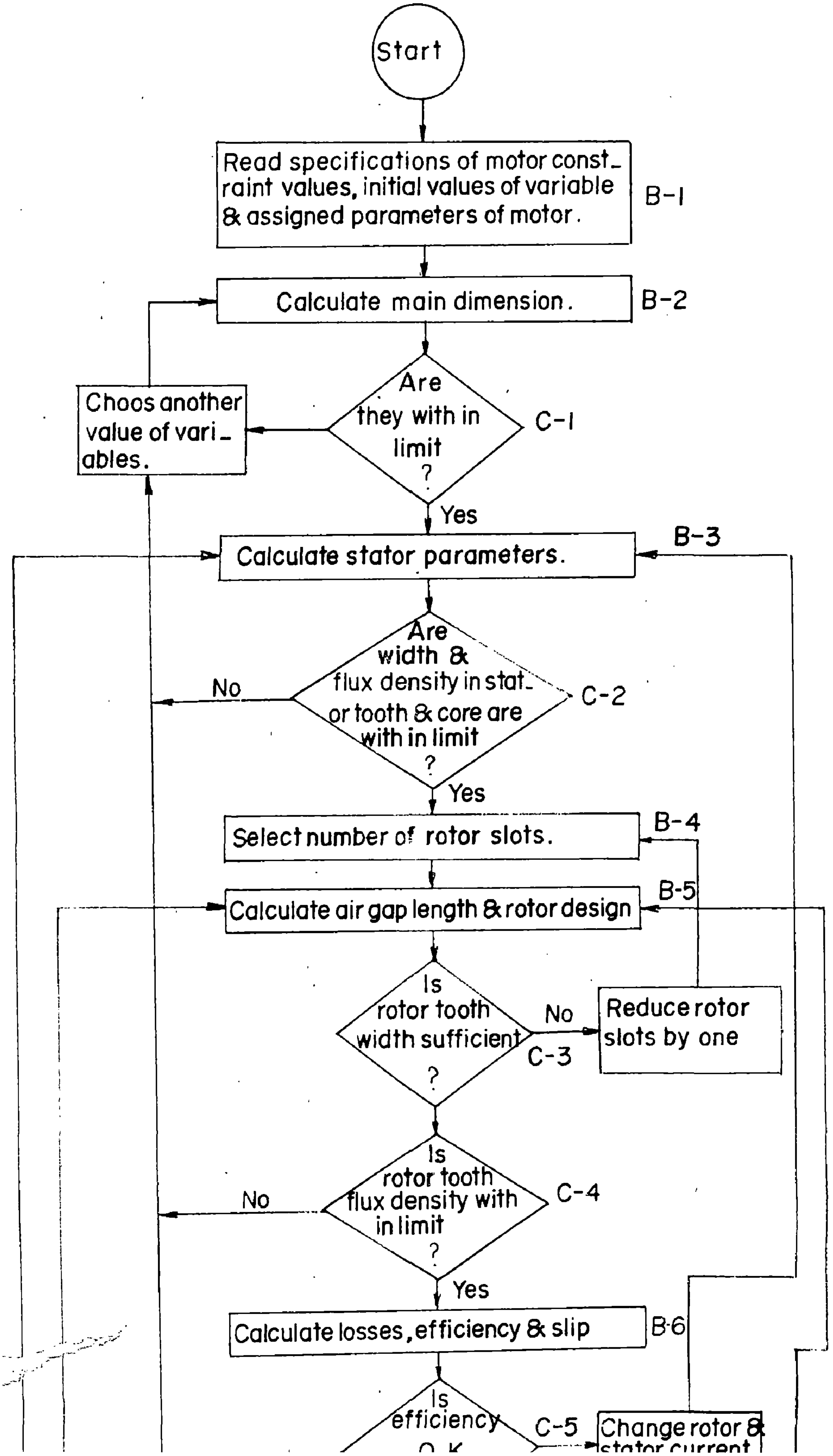
CO = .011 *AKW *BAV *AC .... (2.9)

SYN = 2 * 50/POL .... (2.10)

RKVA = RKW/(PF *EFF) .... (2.11)



OW CHART FOR DESIGNE SYNTHESIS OF INDUCTION
TOR.


Start
Read specifications of motor constraint values, initial values of variable & assigned parameters of motor.
B-1
Calculate main dimension.
B-2
Are they with in limit ?
C-1
Choos another value of variables.
Yes
Calculate stator parameters.
B-3
Are width & flux density in stator tooth & core are with in limit ?
No
C-2
Yes
Select number of rotor slots.
B-4
Calculate air gap length & rotor design
B-5
Is rotor tooth width sufficient ?
No
C-3
Reduce rotor slots by one
Is rotor tooth flux density with in limit ?
No
C-4
Yes
Calculate losses, efficiency & slip
B-6
Is efficiency O.K
C-5
Change rotor & stator current

$$DIA = \sqrt[3]{RKVA * POL/(CO * SYN * PR * \pi)} \quad \ldots\ldots \quad (2.12)$$

$$SLTH = PR * \pi * DIA / POL \quad \ldots\ldots\ldots\ldots \quad (2.13)$$

After calculating the stack length, the net iron length is calculated taken into account the space occupied by cooling ducts and stacking factor for laminations.

$$SLTNI = STKF * (SLTH - ND * WD) \quad \ldots\ldots\ldots \quad (2.14)$$

B -3 - In this block the following equations are fed to calculate stator parameters:

$$FLUX = BAV * \pi * DIA * SLTH /_{POL} \quad \ldots\ldots \quad (2.15)$$

$$TS = ES/(4.44 * 50 * FLUX * AKW) \quad \ldots\ldots \quad (2.16)$$

Here the number of slots per pole per phase QS, has to be decided by designer. They are generally kept between 2 to 5, taking higher values for smaller number of poles.

Total number of stator slots

$$S1 = 3 * POL * QS \quad \ldots\ldots\ldots\ldots \quad (2.17)$$

Stator slot pitch

$$YSS = \pi * DIA / S1 \quad \ldots\ldots\ldots\ldots \quad (2.18)$$

Stator conductors per slot

$$ZSS = 6 * TS/S1 \quad \ldots\ldots\ldots\ldots \quad (2.19)$$

Stator current per phase

$$CI\ 1 = RKVA * 1000/3 * ES \quad \ldots\ldots\ldots \quad (2.20)$$

At this point the current density in stator conductors has to be selected by designer suitably.

Area of stator conductor

$\mathrm{CONA} = \mathrm{CI}\ 1 / \mathrm{DELTA}$ .... (2.21

Taking a suitable value of slot factor (depending upon insulation needed).

Area of stator slot = Area occupied by conductors in slot/slot factor

$\mathrm{ASS} = \mathrm{ZSS} * \mathrm{CONA} / \mathrm{SLF}$ .... (2.22

AX is the ratio stator slot depth to width which is fixed by designer at an initial value. Hence depth of stator slot -

$\mathrm{DSS} = \sqrt{\mathrm{ASS} * \mathrm{AX}}$ .... (2.23

and $\mathrm{WSS} = \mathrm{ASS} / \mathrm{DSS}$ .... (2.24

ASS, DSS and WSS are in m.m.

Stator tooth width

$\mathrm{TWS} = \mathrm{YSS} - .001 * \mathrm{WSS}$ .... (2.25

After calculating thestator tooth width, the flux density in stator tooth may be calculated. Stator tooth is the part of stator where flux density is maximum (Being a low reluctance path) The flux in this part are about 1.5 times flux per pole (less than $\pi/2$ times on account of saturation). So,

$\mathrm{BT}\ 1 = 1.5 * \mathrm{FLUX}/(\mathrm{S1} * \mathrm{TWS} * \mathrm{SLTNI}/\mathrm{POL})$ .... (2.26

depth of stator core

$$DCS = (OD - DIA - .001* DSS)/2 \quad .... \quad (2.27)$$

Where OD is outer diameter, whichis fixed for a standard frame size.

Flux density in stator core

$$BCS = FLUX / DCS * SLTNI \quad .... \quad (2.28)$$

B-4 - In this block the number of rotor slots are so selected that smooth starting and accelerating conditions are obtained as discussed in Article 2.7. For this purpose the initial value of number of rotor slots are taken equal to 1.25 time S1, and thi is modified until the following conditions are obtained -

$$S2 - S1 \neq 0, 1, 2, POL, POL \pm 1, POL \pm 2, 2* POL, 3* POL, \text{ and } 5* POL \quad .... \quad (2.29)$$

The minimum value of number of slots should not go below .8 S1.

B-5 - In this block the air gap length and rotor parameters are calculated with the help of following equations -

Air gap length

$$AGL = 0.3 + 2* \sqrt{DIA* SLTH} \text{ mm.} \quad .... \quad (2.30)$$

Where DIA and SLTH are in meters.

(The air gap length is generally given by the expression replacing 0.3 by 0.2 in above expression but in present case

0.1 mm additional gap is added due to mechanical difficulties faced by large sized machine with small air gap length).

Rotor diameter

RDIA = DIA - .002 * AGL .... (2.31)

Rotor slot pitch

YRS = π * RDIA/S2 .... (2.32)

Rotor bar current(19)

CIB = 0.85 * 6 * CI 1 * TS/S2 .... (2.33)

Area of each bar

BARA = CIB/DELB .... (2.34)

Rotor tooth width and slot width is taken equal as per standard practice.

WRS = TWR = 1000* YRS/2 .... (2.35)

In the rotor slot, 1 mm clearance is left in slot width and 3 mm in slot depth to determine the bar area, hence depth of rotor bar -

DRB = BARA/(WRS-1) .... (2.36)

and depth of rotor slot is

DRS = DRB + 3 .... (2.37)

As in the stator tooth, the flux in rotor tooth is also 1.5 time that of main flux, and so the flux density in rotor tooth is given as,

$$BT2 = 1.5 * FLUX/_{(S2 * TWR * 0.001 * SLTNI/POL)} \ldots\ldots (2.38)$$

The rotor bars are skewed. Extending the bars by about 2 cm. beyond the core on each side and taking 1 cm. as increase in length because of skewing, length of rotor bar

$$BLTH = SLTH + .05 \quad m. \quad \ldots\ldots\ldots \quad (2.39)$$

End ring current:- The end ring current lags behind the rotor bar current by $\pi/2$ and is given by following relationship(19),

$$CIE = S2 * CIB / \pi * POL \quad \ldots\ldots\ldots \quad (2.40)$$

The current density in end rings is taken same as that in rotor bars. So end ring area

$$ERAR = CIE / DELB \quad \ldots\ldots\ldots \quad (2.41)$$

The end ring strip of depth DE and thickness TE is used. The depth and thickness ratio is fixed as,

$$DE = TE + 3, \quad mm. \quad \ldots\ldots \quad (2.42)$$

Outer dia of end ring

$$DEO = RDIA - .002 * DRS \quad \ldots\ldots \quad (2.43)$$

Inner dia. of end ring

$$DEI = DEO - .002 * DE \quad \ldots\ldots \quad (2.44)$$

Mean dia. of end rings is taken as average of outer and inner diameters.

Depth of rotor core is taken equal to depth of stator core.

Inner dia of rotor stamping - Allowing for an axial ventilating duct of 70 mm width in rotor to allow air circuit through rotor, the inner dia of rotor stampings is

$$RSID = RDIA - .002 * DRS - 2 * DCS - .07 \quad \ldots\ldots \quad (2.45)$$

B -6 - In this block the process of performance evaluation of the designed machine begins. Here the no load current, no load power factor, losses and efficiency are calculated.

No load current :-

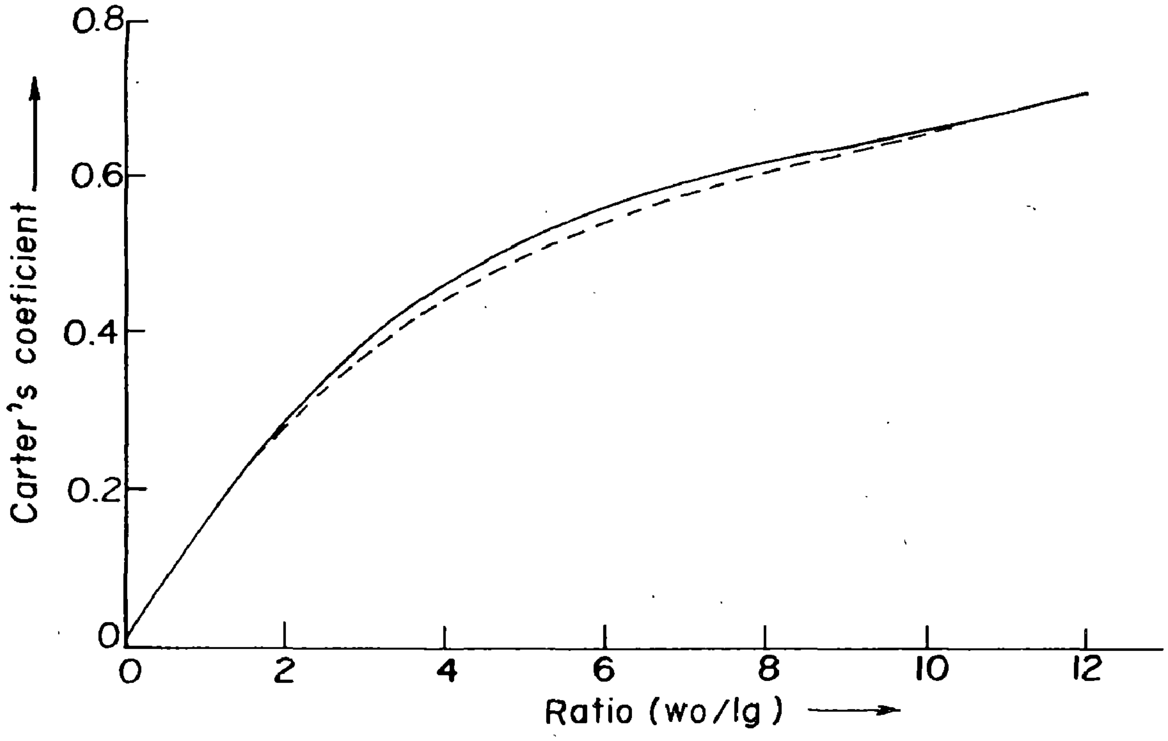
(a) Magnetising current :- In order to calculate magnetising component of no load current, the m.m.f. required for various parts of magnetic circuit of machine are calculated as below:

(i) Air gap :- For the purpose of calculating air gap m.m.f. the distribution of air gap flux is assumed to be over the whole slot pitch except for a fraction of slot width as shown in figure (2.2). This fraction depends upon the ratio of slot widtl to air gap length.

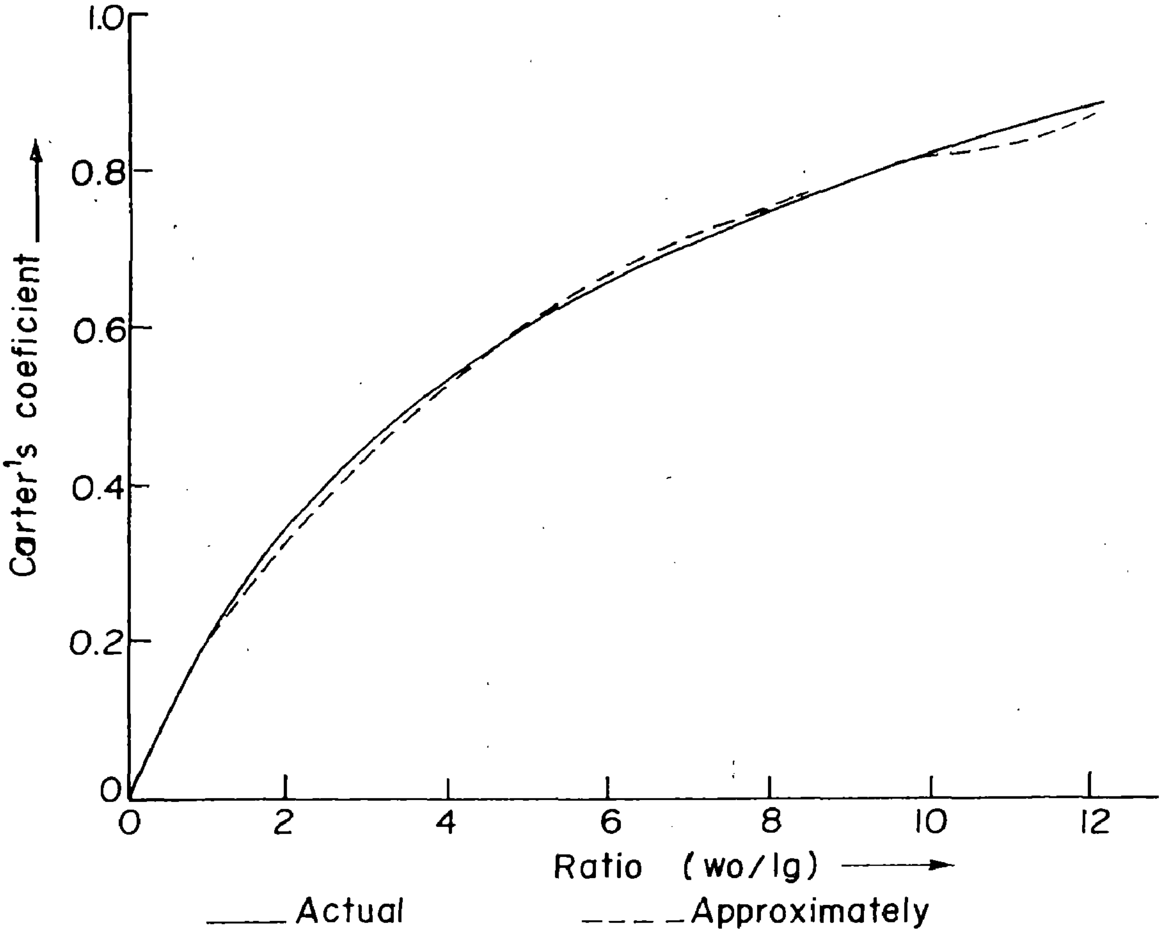
The effective or contracted slot pitch is given as

$$YSS' = YSS - CGCS * WSO$$

Where CGCS is carter's gap coefficient, which depends upon the ratio slot width/gap length. Standard curves are available to give the value of carter's gap coefficient(19). The curve is approximated by the following equation for the



(a) OPEN SLOT



(b) SEMI ENCLOSED SLOT

FIG.2.2 CARTER'S CURVES.

purpose of computer solution

$$CGCS = {}^{1}/_{(1 + 3.5 * AGL / WSO * .001)} \quad .... \quad (2.46)$$

Reluctance of air gap with slotted armature

$$R'_{gs} = {}^{AGL}/_{\mu_o} * YSS' * SLTH$$

and the reluctance of air gap with smooth armature

$$R_{gs} = {}^{AGL}/_{\mu_o} * YSS * SLTH$$

The ratio of reluctance of air gap of slotted armature to reluctance of air gap with smooth armature is known as gap contraction factor. So the gap contraction factor for stator slot

$$GCFS = {}^{YSS}/_{(YSS - CGCS * WSO)} \quad .... \quad (2.47)$$

Similarly carter's gap coefficient and gap contraction factor for rotor slot are given as,

$$CGCR = {}^{1}/_{(1 + 3.5 * AGL/WRS * .001)} \quad ...... \quad (2.48)$$

$$GCFR = {}^{YRS}/_{(YRS - CGCR * WRS * .001)} \quad ...... \quad (2.49)$$

For ventilating ducts we may assume half the gap length on stator side and half on rotor side. So the carter's gap coefficient and gap contraction factor for ducts are -

$$CGCD = {}^{1}/_{(1 + 3.5 * AGL/_{2} * WD)} \quad .... \quad (2.50)$$

$$GCFD = {}^{SLTH}/_{(SLTH - CGCD * ND * WD)} \quad ...... \quad (2.51)$$

Total gap contraction factor is given as,

$$GCFT = GCFS * GCFR * GCFD \quad \ldots\ldots\ldots \quad (2.52)$$

Effective air gap length, taking into account, the gap contraction factor -

$$EAGL = GCFT * AGL \quad \ldots\ldots\ldots \quad (2.53)$$

The flux density in the air gap is taken as 1.36 times, the average flux density, BAV, to take into account the saturation and skew by 60°. Hence air gap m.m.f(19) -

$$ATG = 800000 * 1.36 * BAV * EAGL / _{1000} \quad \ldots\ldots\ldots \quad (2.54)$$

(ii) Stator teeth :- Width of stator teeth at $1/3^{rd}$ height from narrow end

$$WTS = \quad * (DIA + .002 * DSS/3) /_{S1} - WSS * .001 \quad ..(2.55)$$

Area of stator teeth per pole at $1/3^{rd}$ height

$$AST = S1 * WTS * SLTNI/POL \quad \ldots\ldots\ldots \quad (2.56)$$

Flux density considering effect of saturation

$$BTSS = 1.36 * FLUX/_{AST} \quad \ldots\ldots\ldots \quad (2.57)$$

Corresponding to this the m.m.f. per metre SATST is to be seen from the curve in figure (2.3). But for the purpose of computer solution the curve is approximated by equations as given in Table 2.1.

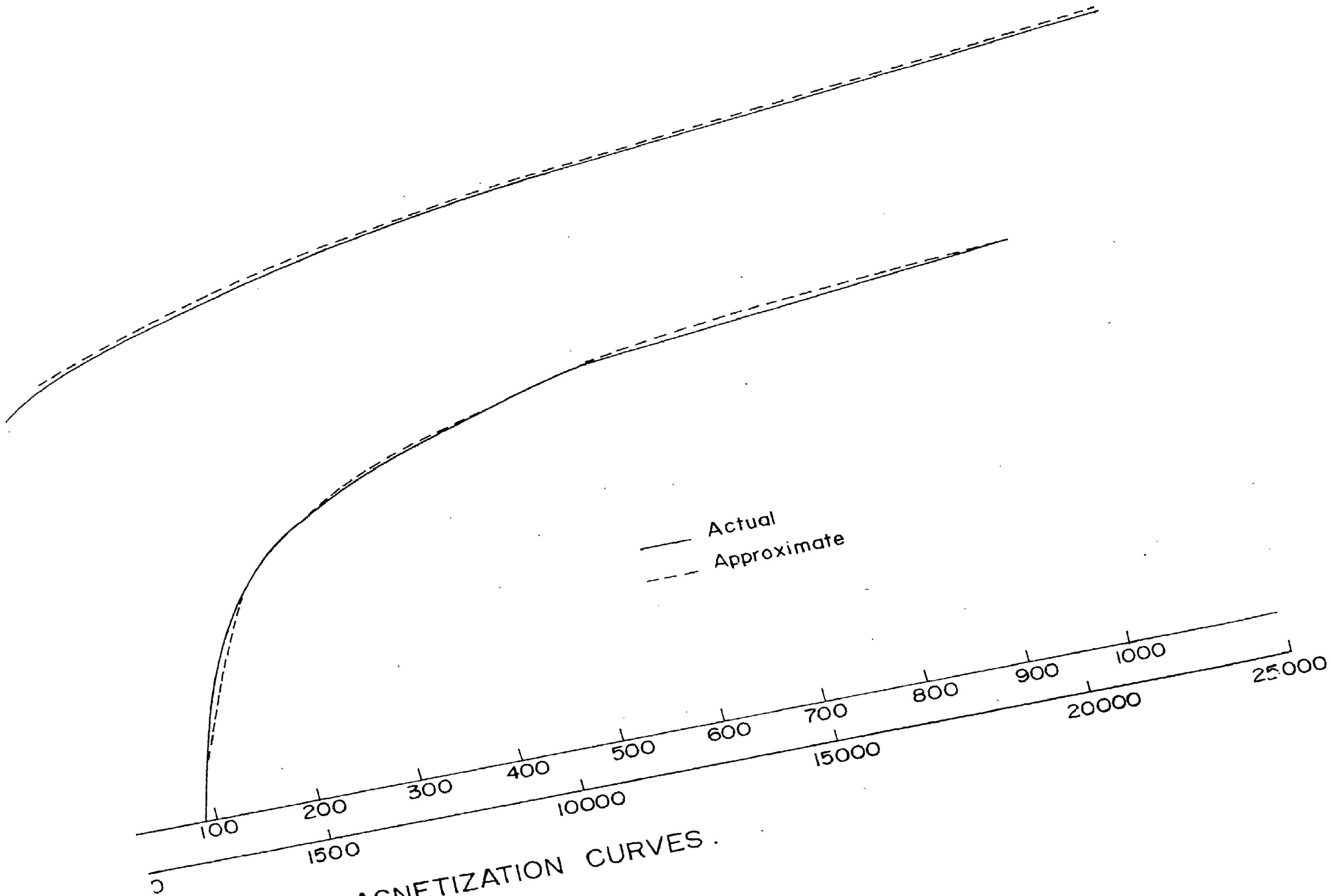


FIG.2.3 MAGNETIZATION CURVES.

Hence the total m.m.f. required for stator teeth are -

$$ATST = SATST * .001 * DSS \quad .... \qquad (2.58)$$

(iii) Stator core :- The flux density in stator core is BCS (equation 2.28), corresponding to this flux density the m.m.f. per metre SATSC are calculated as per Table 2.1. This m.m.f. has to be multiplied by length of flux path through stator core which is -

$$SCPATH = \pi * (DIA + .002 * DSS + DCS)/\ 3 * POL \quad ..(2.59)$$

Hence m.m.f. required for stator core,

$$ATSC = SATSC * SCPATH \quad .... \qquad (2.60)$$

(iv) Rotor teeth :- Width of rotor teeth at 1/3rd height from narrow end

$$WRT = \pi * (RDIA - .004 * DRS/3)/_{S2} - .001 * WRS..(2.61$$

Area of rotor teeth per pole at 1/3rd height ......

$$ART = S2 * WRT * SLTNI/POL \quad ...... \qquad (2.62$$

Flux density in rotor teeth considering effect of saturation

$$BTRS = 1.36 * FLUX\ /_{ART} \quad .... \qquad (2.63$$

Corresponding to this flux density the m.m.f. per metre SATRT is calculated as per table 2.1. Total m.m.f. required for rotor teeth.

$$ATRT = SATRT * DRS * .001 \quad ...... \qquad (2.64)$$

(v) Rotor core :- Flux density in rotor core is taken to be same as that in stator core i.e. BCS and hence m.m.f. per metre is also same as SATSC. This m.m.f. has to be multiplied by length of flux path through rotor core which is

RCPATH = π * (RDIA - .001 * DRS - DCS) / 3 * POL.... (2.65)

M.M.F. required for rotor core

ATRC = SATSC * RCPATH .... (2.66)

Total m.m.f. requirement of the motor -

TAT = ATG + ATST + ATSC + ATRT + ATRC ...... (2.67)

Magnetising current per phase(19)

CIM = 0.427 * POL * TAT $/_{AKW}$ * TS ...... (2.68)

Table 2.1

Range of flux density FD Wb/m^2	Corresponding equation
0 to 0.6	AT = 91.8 * FD + 45.0
0.6 to 1.0	AT = 200.0 * FD - 20.0
1.0 to 1.45	AT = 6.444 * EXP (3.2 * FD)
1.45 to 1.7	AT = 0.0052 * EXP (8.1 * FD)
1.7 to 2.0	AT = 0.687 * EXP (5.23 * FD)

(b) <u>Loss component</u> :- The loss component of the current is being calculated as under.

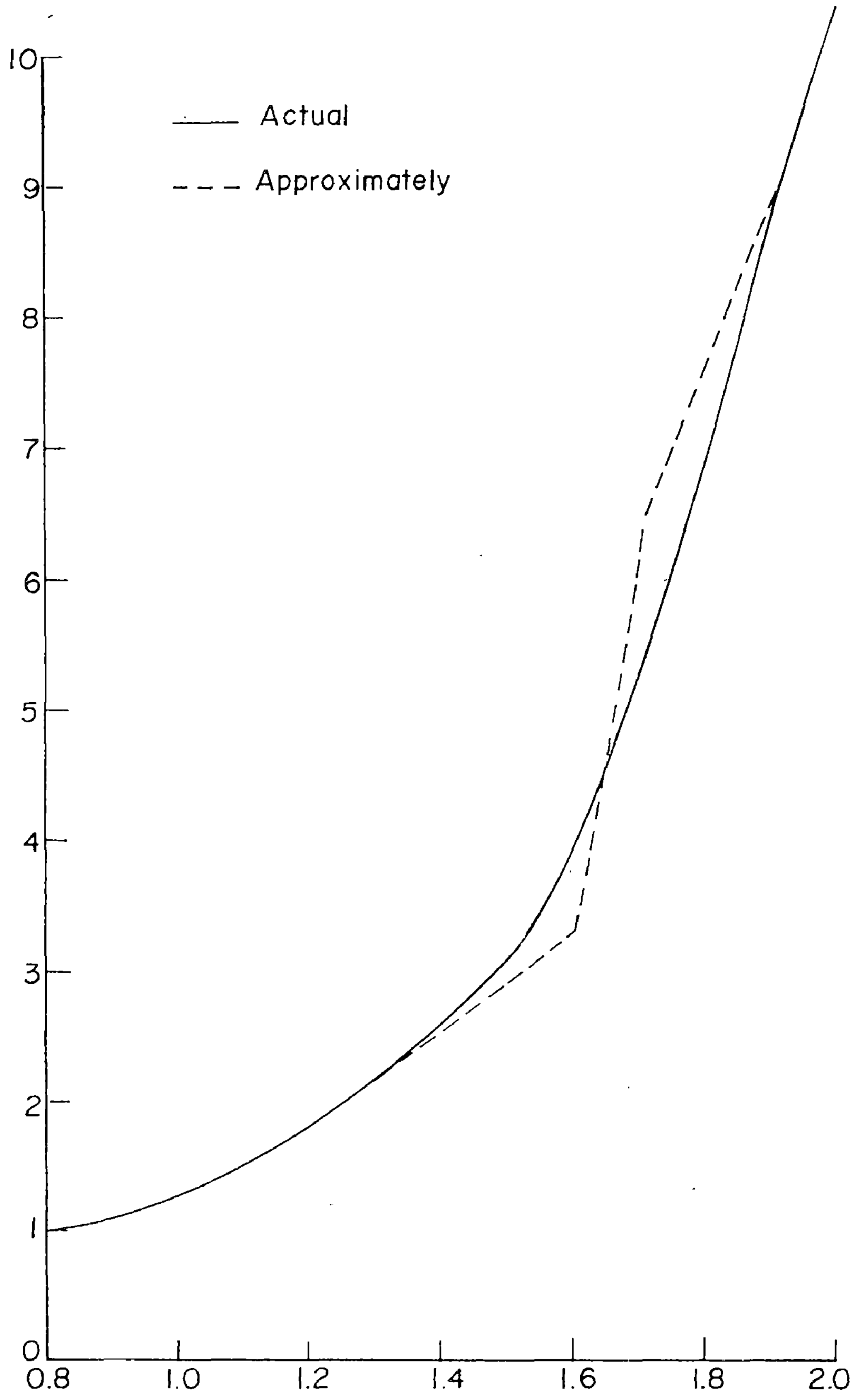


FIG.2.4 CORE LOSSES

Mean width of stator teeth

$$TWM = \pi * (DIA + .001 * DSS) /_{S1} - .001 * WSS \quad .... \quad (2.69)$$

Weight of stator teeth

$$WTST = DENI * S1 * TWM * SLTNI * DSS * .001 \quad ...... \quad (2.70)$$

Maximum flux density in teeth at 1/3rd height

$$BTSM = \pi * FLUX /_{2} * AST \quad .... \quad (2.71)$$

Corresponding to this flux density the loss per Kg, SPLST, is determined by the curve in figure 2.4. The curve is approximated by square rule upto flux density 1.6 Wb/m^2 and by cube rule beyond that value, for computer solution. Hence iron loss in stator teeth

$$LIST = SPLST * WTST \quad .... \quad (2.72)$$

Mean periphery of stator core = * (OD - DCS)

Weight of iron in stator core -

$$WTCI = DENI * \pi * (OD-DCS) * DCS * SLTNI \quad ..... \quad (2.73)$$

Flux density in stator core is BCS (equation 2.28) corresponding to this flux density the loss per Kg SPLC is determined by square rule.

Iron loss in stator core

$$LIC = SPLC * WTCI \quad .... \quad (2.74$$

Allowing the loss in joints etc. the total iron losses are taken double the combined iron losses in stator teeth and core. Therefore

$$TIL = 2 * (LIST + LIC) \quad .... \quad (2.75$$

Friction and windage losses are taken as 1% of output power. Hence,

$$FWL = 10 * RKW \quad \ldots\ldots\ldots \qquad (2.76)$$

Total no load loss

$$NLL = TIL + FWL \quad \ldots\ldots\ldots \qquad (2.77)$$

Loss component of no load current, per phase

$$CIL = NLL/_{3} * _{ES} \quad \ldots\ldots\ldots \qquad (2.78)$$

No load current

$$CINL = \sqrt{(CIM)^{2} + (CIL)^{2}} \quad \ldots\ldots\ldots\ldots \qquad (2.79)$$

No load power factor

$$PFNL = CIL/_{CINL} \quad \ldots\ldots\ldots \qquad (2.80)$$

The magnetising reactance

$$XM = ES/CIM \quad \ldots\ldots\ldots \qquad (2.81)$$

The resistance due to core losses

$$RM = ES/_{CIL} \quad \ldots\ldots \qquad (2.82)$$

<u>Copper losses</u> :-

Mean length of stator conductor

$$SCML = SLTH + 1.15 * \pi * DIA/_{POL} + .012 \text{ m} \quad \ldots\ldots \qquad (2.83)$$

Length of conductor per phase

$$SCLP = 2 * SCML * TS \quad \ldots\ldots \qquad (2.84)$$

Stator resistance per phase

$$RS = .021 * SCLP/_{CONA} \quad \ldots\ldots \qquad (2.85)$$

Where .021 is specific resistivity of copper in Ohm-mm^2.

Total stator copper loss

$$SCLOS = 3 * RS * (CI1)^2 \quad \ldots\ldots\ldots \quad (2.86)$$

Resistance of each rotor bar

$$RB = .021 * BLTH/_{BARA} \quad \ldots\ldots\ldots \quad (2.87)$$

Copper losses in bars

$$BCLOS = S2 * RB * (CIB)^2 \quad \ldots\ldots\ldots \quad (2.88)$$

Resistance of each end ring

$$RE = .021 * \pi * DEM/_{ERAR} \quad \ldots\ldots\ldots \quad (2.89)$$

Copper loss in two end rings

$$ECLOS = 2 * RE * (CIM)^2 \quad \ldots\ldots\ldots \quad (2.90)$$

Rotor copper loss

$$RCLOS = BCLOS + ECLOS \quad \ldots\ldots\ldots \quad (2.91)$$

Total copper loss

$$TCLOS = SCLOS + RCLOS \quad \ldots\ldots\ldots \quad (2.92)$$

Efficiency $EFF = {}^{RKW * 1000}/_{(RKW * 1000 + TCLOS + NLL)} \ldots\ldots (2.93)$

and

$$SLIP = RCLOS/_{(RKW * 1000 + RCLOS + FWL)} \quad \ldots\ldots \quad (2.94)$$

B-7 - In this block the equivalent circuit parameters and full load power factor are calculated. The equivalent circuit of cage induction motor is shown in figure (2.5). The parameters RS, RM, XM and slip are already calculated in block 6. The remaining parameters are RSR, XS and XR.

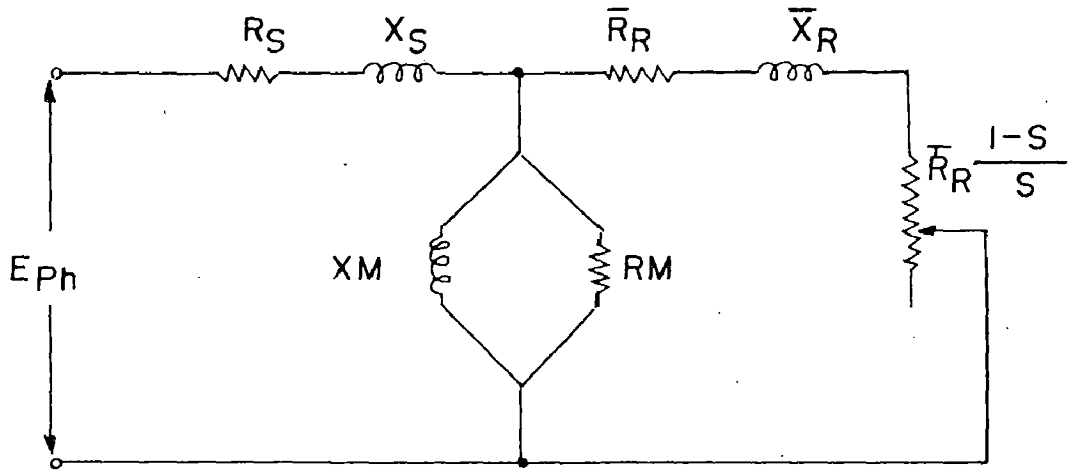


FIG.2.5 EQUIVALENT CIRCUIT OF INDUCTION MOTOR.

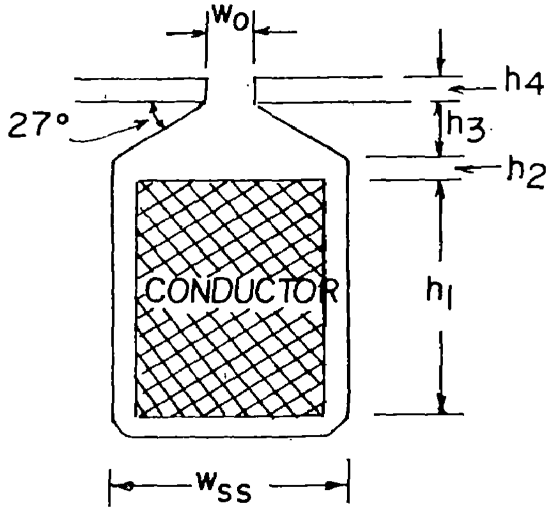


FIG.2.6 STATOR SLOT CONSIDERED.

The total rotor resistance

$$RROT = S2 * RB + 2 * RE \quad \ldots\ldots\ldots \quad (2.95)$$

To determine transforming ratio to transform rotor resistance to stator side, a cage can be considered as a polyphase winding in which there are S2 conductors connected in pairs a pole pitch apart to form (S2/2) phases of one turn each (20). In a cage rotor the transformation ratio can be determined as -

$$TFR = 3*TS*AKW/_{(S2/_{POL})} * (POL/_2)$$

or $$TFR = 6*TS * AKW/_{S2} \quad \ldots\ldots\ldots\ldots \quad (2.96)$$

Stator referred rotor resistance per phase

$$RSR = RROT*(TFR)^2/_3$$

To calculate reactance the height occupied by conductor portion in the slot is H1 as shown in figure (2.6). H1 may be given as(1

$$H1 = \sqrt{ZSS*CONA*AX} \quad \ldots\ldots\ldots \quad (2.97)$$

H3 and H4 may be taken as 3.5 m.m. and 1 mm respectively this gives

$$H2 = DSS - H1 - H3 - H4 \quad \ldots\ldots\ldots \quad (2.98)$$

Specific slot permeance for stator slot is given by(19)

$$PSS = \mu_0 * (H1/_{3*WSS} + H2/_{WSS} + 2*H3/_{(WSS+WSO)} + H4/_{WSO}) \ldots . (2.99)$$

The stator slot leakage reactance now may be calculated as

$$SSLR = 8*\pi*50*(TS)^2 * SLTH*PSS/_{(POL*QS)} \quad \ldots\ldots\ldots \quad (2.100)$$

Similarly for calculating rotor slot leakage reactance HR1 may be taken same as depth of rotor bar, while HR2, HR3 and HR4 are taken as .75 mm, 1.75 mm and .5 mm respectively.

Specific slot permeance for rotor slot is

$$PRS = \mu_o * (HR1/_{3*WRS} + HR2/_{WRS} + HR3/_{WRS} + HR4/_{WRS}) \; ..... \qquad (2.101)$$

The specific slot permeance has to be referred to stator side in order to calculate rotor leakage reactance referred to stator side. Hence rotor slot specific slot permeance referred to stator side is -

$$RPRS = PRS * (AKW)^{2} * S1/S2 \; .... \qquad (2.102)$$

Rotor slot leakage reactance as referred to stator side now may be calculated as,

$$RSLR = 8 * \pi * 50 * (TS)^{2} * SLTH * RPRS/_{(POL*QS)} \; ...... \qquad (2.103)$$

The permeance of overhang portion is given by,

$$OP = \mu_o * (\pi * DIA)_{POL})^{2}/_{\pi} * YSS \; .... \qquad (2.104)$$

(Assuming full pitch winding)

The overhang leakage reactance is

$$OLR = 8 * \pi * 50 * (TS)^{2} * OP/_{(POL*QS)} \; .... \qquad (2.105)$$

The zig zag leakage reactance is given by equation,

$$XZ = 5 * XM/_{6*(3)^{2}} * ((1/_{QS})^{2} + (1/_{QR})^{2}) ...... \qquad (2.106)$$

Here the number of rotor slots per pole per phase may be calculated as,

$$QR = S2/_{3*POL} \quad \ldots\ldots\ldots \quad (2.107)$$

The differential leakage reactance is ignored for squirrel cage induction motor.

Total leakage reactance of machine

$$XL = SSLR + RSLR + OLR + XZ \quad \ldots\ldots\ldots \quad (2.108)$$

Total stator leakage reactance

$$XS = SSLR + 0.5*OLR + XZ \quad \ldots\ldots\ldots \quad (2.109)$$

And total rotor leakage reactance, referred to stator side,

$$XR = RSLR + 0.5 * OLR \quad \ldots\ldots\ldots \quad (2.110)$$

Hence all the equivalent circuit parameters are determined.

Now the equivalent circuit may be solved by dividing it into three part in order to determine the full load power factor.

(i) Stator circuit impedance $ZS = RS + j\ XS$

(ii) Rotor circuit impedance $ZR = RSR/_{SLIP} + j.XR$

(iii) Magnetic circuit impedance ZM

$$ZM = {}^{j\ RM*\ XM}/_{(RM\ +\ j\ XM)}$$

$$= RM*(XM)^2 + j(RM)^2*XM/_{\ (RM)^2 + (XM)^2}$$

This may be written as,

$$ZM = G1 + j\ G2$$

Where

$$G1 = RM*(XM)^2/\ (RM)^2+(XM)^2 \quad \ldots\ldots\ldots \quad (2.111)$$

and

$$G2 = (RM)^2*XM/\ (RM)^2+(XM)^2 \quad \ldots\ldots\ldots \quad (2.112)$$

Now solving the parallel combination of rotor and magnetic circuit, the impedance comes to be,

$$ZRM = G3 + j\ G4$$

Where

$$\begin{aligned} G3 = {} & (RSR*G1/_{SLIP} - XR*G2)*(RSR/_{SLIP} + G1) \\ & + (RSR*G2/_{SLIP} + XR*G1)*\ (XR+G2)/ \\ & (RSR/_{SLIP}+ G1)^2 + (XR + G2)^2 \quad \ldots\ldots\ldots \quad (2.113) \end{aligned}$$

and

$$\begin{aligned} G4 = {} & (RSR/_{SLIP} + G1)*(RSR*G2/_{SLIP}+ XR*G1) - \\ & (XR+G2)*(RSR*G1/_{SLIP} - XR*G2)/\ (RSR/_{SLIP}+ G1)^2 \\ & + (XR + G2)^2 \quad \ldots\ldots \quad (2.114) \end{aligned}$$

The total series impedance referred to side can now be expressed as,

$$\begin{aligned} Z1 &= RS + j\ XS + G3 + j\ G4 \\ &= (RS+G3) + j\ (XS + G4) \end{aligned}$$

Full load power factor may now be calculated as,

$$PFFL=(RS+G3)/\ (RS+G3)^2+\ (XS+G4)^{2\ \frac{1}{2}} \quad \ldots\ldots\ldots\ldots \quad (2.115)$$

B-8 - In this block the starting resistance of rotor is calculated, taking into consideration the deep bar effect. The deep bar effect is discussed in article (2.10). The bar impedance may be calculated using equation (2.6) and (2.7).

$$\mathrm{BIMP} = \mathrm{BLTH}/_{\mathrm{WRS}} * \sqrt{\pi * 50 * \mu_0 * .021 * (1+J) * (\mathrm{SINH}(2*\mathrm{THETA}) - J\ \mathrm{SIN}(2*\mathrm{THETA})) / (\mathrm{COSH}(2*\mathrm{THETA}) - \mathrm{COS}(2*\mathrm{THETA}))} \quad \ldots\ldots\ldots\ldots \quad (2.116)$$

Where

$$\mathrm{THETA} = .001*\mathrm{DRB}* \sqrt{\pi * 50 * \mu_0/.021} \quad \ldots\ldots\ldots \quad (2.117)$$

Now separating real and imaginary terms the bar resistance at the time of starting,

$$\mathrm{BRS} = \mathrm{REAL}\ (\mathrm{BIMP}) \quad \ldots\ldots\ldots \quad (2.118)$$

Total rotor resistance at the time of starting

$$\mathrm{SRROT} = \mathrm{S2} * \mathrm{BRS} + 2 * \mathrm{RE} \quad \ldots\ldots\ldots \quad (2.119)$$

Transforming it to stator side, the stator referred rotor resistance per phase at the time of starting

$$\mathrm{SRSR} = \mathrm{SRROT} *(\mathrm{TFR})^2/3 \quad \ldots\ldots\ldots \quad (2.120)$$

B-9 - In this block the full load torque, pull out torque and starting torque are calculated. Let C1 be the effect of magnetising branch on torque of motor. This effect is approximated as,

$$\mathrm{C1} = 1 + \frac{\mathrm{RS}}{\mathrm{RM}} + \mathrm{XS}/_{\mathrm{XM}} \quad \ldots\ldots\ldots \quad (2.121)$$

The full load torque is given by the equation(17),

$$TFL = \frac{3*(ES)^2* RSR/SLIP}{(RS+C1 * RSR/_{SLIP})^2 + (XS+C1 * XR)^2} \quad \ldots\ldots \quad (2.122)$$

At the time of starting the SLIP is unity and the rotor resistance will be replaced by its value at the time of starting. Thust starting torque is,

$$TST = \frac{3*(ES)^2* SRSR}{(RS+C1 * SRSR)^2 + (XS + C1 * XR)^2} \quad \ldots\ldots\ldots \quad (2.123)$$

The p.u. starting torque is given by the ratio of starting torque to full load torque thus,

$$TRT1 = TST/_{TFL} \quad \ldots\ldots\ldots \quad (2.124)$$

The slip corresponding to maximum torque is given by(21) -

$$S_{Cr} = RSR/\sqrt{(RS)^2 + (XS + XR)^2}$$

Substituting this value in equation (2.122), the maximum or pull out torque may be calculated,

$$TMAX = \frac{3*(ES)^2}{2*C1 * RS+ \sqrt{(RS)^2 + (XS + C1*XR)^2}} \quad \ldots\ldots\ldots \quad (2.125)$$

The ratio maximum torque to full load torque is called p.u. maximum torque,

$$TRT2 = TMAX/_{TFL} \quad \ldots\ldots\ldots \quad (2.126)$$

B-10 - In this block the ratio starting current to full load current is calculated. The full load current is given by relationship,

$$CIFL = ES/\sqrt{(RS+C1 * RSR/SLIP)^2 + (XS + C1 * XR)^2} \quad ...(2.127$$

The starting current may be calculated by replacing RSR by SRSR and putting SLIP = 1,

$$CIST = ES/\sqrt{(RS + C1 * SRSR)^2 + (XS + C1* XR)^2} \quad ..... (2.128$$

The ratio starting current to full load current is,

$$STCR = CIST /_{CIFL} \quad .... \quad (2.129$$

B-11 - In this block the stator and rotor temperature rise are calculated. For determining the temperature rise the cooling coefficients for various portions of machine are taken from Table (2.2),(20).

For stator temperature rise -

Outside cyllindrical surface of stator

$$SSO = * OD * SLTH \quad .... \quad (2.130$$

cooling coefficient for outside surface CO = 0.033
(from table 2.2)
Inside cyllindrical surface of stator

$$SSI = * DIA * OHL \quad .... \quad (2.131$$

Where overhang length

$$OHL = SLTH + 0.0254 *(.001 * ES + 3.0 + YSS/4) ....(2.132$$

Relative peripherial speed of inner surface

$$SPS = \quad * DIA * SYN \quad \ldots\ldots\ldots \tag{2.133}$$

Cooling coefficient for inner surface

$$SCI = .033/_{(1 + 0.1 * SPS)} \quad \ldots\ldots\ldots \tag{2.134}$$

Surface of ventilating ducts

$$SSD = \quad * ((OD)^2 - (DIA)^2) * (2 + ND) / 4 \ldots\ldots \tag{2.135}$$

Cooling coefficient for ventilating ducts,

$$SCD = 0.15/_{0.1} * SPS \quad \ldots\ldots\ldots \tag{2.136}$$

Total stator loss

$$SLOS = SCLOS * SLTH/_{SCML} + TIL \quad \ldots\ldots\ldots \tag{2.137}$$

Stator temperature rise

$$STRISE = SLOS/_{(SSO/_{SCO} + SSI/_{SCI} + SSD/_{SCD})} \ldots\ldots \tag{2.138}$$

Table 2.2

Part	Cooling coefficient	Speed	Remarks
Cyllindrical surface of stator and rotor	$\frac{.03 \text{ to } .05}{1 + .1\,u}$	Relative peripherial speed	Lower figures for forced cooling
Back of stator core	.025 to .04	0	-
Rotating field coils	$\frac{.08 \text{ to } .12}{1 + .1\,u}$	Armature peripherial speed	Based on total coil surface.
-do-	$\frac{.06 \text{ to } .08}{1 + .1\,u}$	-do-	Based on exposed coil surface only.
Ventilating ducts in cores	$\frac{.08 \text{ to } .2}{u}$	Air velocity in ducts	u can be taken as 10% of peripherial veloci of core.

For rotor temperature rise

Outside cyllindrical surface of rotor

$$\mathrm{RSO} = \pi * \mathrm{RDIA} * \mathrm{SLTH} \quad \ldots\ldots\ldots\ldots \tag{2.139}$$

Cooling coefficient of outside rotor surface

$$\mathrm{RCO} = .033/(1 + .1 * \mathrm{RPS}) \quad \ldots\ldots\ldots \tag{2.140}$$

Where

$$\mathrm{RPS} = \pi * \mathrm{RDIA} * \mathrm{SYN} \quad \ldots\ldots\ldots \tag{2.141}$$

Surface of ventilating ducts

$$\mathrm{RSD} = \pi * ((\mathrm{RDIA})^2 - (\mathrm{RSID})^2) * (2 + \mathrm{ND})/_4 \quad \ldots\ldots \tag{2.142}$$

Cooling coefficient for ventilating ducts

$$RCD = 0.15 /_{0.1} * RPS \qquad \ldots\ldots\ldots\ldots \qquad (2.143)$$

Rotor temperature rise

$$RTRISE = \frac{(RCLOS + FWL)}{RSO/_{RCO} + RSD/_{RCD}} \qquad \ldots\ldots\ldots \qquad (2.144)$$

B-12 - Here the output is printed.

In blocks C-1 to C-8, the various constraints are checked as given in blocks.

2.13. Cost of active materials

Weight of iron in stator teeth and core is already calculated in preceding sections. Weight of iron in rotor,

$$WTRI = DENI * SLTNI * \pi * (RDIA)^2 - (RSID)^2 / 4$$

$$- (S2 * DRS * WRS * 10^{-6})$$

$$\ldots\ldots\ldots \quad (2.145)$$

Total iron cost

$$TIC = CI * (WTST + WTCI + WTRI) \qquad \ldots\ldots\ldots \qquad (2.146)$$

Where CI is the specific cost of iron.

Weight of stator winding

$$WTSW = \text{Volume of winding in } m^3 * \text{ Density in } Kg/m^3$$

So

$$WTSW = ZSS*CONA * SCML * 6 * TS * DENC * 10^{-6} \ldots\ldots \qquad (2.147)$$

Weight of rotor winding

$$WTRW = (S2 * BARA * BLTH + 2 * \pi * ERAR * DEM) * DENC * 10^{-6} \quad \ldots\ldots\ldots \quad (2.148)$$

Thus the cost of winding

$$TCW = CC * WTSW + CR * WTRW \quad \ldots\ldots\ldots\ldots \quad (2.149)$$

Where 'CC' is specific cost of winding material. Total cost of active materials

$$TC = TIC + TCW \quad \ldots\ldots\ldots \quad (2.150)$$

2.14. CONCLUSION

With the design procedure given in this chapter, the general design of induction motor is formulated and from this design the one value of bore diameter is suitably fixed, for the series. The cost of active materials for unoptimized motor is also estimated here.

Chapter - 3

" OPTIMIZATION TECHNIQUES "

****

3.1. Introduction

In this chapter, the different optimization techniques, suitable for application to induction motor design problem, selected on the basis of critical survey of the optimization techniques(17), are discussed. The factors governing the choice of optimization technique are considered in deciding a particular method to solve the problem.

3.2. Optimization techniques

From the basis of literature survey(17), the available methods for the solution of nonlinear programming problems can be categorised in three different types as (i) One dimensional minimizations, (ii) Constrained minimization methods and (iii) Unconstrained minimization methods. These can be further classified into two groups - direct and indirect methods as shown in table (3.1).

Considering one dimensional methods, the use of analytical method for this design optimization problem is difficult since the functions are not directly differentiable and hence numerical methods are to be employed for differentiating the objective and constraints functions. Interpolation methods are efficient than elimination methods but they fail to converge at global minimum if the function is a multimodel one. The simplest method which can give reasonably accurate results by approximately fixing the step size is incremental search method. In this method an ordered search from a given starting point considering each variable in turn, is conducted using a fixed step size. Hence this method, though inefficient, is considered for application to optimize induction motor design.

The constrained minimization techniques, for non-linear function and constraints, are more justified to select. In this category, amongst the direct methods, cutting plane method requires convex programming problem with objective function and constraints as nearly linear functions and hence cannot be used. Feasible directions methods are more effective for the problems using linear constraints or for linear programming problems. For this reason Box's complex method and Rosenbrock's method can conveniently be applied to the induction motor design problem. In Box's complex method, a new method of constrained optimization devised by Box(22) in 1965, a general nonlinear function of several variables and constraints is described and solved. It is claimed there, that this method is efficient as compared to existing methods. The efficiency of using effective constraints to eliminate variables is demonstrated, and a program to achieve this easily and automatically is described. The method of rotating coordinates was presented by Rosenbrock(24), which resembles with the earlier method named pattern search method and given by Hooke and Jeeves(25). The pattern search method is a sequential technique, each step of which consists of two types of moves, one called the explorato move and the other called the pattern move. Exploratory move explores the local behaviour of the objective function and the second move takes the advantage of the pattern directions.

This method does not require to calculate the derivatives of the function and quadratic convergence criterion gives fast convergence than earlier methods although the global minimum is not guaranteed. The method is applicable to unconstrained problems.

The Rosenbrock's method can be considered as further development of pattern search method. The method rotates the coordinate system in each stage during the process of minimization, in such a way that the first axis is directed towards the locally estimated direction of the valley and all the other axes are made mutually orthogonal and normal to the first one. The evaluation of derivatives is not necessary in this method and is applicable only to unconstrained problems. To start with, the feasible design is needed and optimization process starts from the given point taking the variables in sequence. The direction of search for the variables is the direction of respective coordinate axis. In the event of a success, i.e., the current point design giving better optimum, the step size in the next cycle is enlarged by a factor $\alpha > 1$. During failure, the step size is reduced by a factor β $(0 < \beta < 1)$ in the reversed direction in the next cycle. The stage is completed when atleast one success and one failure in each direction is encountered. In the next stage the optimization process starts from the best point in the previous cycle. This method has proved to be very efficient in convergence but it assumes the function to be unimodel and hence for functions with multimodel nature the method is to be started with several starting points and the best solution selected. A detailed study presented by Box(23) resulted in concluding that the complex method is likely to be more reliable than Rosenbrock's method for highly nonlinear (multimodel) functions.

Amongst indirect methods the transformation of variabl method requires, constraints as simple functions of variables and thus can not be used with problems like induction motor design optimization. Penalty function methods are varsatile in application and can solve any optimization problem. This metho converts the constrained optimization problem into alternative form in such a way that numerical solutions are sought by solving a sequence of unconstrained minimization problem.

Some methods using penalty function approach are discussed here. Carrol(26), presented a method based upon this approach in 1961. He has converted the original objective function of constrained nature, into unconstrained modified objective function by augmenting a penalty term to original objective function. He described the new objective function as

$$P\ (X,\ r_K) = F(X) - r_K \sum_{j=1}^{m} \frac{1}{g_j(X)} \quad \ldots\ldots\ldots \quad (3.1)$$

Where r_K is a penalty parameter. Expression (3.1) shows that the value of function 'P' will always be greater than the value of 'F' since for all feasible values of X, the penalty term will always be negative. If any of the constraints is satisfied critically, i.e., $g_j(X)=0$, the value of 'P' then tends to infinity. The shortcoming of the equation (3.1) is that the penalty term is not defined for infeasible X. The method requires a starting feasible point and derivatives of the functions. Interior penalty is imposed to solve the problem so that r_K is re-evaluated every time in a monotonically decreasing order $r_1 > \gamma_2 > \gamma_3 \ldots, > \gamma_K > 0$ and as r_K becomes sufficientl small 'P' approaches X and the problem is converged.

The method presented by Fletcher and Powell(27) in 1963 has made use of derivatives in their rapidly convergent descent method for minimization. This method is very stable and continues to progress towards the minimum even for highly distorted and ecentric functions. The stability of this method can be attributed to the fact that it carries the information obtained in previous iterations through positive definite symmetric matrix.

The sequential unconstrained minimization technique (SUMT) for nonlinear programming problem was developed by Fiacco and McCormicks'(28). They extended the approach of Carrol in a more general way. The penalty function approach by them differs in selecting the penalty term. The modified objective function formulated is of the form -

$$P(X,\gamma) = F(X) - \gamma \sum_{j=1}^{m} \log (g_j) + \sum_{j=m+1}^{m+p} l_j^2/\gamma \quad \ldots\ldots(3.2)$$

Where r is the penalty parameter. Three terms on the right hand side pertain to the original objective function, inequality constraints and equality constraints respectively. As the algorithm progresses the value of r is re-evaluated to form a monotonically decreasing sequence $r_1 > r_2 - - - > 0$. As r becomes small, 'P' approaches 'F' and the solution is sought. Equation (3.2) is of general nature and any problem can be fitted for solution. An unconstrained problem means m=0, p=0, only equality or inequality constraints exist depending upon whether m=0 or p=0. Interior penalty function method does not necessarily demand the feasible starting point but the algorithm searches for feasible design.

In the method given by Waren et al.(29) in 1967, the modified objective function is of the form,

$$P\,(X,\ F, r\,) = F + r \sum_{j=1}^{m} \frac{1}{g_j(X, F)} \quad \ldots\ldots\ldots \qquad (3.3)$$

In this case F is assumed to be both objective function and independent parameter. The starting point violates the constraints so that reasonably good initial design can be found. However, the method does not guarantee the constraint satisfaction.

3.3. Choice of optimization technique

Several factors have to be considered in deciding a particular method to solve a nonlinear programming problem. Some of them are:

(i) Nature of the problem to be solved and required accuracy.

(ii) The running time costs to solve the desired optimization problems.

(iii) The expected reliability of the program in finding the desired solution.

(iv) The generality of the program, necessity of derivatives previous knowledge of the methods and their efficiency etc.

(v) The time necessary for preparation of the program. Available programmes, if any, for direct use or improvement.

(vi) The ease with which the program can be used and its output interpreted.

Amongst the optimization technique discussed previousl the incremental search method, though easy to program and gives good results, makes exhaustive search for optimum solution by evaluating the objective function and constraints functions at each point. Hence the method is slow in convergence and require large computational time. Rosenbrock's method has been found very effective in convergence(15). However, it does not guarante global optimum for multimodel functions. Complex Box method makes a search for optimum point by randomly scattering, the points throughout the feasible range and hence gives better optimum. The convergence of this method is found tobe very fast, and also this method is simple to program. Penalty function method, though more systematic in approaching the optimum point, the method is useful only if the number of variables are large as it is a little complicated method. With a small number of variables, as used in the present problem, the complex Box method has been found to be better than penalty function method. For these reasons the complex Box method is selected as the optimization method for the present problem.

3.4. CONCLUSIONS

The selection of complex Box method as the optimization method has been made after discussing different optimization techniques, on the basis of critical literature survey. It has also been stated that if the number of variables goes high, the penalty function method will be more appropriate method for optimization of induction motor.

Table 3.1 Nonlinear optimization methods

1. One dimensional minimisation
   - Analytical methods(Differential calculas methods - function should be differentiable)
   - Numerical methods
     - Elimination
       - (i)Unrestricted search
       - (ii)Exhaustive search
       - (iii)Dichotomous search
       - (iv)Fibonnaci method
       - (v)Golden section method
     - Interpolation
       - Requiring derivatives
         - (i) Cubic
         - (ii) Direct root
       - Requiring no derivatives (Quadratic)
2. Constrained minimization techniques
   - Direct methods
     - (i)Complex Box method
     - (ii)Cutting plane
     - (iii)Feasible directions
     - (iv)Rosenbrock's method
   - Indirect methods
     - Transformation of variables
     - Penalty function
       - Interior
       - Exterior
3. Unconstrained minimization methods
   - Direct methods
     - (i)Random search
     - (ii)Univariate Powell's
     - (iii)Pattern search Hooke and Jeeves
     - (iv)Simplex
     - (v)Rosenbrock's method of rotating coordinates.
   - Descent methods (derivatives are required)
     - (i)Steepest descent
     - (ii)Conjugate gradient
     - (iii)Newton's method
     - (iv)Variable metric method

4.1. Introduction

In the design optimization of the series of frame designed induction motors the main and foremost task is to develop objective function. The whole process of optimization is based upon formulation of objective function. There may be many objective functions in the design of induction motors based upon which parameter has to be optimized e.g., cost optimization, weight optimization etc. Here the objective function is based upon the cost optimization. Each machine of the series is being optimized separately for minimum cost of active material and using same value of bore diameter. The cost of whole series then considered as a whole using a weightage function for each machine. The weightage function is based upon the cost, the manufacturing constraints and the market value for each machine. The complex Box algorithm has been presented in this chapter.

4.2. Statement of Problem

The problem under consideration has been found to be a nonlinear one with several constraints of inequality type imposed on it. The variables selected are the continuously varying type. The problem can be stated mathematically as,

$$\text{Minimize } F(V_1, V_2, ---, V_N)$$

$$\text{Subject to } G_K \leqslant V_K \leqslant H_K, \quad K=1,2,---, M.$$

Where $V_1, V_2, - - -, V_N$ are explicit, independent variables of continuous type, and $V_{N+1}, - - -, V_M$ are implicit variables which are functions of explicit independent variables. G_K and H_K are the lower and upper limits of explicit and implicit variables.

4.3. Objective Function

In the present problem there are two different objective function has been formulated:

(i) The objective function for every machine in the series.

(ii) The combined objective function for whole series.

In the first part the cost of active material for each machine has been considered as objective function. The cost of active material has been calculated as in article (2.13). This consists of cost of iron stampings and the cost of winding materia on stator and rotor. The cost of iron has been taken as Rs. 15 per Kg. and the cost of copper as Rs. 100 per Kg. and Rs. 70 per Kg. for stator and rotor conductors respectively. The objective function for each machine f_1, f_2, f_3 etc. are minimized independently within the constraints.

After getting minimum values of f_1, f_2, f_3 etc. the objective function for whole series has been evaluated using two approaches:

(i) Giving weightage functions to each machine in the series - The objective function by giving weightage function is calculated as follows(30):

$$F(x) = \alpha_1 \; F_1(x) + \alpha_2 \; F_2(x) + \alpha_3 \; F_3(x)$$

Where $\alpha_1, \alpha_2, \alpha_3$ etc. are the assigned weightage parameters depending upon the cost, manufacturing constraints and the demand for each machine. The minimum value of F(x) is approached.

(ii) Taking root mean square of all individual functions - The objective function is evaluated taking root mean square of all individual objective functions

$$F(x) = \sqrt{F_1^2(x) + F_2^2(x) + F_3^2(x) - - -}$$

The combined objective function evaluated by two approaches above is assessed for the minimum value. Corresponding to the minimum the values of F_1, F_2, F_3 etc. are compared to the individual minimum values of F_1, F_2, F_3 etc.

4.4. Constraints

In any production process the manufacturer has to produce the product with the material available to the satisfaction of the customer and within the scope of national and international standards. Thus the selection of constraints for induction motor design is a matter of mutual agreement between the customer, manufacturer and national and international standards. The constraints imposed upon the design in the present case are as follows: as per usual practice by manufacturers,

(a) Maximum flux density in stator and rotor teeth	1.65 Wb/m^2
(b) Slot fullness factor	0.4
(c) Full load efficiency	92%

(d) Full load power factor	0.8
(e) p.u. starting torque	1.0
(f) p.u. maximum torque	1.5
(g) p.u. starting current	6.0
(h) Full load stator and rotor temperature rise	75°C

4.5. Complex Box Algorithm

Inthe Box's complex method, several feasible points are generated using random numbers, corresponding to a starting feasible point. The simplex so formed is then moved towards the optimum point by reflecting the worst point every time till the minimum is sought. This means that during the process of optimization a critical search has been made by scattering the feasible points throughout the specified range. The variables vary in a random way and finally settles down to give optimum value. Basically the method is a sequential search technique which has proven effective in solving problems with nonlinear objective functions subject to nonlinear inequality constraints.

The algorithm for finding out minimum active materials cost, subject to nonlinear inequality constraints, which are functions of design variables chosen, using complex Box method proceeds as follows:-

Step 1 - Pick up starting feasible point

Step 2 - Generate an original complex of $K = (N+1)$ points consisting of feasible starting point and $(K-1)$

additional points generated from random numbers and constraints for each of the independent variables

$$X_{i,j} = G_i + r_{i,j}\,(H_i - G_i)$$

Where $i = 1, 2, ---, N$

and $j = 1, 2, ---, (K-1)$

$r_{i,j}$ are random numbers between 0 and 1

Step 3 -Check explicit constraints. If violated go to step 4, otherwise go to step 5.

Step 4 -Move the point a small distance inside the violated limit.

Step 5- Check implicit constraints. If violated go to step 6, otherwise go to step 7.

Step 6- Move the point one half of the distance into the centroid of the remaining points as follows;

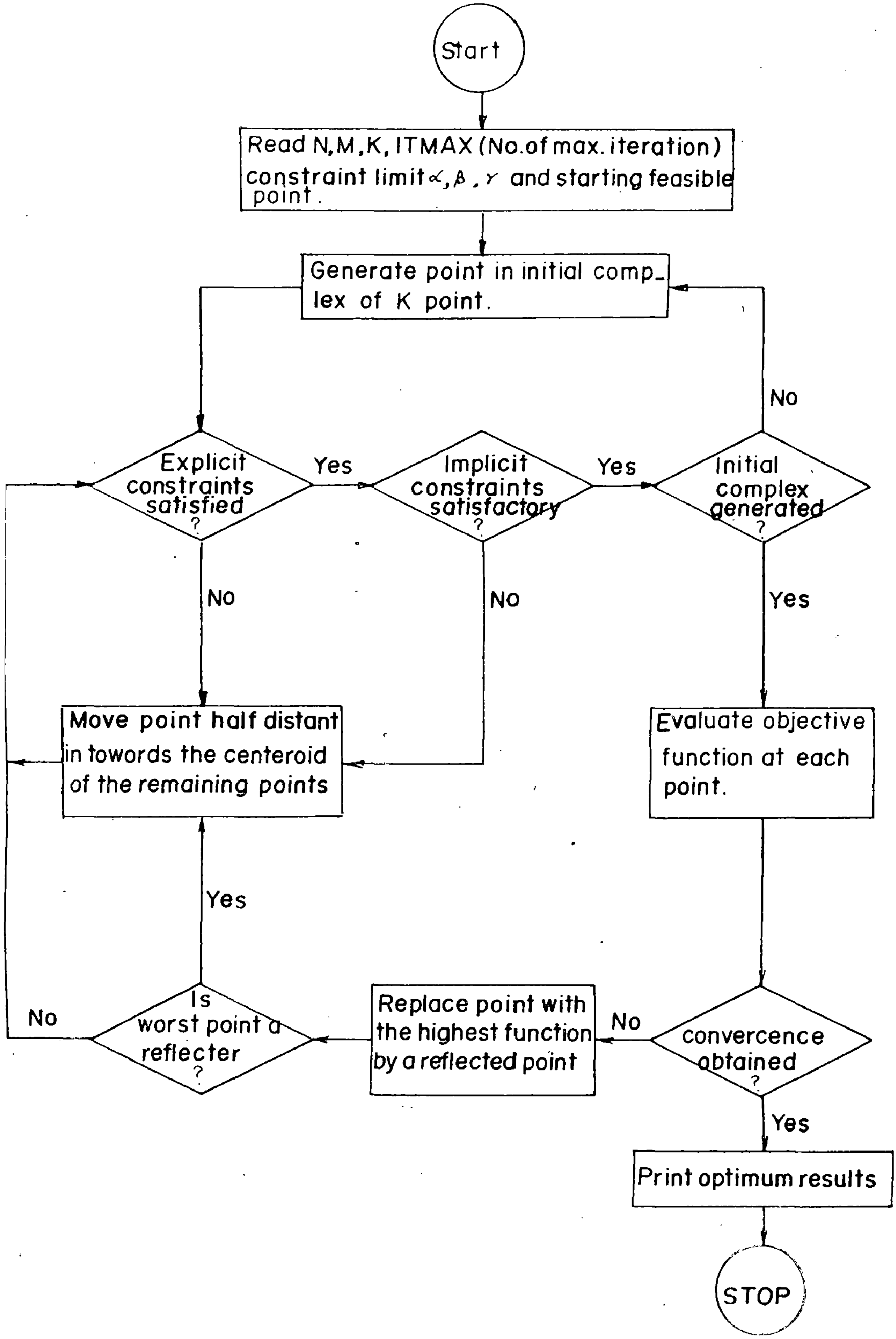
$$X_{i,j}\text{ (new)} = 0.5\,(X_{i,j}\text{ (old)} + \bar{X}_{i,c})$$

Where $i=1, 2, ---, N$.

And the coordinates of the centroid of the remaining points, $\bar{X}_{i,c}$, are defined as

$$\bar{X}_{i,c} = \frac{1}{K-1}\left(\sum_{j=1}^{K} X_{i,j} - X_{i,j}\text{ (old)}\right)$$

Go to step 3, i.e.repeat the procedure until all the implicit constraints are satisfied.



IG.4.1 COMPUTER FLOW CHART FOR COST MINIMIZATION OF CAGE INDUCTION MOTOR USING COMPLEX BOX METHOD.

Step 7 - Is initial complex generated? If yes, go to step 8, otherwise go to step 2.

Step 8 - Evaluate objective function at each point.

Step 9 - Check convergence

(Convergence is assumed when the objective function values at each point are within predecided limit for consecutive prescribed number of itrations. An iteration is defined as the calculations required for selecting a new point which satisfies the constraints and does not repeat in yielding the highest function value). If converged go to step 12, otherwise go to step 10.

Step 10 - The point having the highest function value is replaced by a point which is located at a distance α times as far from the centroid of the remaining points, as the distance of the rejected point and the centroid, and is given by -

$$x_{i,j}\,(\text{new}) = \alpha(\,\bar{x}_{i,c} - x_{i,j}(\text{old})\,) + \bar{x}_{i,c}$$

Step 11 - Check whether the worst point is a repeater, If so go to step 6, otherwise go to step 3.

Step 12 - Print optimum results

Step 13 - Stop

The computer flow chart is shown in figure 4.1.

4.6. CONCLUSIONS

In this chapter the optimization problem has been stated in mathematical form. The objective function is formulated firstly for individual machines of series and then a combined objective function is formulated, using two approaches, namely weightage function approach and root mean square method. The complex Box algorithm and a flow chart for complex Box method of optimization has been given in the end.

5.1. Introduction

In this chapter the results obtained for induction motor design optimization and the series optimiation are compiled and discussed. The results of series optimization obtained using root mean square value of objective function and by assigning the weightage function, are compared with the result of individual design of induction motors. The cost of normal design is also compared with that of individually optimized motors.

5.2. Results and specifications

The specifications and results of individual optimization of five motors of the series to be optimized, are tabulated in tables 5.1 and 5.2 respectively. The specifications also include the assigned parameters which are fed as input values. The value of bore diameter is fixed at .71 m for all the motors in the series. This value is determined by general design procedure. The results of optimized design of individual motors include the values selected for variables, final values of constraints and objective function. Objective function is the cost of active materials for individual motor.

In table 5.3 the cost of active materials with normal design, individual optimization and the cost of each machine, corresponding to optimized series objective functions, are tabulated. Series objective functions are obtained by two methods as described in article 4.3. The optimized cost by root mean square method is Rs. 83997, and with weightage function method is Rs.138308. The cost of each motor in the series, corresponding to these optimized values are given in table 5.3. The weightage factor has been assigned after studying the demand for each machine. It is found that the 6 pole machine is the maximum demanded machine and the 12 pole machine, the minimum. Weightage factors for each mahine are also given in table 5.3. The cost of active materials with individually optimized design is compared with the cost of active materials with unoptimized normal design. Also, the cost of active materials for each machine corresponding to series optimized cost are compared to the individually optimized costs in table 5.3.

5.3. Discussions

As is evident from table 5.3, the cost of active materials with series optimization is a little higher than the cost of individually optimized motor. This may be visualised by the fact that in series optimization some parameters are fixed which were free in individual optimization. But this increase in cost is not very high as compared to the computer time saving in the case of series optimization. If we take into account the computer time cost also, series optimization will always be found less costly than individual optimization of motors. To add to this in series optimized motor the single die-punch is required as the bore diameter is fixed, this will further reduce the overall cost of series optimized motors.

This is also evident from table 5.3 that if the whole series has to be optimized uniformly, the r.m.s. method of series optimization is better than weightage function method, as in r.m.s. method the cost of each machine uniformly increases as compared to individually optimized results. But if any of the machine in series has to be given special consideration, the weightage function method is more appropriate, as seen by the results, the increase in cost with respect to individually optimized machine largely depends upon weightage factor for that machine.

5.4. Conclusion

The results obtained are compared and discussed in this chapter and although the cost of active material of each machine corresponding to the series optimized cost is a little higher than individually optimized cost, it is concluded that the series optimization method should be preferred as a lot of computer time is saved by this method, the cost of which is more than the increase in cost of active materials.

Table 5.1

Specifications constraints and Assigned parameters

S.No.	Parameters	1	2	3	4	5
1.	No.of poles	4	6	8	10	12
2.	KW Rating	1000	700	500	350	280
3.	Voltage (KV)	6.6	6.6	6.6	6.6	6.6
4.	Stator OD (m.)	.96	.96	.96	.96	.96
5.	Efficiency	.94	.94	.94	.93	.93
6.	Power factor	.86	.84	.82	.8	.78
7.	Pull out torque(p.u)	2.0	2.0	2.0	2.0	2.0
8.	Starting torque(p.u)	1.0	1.0	1.0	1.0	1.0
9.	Permissible temperature rise	75°	75°	75°	75°	75°
10.	Permissible stack length (m.)	.56	.56	.56	.56	.56
11.	Bore diameter (m.)	.71	.71	.71	.71	.71
12.	Slot factor	0.4	0.4	0.4	0.4	0.4
13.	Slot per pole per phase	5	4	3.5	3	2.5
14.	Average air gap flux density	0.5	0.5	0.49	0.47	0.46
15.	Ampere conductors per metre	36500	36500	36500	33500	32500
16.	Winding factor	.955	.955	.955	.955	.955

Table 5.2

Optimized results of individual motors

S.No.	Parameters	1	2	3	4	5
1.	PR	0.9	1.4	1.9	2.5	3.0
2.	AX	3.5	3.5	3.5	3.5	3.5
3.	DELTA	7.6	7.8	7.5	7.4	7.1
4.	DELB	8.2	8.0	8.3	8.1	7.9
5.	SLTH	0.5	0.52	0.53	0.535	0.5575
6.	BT1	1.57	1.58	1.61	1.63	1.64
7.	BT2	1.59	1.59	1.62	1.64	1.645
8.	EFF	.955	.951	.948	.942	.931
9.	PFFL	.822	.814	.808	.79	.783
10.	TRT1	1.08	1.06	1.09	1.04	1.02
11.	TRT2	2.14	2.15	2.08	2.12	2.07
12.	STRISE	61.3	63.2	64.1	67.2	70.3
13.	RTRISE	67.5	69.9	71.5	73.2	74.5
14.	Cost of Active materials	48542	42387	35438	29135	24742

Table 5.3

Comparison of cost of individually optimized and series optimized motors.

S.No.	Machine No.	1	2	3	4	5
1.	Cost with normal design (Rs.)	50582	44507	37815	31294	26828
2.	a) Cost with individual optimization (Rs.)	48542	42387	35438	29135	24742
	b) %age variation to normal design	-4.03	-4.76	-6.28	-6.9	-7.75
3.	a) Cost with series optimization r.m.s. method (Rs.)	49127	42943	35927	29635	25087
	b) %age variation to individual optimization.	+1.2	+1.3	+1.38	+1.71	+1.4
	c) %age variation to normal design	-2.87	-3.51	-5.00	-5.3	-6.49
4.	a) Cost with series optimization-Weightage function method(Rs.)	49327	42438	36385	30714	26725
	b) Weightage factor	0.8	1.0	0.75	0.6	0.4
	c) %age variation to individual optimization	+1.62	+0.12	+2.67	+5.42	+8.01
	d) %age variation to r.m.s. method	+0.4	-1.18	+1.27	+3.64	+6.53
	e) %age variation to normal design	-2.48	-4.65	-3.78	-1.85	-0.38

Chapter -6

CONCLUSIONS

The optimization of series of induction motors has been achieved using complex Box method of optimization. The four variables selected for optimizing the series are, the ratio pole are to pole pitch, the ratio slot depth to width, stator conductor current density and rotor bar current density. The results of series optimization has been obtained and compared with individual optimization results. For series optimization the bore diameter of the series is kept same, with outer diameter already fixed for standard frames the single die punch is sufficient for cutting stampings for whole of the series.

For the design of squirrel cage motor of high rating, as in the present case, certain special features have to be employed. Firstly, the rotor bars need the special consideration. The rotor bars shoud be of special shape to meet the high starting torque requirement. Although the starting torque equal to load torque has been attained by the author, but not without affecting adversely other performance indices, such as power factor. The low value of power factor is due to the fact that deep rectangular bars are used here. The leakage reactance of such bars is quite high.

SCOPE OF FURTHER WORK

The method used inthe present work for optimizing the series, the complex Box method, needs variables to vary continuously and for this reason the standard conductor selection has not been possible in the present work. As in induction motor design the variables are continuous as well as discrete other methods (16) permitting the use of discrete as well as continuous variables may be tried to optimize the series of induction motors. The scope is also there to work with a greater number of variables to optimize the series in order to get the better designs. In dealing with greater number of variables the complex Box method is found to be inefficient development of some method using mixed integer nonlinear programming is essential.

REFERENCES

1. Vienott,C.G., "Induction Machinery Design Being Revolutionalised by the Digital Computer", Trans. A.I.E.E., Pt.III Vol.75, pp 1509-1517, 1956.

2. Abetti,P.A., Cuthbertson,W.J. and Williams,S.B., "Phylosophy of Applying Digital Computers to the Design of Electrical Apparatus", Trans. A.I.E.E.,Vol.77 Pt.i, pp.367-379, 1958.

3. Herzog,G.W., Anderson,O.W., Scrimgeour, J. & Chow,W.S., "The Application of Digital Computers to Rotating Machine Design", Trans.A.I.E.E., P.A.S.78,No.44 pp.814-829, 1959.

4. Godwin,G.L., "Optimum Machine Design by Digital Computer", Trans.A.I.E.E., PAS-78, Pt.III pp.478-488, 1958.

5. Appelbaum,J. and Erlichi,M.S.
   - (a)"A problem of Economic optimization of Electric Equipment Design", Trans. I.E.E.E. Comm. and Electronics, Vol.33, pp.773-776, 1964.
   - (b)"Optimized Parameter Analysis of an Induction Machine", Trans. I.E.E.E., PAS-84, No.11, pp.1017-1024, 1965.

6. Artanov.S.G., "Determination of Optimum parameters of Electrical Machines", Elecktrichestvo (U.S.S.R.), No.3, pp.13-18, 1966.

7. Chalmers, B.J. and Bennington,B.J., "Digital Computer Programme for Design Synthesis of Large Squirrel Cage Induction Motors", Proc. I.E.E.,Vol.114,No.2, pp.261-268, 1967.

8. Ramrathnam, R. and Desai,B.G., "Optimization of Polyphase Induction Motor Design, A Nonlinear Programming Approach", Trans. I.E.E.E., PAS-90, No.2, pp. 570-578, 1971.

9. Bhattacharya,S.C. and Mukherjee,P.K., "Optimization in the Design of an Induction Motor", J.I.E.E.(India) Elect.Engg.Div., Vol.52, No.6,pp.161-167, 1971.

10. Menzies,R.W. and Neal,G.W., 'Optimization Programme for large Induction Motor Design", Proc. I.E.E. Vol.122, No.6, pp.643-646, 1975.

11. Rajsekhar,G., Bhattacharya, M. and Mahendra,S.N., "Computer Aided Design of three phase cage Induction Motors - Design Techniques, Hybrid Process and Optimization", J.I.E.E.(India),Vol. 55, page 42, 1974.

12. Schwarz, B., "Geometrical Approach to the Economical Design of Rotating Electrical Machines", Proc. I.E.E., Vol.113, No. 3, pp. 493-499, 1963.

13. Fulton,N.N., Slaver,R.D. and Wood,W.S., "Design Optimization of small 3-phase Induction Motors", Proc.I.E.E. Vol.123, No.2, pp.141-144, 1976.

14. Ramrathnam, R., Desai,B.G. and Subbarao, V., "A Comparative Study of Minimization Techniques for Optimization of Induction Motor Design", Trans. I.E.E.E.,PAS-92,No.5, pp.1448-1454, 1973.

15. Bhardwaj,D.G., Venkatesan,K. and Saxena,R.B., "Experience with Direct and Indirect Search Methods Applied to cage Induction Motor Design Optimization", Electric Machines and Electromechanism, Vol.4, pp.85-93, 1979.

16. Bhardwaj, D.G., Venkatesan,K. and Saxena, R.B., "Cost Optimization of Frame Designed Induction Motors - A Multitechnique Approach", Proc. Symposium on Optimization of Electrical Apparatus and Systems, B.H.U., Varanasi (India),March 79, pp. 6-10.

17. Bharadwaj,D.G., "Application of Certain Optimization Techniques for Cage Induction Motor Design", A Ph.D. Thesis, Elect. Engg. Deptt.,University of Roorkee, Roorkee, 1979.

18. Adkins, B.,"General Theory of Electrical Machines"

19. A.K.Sawhney, "A course in Electrical Machine Design".

20. M.G.Say, "The performance and design of Alternating Current Machines", Third Edition, Pitman Publishing Corporation, New York.

21. M.Chilliken - Electric Drives.

22. Box,M.J., "A New Method of Constrained Optimization and a Comparision with other Methods", Computer Journal,Vol. 8, pp. 42-52, 1965.

23. Box, M.J., "A comparision of several optimization methods and use of transformations in constrained problems", Computer Journal,Volume 9, No.1, Page 67, 1966.

24. Rosenbrock, H.H., "An Automatic method of finding the Grestest or Least value of Function", Computer Journal, Vol. 3, pp. 175-184, 1960.

25. Hooke, R. and Jeeves, T.A., "Direct Search solution of Numerical and Statistical Problems", J.Assoc. Comp. March, Vol.3, No.2, pp.212-229, 1961.

26. Carrol, C.W., "The created response surface technique for optimizing nonlinear restrained systems", Operations Research, Vol. 9, pp.169-184, 1961.

27. Fletcher,R.and Powell, M.J.D., "A Rapidly Convergent Descent Method for Minimization", Computer Journal, Vol.6, pp.163-168, 1963.

28. Fiacco,A.V. and McCormick,G.P.," Non-linear Programming Sequential Unconstrained Minimization Technique", John Wiley and Sons, Inc. New York, 1969.

29. Waren,A.D., Lasdon,L.S. and Suchman,D.F., "Optimization in Engineering Design", Proc.I.E.E.E.,Vol.55, pp.1885-1897, 1967.

30. Rao,S.S., "Optimization Theory and Applications", Wiley Eastern Limited, 1978.

31. Fox,R.L., "Optimization Methods for Engineering Design", Addison-Wesley Publishing Co.,1973.

32. Wismer,D.L., "Optimization methods for Large Scale Systems, with Applications".

33. Still,A. and Sinkind,C.S., "Elements in Electrical Machine Design", McGraw-Hill Book Company Inc., London.

```
C      MAIN LINE PROGRAME FOR COMP LEX 30X ALGORITHM APM
       DIMENSION X(10,20),R(10,20),F(10),XC(10)
       COMMON G(15),H(15)
       INTEGER GAMMA
       READ 301,N,M,K,IMAX,IC,IPRINT
   301 FORMAT(8I5)
       READ 302,ALPHAO,BETAO,GAMMA
   302 FORMAT(2F12.5,I5)
       READ 304,(X(1,J),J=1,N)
   304 FORMAT(8F12.5)
       DELTAO=0.0001
       DO 100 I1=2,K
       READ 303,(R(II,JJ),JJ=1,N)
   303 FORMAT(16F5.4)
   100 CONTINUE
       PRINT 310
   310 FORMAT(1H1,//,18X,24HCOMPLEX PROCEDURE OF BOX)
       PRINT 318
   318 FORMAT(//,2X,10HPARAMETERS)
       PRINT 311,N,M,K,ITMAX,IC,ALPHAO,BETAO,GAMMA,DELTAO
   311 FORMAT(//,2X,4HN = ,I2,3X,4HM = ,I2,3X,4HK = ,I2,2X,@ITMAX =@
      12X,@IC =@ ,I2,//2X,9HALPHAO = ,F5.2,5X,8HBETAO = ,F12.5,3X,8HG
      2 = ,I2,3X,9HDELTAO = ,F8.5)
       IF(IPRINT)340,350,340
   340 PRINT 312
   312 FORMAT(//,2X,14HRANDOM NUMBERS)
       DO 200 J=2,K
       PRINT 313,(J,I,R(J,I),I=1,N)
   313 FORMAT(/,3(2X,2HR=,I2,1H ,I2,4H(   ,F8.4))
   200 CONTINUE
   350 CALL CONSX(N,M,K,ITMAX,ALPHAO,BETAO,GAMMA,DELTAO,X,R,F,IT,IEV2
      1IPRINT)
       IF(IT-ITMAX)320,320,330
       CALL FUNC(N,M,K,X,F,I)
       PRINT 321
       N1=N+1
       DO 400 J=N1,M
       PRINT 316,J,X(IEV2,J)
   400 CONTINUE
   321 FORMAT(3X,24HFINAL CONSTRAINST VALUES//)
   320 PRINT 314,F(IEV2)
   314 FORMAT(//2X,30HFINAL VALUE OF THE FUNCTION = ,E15.7)
       PRINT 315
   315 FORMAT(//,2X,14HFINAL X VALUES)
       DO 300 J=1,N
       PRINT 316,J,X(IEV2,J)
   316 FORMAT(/,2X,2HX ,I2,4H    ,E15.7)
   300 CONTINUE
       GO TO 333
   330 PRINT 317,ITMAX
   317 FORMAT(//,2X,38HTHE NUMBER OF ITERATIONS HAS EXCEEDED ,I4,8X,
      120HPROGRAMME TERMINATED)
   333 STOP
       END
       SUBROUTINE CONSX(N,M,K,ITMAX,ALPHAO,BETAO,GAMMA,DELTAO,X,R,F,I
```

```
     1IEV2,XC,IPRINT)
C     COORDINATES SPECIAL PURPOSE SUBROUTINES
C     ARGUMENT LIST
C     IT ITERATION INDEX.
C     IEV1 INDEX OF POINT WITH MINIMUM FUNCTION VALUE.
C     IEV2 INDEX OF POINT WITH MAXIMUM FUNCTION VALUE.
C     I    POINT INDEX
C     K1   DO LOOP LIMIT
C     KODE CONTROL KEY USED TO  DETERMINATE IF IMPLICIT CONSTRAINTS ARE
C          PROVIDED.
      DIMENSION X(10,20),R(10,20),F(10),XC(10)
      COMMON G(15),H(15)
      INTEGER GAMMA
      IT=1
      KODE=0
      IF(M-N)344,344,346
  346 KODE=1
  344 CONTINUE
      DO 360 II=2,K
      DO 370 J=I,N
  370 X(II,J)=0.0
  360 CONTINUE
C     CALCULATE COMPLEX POINTS AND CHECK AGAINST CONSTRAINSTS
      DO 345 II=2,K
      DO 355 J=1,N
      X(II,J)=G(J)+R(II,J)*(H(J)-G(J))
  355 CONTINUE
      I=II
      K1=II
      CALL CHECK(N,M,K,X,KODE,XC,DELTA0,K1)
      IF(II-2)341,341,342
  341 IF(IPRINT)343,345,343
  343 PRINT 361
  361 FORMAT(//,2X,30HCOORDINATES OF INITIAL COMPLEX)
      IC=1
      PRINT 362,(IC,J,X(IC,J),J=1,N)
  362 FORMAT(/,3(2X,2HX ,I2,1H,,I2,4H    ,1PE13.6))
  342 IF(IPRINT)347,345,347
  347 PRINT 362,(II,J,X(II,J),J=1,N)
  345 CONTINUE
      K1=K
      DO 365 I=1,K
      CALL FUNC(N,M,K,X,F,I)
  365 CONTINUE
      KOUNT =1
      IA=0
C     FIND POINT WITH LOWEST FUNCTION VALUE
      IF(IPRINT)348,349,348
  348 PRINT 363
  363 FORMAT(/,2X,22HVALUES OF THE FUNCTION)
      PRINT 364,(J,F(J),J=1,K)
  364 FORMAT(/,3(2X,2HF ,I2,4H    ,1PE13.6))
  349 IEV1=1
      DO 375 ICM=2,K
```

```
      IF(F(IEV1)-F(ICM))375,375,351
  351 IEV1=ICM
  375 CONTINUE
C     FIND POINT WITH HIGHEST FUNCTION VALUE
      IEV2=1
      DO 380 ICM=2,K
      IF(F(IEV2)-F(ICM))352,352,380
  352 IEV2=ICM
  380 CONTINUE
C     CHECK CONVERGENCE CRITERIA
      IF(F(IEV2)-(F(IEV1)+BETAO))354,353,351
  353 KOUNT=1
  354 KOUNT=KOUNT+1
      IF(KOUNT-GAMMA)356,399,399
C     REPLACE POINT WITH LOWEST FUNCTION VALUE
  256 CALL CENTR(N,M,K,IEV1,I,XC,X,K1)
      DO 385 JJ=1,N
  385 X(IEV1,JJ)=(1.0+ALPHAO)*(XC(JJ))-ALPHAO*(X(IEV1,JJ))
      I=IEV1
      CALL CHECK(N,M,K,X,I,KODE,XC,DELTAO,K1)
      CALL FUNC(N,M,K,X,F,I)
C     REPLACE NEW POINT IF IT REPEATS AS LOWEST FUNCTION VALUE
  357 IEV2=1
      DO 390 ICM=2,K
      IF(F(IEV2)-F(ICM))390,390,358
  358 IEV2=ICM
  390 CONTINUE
      IF(IEV2-IEV1)395,359,395
  359 DO 405 JJ=1,N
      X(IEV1,JJ)=(X(IEV1,JJ)+XC(JJ))/2.0
  405 CONTINUE
      I=IEV1
      CALL CHECK(N,M,K,X,I,KODE,XC,DELTAO,K1)
      CALL FUNC(N,M,K,X,F,I)
      GO TO 357
  395 CONTINUE
      IF(IPRINT)371,372,371
  371 PRINT 366,IT
  366 FORMAT(//,2X,17HITERATION NUMBER ,I5)
      PRINT 367
  367 FORMAT(/,2X,30HCOORDINATES OF CORRECTED POINT)
      PRINT 362,(IEV1,JC,X(IEV1,JC),JC=1,N)
      PRINT 363
      PRINT 364,(I,F(I),I=1,K)
      PRINT 368
  368 FORMAT(/,2X,27HCOORDINATES OF THE CENTROID)
      PRINT 369,(JC,XC(JC),JC=1,N)
  369 FORMAT(/,3(2X,2HX ,I2,6H,C    ,1PE14.6,4X))
  372 IT=IT+1
      IF(IT-ITMAX)349,349,399
  399 RETURN
      END
      SUBROUTINE CHECK(N,M,K,X,I,KODE,XC,DELTAO,K1)
      COMMON G(15),H(15)
      DIMENSION X(10,20),XC(10)
  111 KT=0
```

```
C     CHECK AGAINST EXPLICIT CONSTRAINSTS
      DO 115 J=1,N
      IF(X(I,J)-G(J))112,112,113
  112 X(I,J)=G(J)+DELTAO
      GO TO 115
  113 IF(H(J)-X(I,J))114,114,115
  114 X(I,J)=H(J)-DELTAO
  115 CONTINUE
      IF(KODE)119,119,116
C     CHECK AGAINST IMPLICIT CONSTRAINTS
  116 NN=N+1
      DO 125 J=NN,M
      CALL FUNC(N,M,K,X,F,I)
      IF(X(I,J)-G(J))118,117,117
  117 IF(H(J)-X(I,J))118,125,125
  118 IEV1=1
      KT=1
      CALL CENTR(N,M,K,IEV1,I,XC,X,K1)
      DO 135 JJ=1,N
      X(I,JJ)=(X(I,JJ)+XC(JJ))/2.0
  135 CONTINUE
  125 CONTINUE
      IF(KT)119,119,111
  119 RETURN
      END
      SUBROUTINE CENTR(N,M,K,IEV1,I,XC,X,K1)
      DIMENSION X(10,20),XC(10)
      DO 121 J=1,N
      XC(J)=0.0
      DO 122 IL=1,K1
  122 XC(J)=XC(J)+X(IL,J)
      RK=K1
  121 XC(J)=(XC(J)-X(IEV1,J))/(RK-1.)
      RETURN
      END
      SUBROUTINE FUNC(N,M,K,X,F,I)
      COMPLEX BIMP,P,A,B
      DIMENSION X(10,20),F(10),E(10,10)
      COMMON G(15),H(15)
      DO 1000 L=1,5
      READ*,IP,N
      READ*,BAV,AC,RKW,PF,EFF,QS,QMIN
      PR=X(I,1)
      AX=X(I,2)
      DELTA=X(I,3)
      DELB=X(I,4)
      AKW=.955
      DIA=.71
      FREQ=50.
      SLTHM=.56
      ES=3810.5
      DELTA=4.
      SLF=.4
```

```
      AX=3.5
      OD=.96
      DELB=4.5
      STKF=.9
      WD=.01
      H3=3.5
      H4=1.
      WSO=5.
      SCO=.033
      ALPHA=0.0
      BETA=1.
      SPRB=.021
      SPRE=SPRB
      CC=100.
      CR=70.
      CI=15.
      DENC=8900.
      DENR=8900.
      DENI=7800.
C     MAIN DIMENSIONS
   14 CO=.011*AKW*BAV*AC
      POL=IP
      SYN=2.*FREQ*1./POL
      RKVA=RKW/(PF*EFF)
   20 SLTH=PR*3.14159*DIA/POL
      PRINT 800,SLTH,PR,POL
  800 FORMAT(2X,@SLTH=@,F12.4,6X,@PR=@,F8.2,2X,@POL=@,F4.1//)
      IF(SLTH-SLTHM)2,2,68
   68 PR=PR-.05
      GO TO 20
    2 ND=12.*SLTH
      SLTNI=STKF*(SLTH-HD*WD)
      FLUX=BAV*3.14159*DIA*SLTH/POL
      TS=ES/(4.44*FREQ*FLUX*AKW)
    1 SI=3.*POL*QS
      YSS=3.14159*DIA/SI
      ZSS=6.*TSYS1
      CI1=RKVA*1000./(3.*ES)
    9 CONA=CI1/DELTA
      PRINT 1200,S1,YSS,ZSS,CONA
    3 ASS=ZSS*CONA/SLF
    6 DSS=SQRT(ASS*AX)
      WSS=ASS/DSS
      TWS=1000.*YSS-WSS
C     CHECK TWS
      PRINT 190,TWS
  190 FORMAT(2X,@TWS=@,F10.5//)
      IF(TWS-10.)4,5,5
    4 QS=QS-.5
      PRINT 1900,QS
 1900 FORMAT(2X,@QS=@,F10.4//)
      IF(QS-QMIN)101,1,1
  101 QS=QS+.5
      DELTA=DELTA+.5
      IF(DELTA-8.)9,9,8
```

```
  8 DELTA=DELTA-.5
    AX=AX+.2
    IF(AX-5.5)6,6,7
  7 AX=AX-.2
  5 BTI=1.5*FLUX*POL/(S1*TWS*SLTNI*.001)
    PRINT 150,BT1,BAV
150 FORMAT(2X,@BT1=@,F12.5,5X,@BAV=@,F12.5//)
    PRINT 160,AX,DELTA
160 FORMAT(2X,@AX=@,F5.2,6X,@DELTA=@,F5.2//)
    IF(BT1-1.7)12,12,11
 11 DELTA=DELTA+.5
    IF(DELTA-8.)9,9,13
 13 DELTA=DELTA-.5
    AX=AX+.2
    IF(AX-5.5)6,6,15
 15 AX=AX-.2
 12 IF(BT1-1.25)85,85,87
 85 AX=AX-.2
    IF(AX-3.5)92,6,6
 92 AX=AX+.2
    PR=PR+.2
    IF(PR-PRMAX)20,20,86
 86 PR=PR-.2
    DELTA=DELTA-.4
    IF(DELTA-4.)71,9,9
 71 DELTA=DELTA+.4
 87 DCS=.5*(OD-DIA-.002*DSS)
    BCS=FLUX/(2.*DCS*SLTNI)
    PRINT 600,BCS,DCS
600 FORMAT(2X,@BCS=@,F12.5,6X,@DCS=@,F12.5//)
    IF(BCS-1.45)17,17,18
 18 PR=PR+.05
    IF(PR-PRMAX)20,20,19
 19 PR=PR-.05
    AX=AX-.2
    IF(AX-3.5)70,6,6
 70 AX=AX+.2
    DELTA=DELTA+.5
    IF(DELTA-8.)9,9,97
 97 DELTA=DELTA-.5
    ROTOR DESIGN
 17 AGL=.3+2.*SQRT(DIA*SLTH)
    RDIA=DIA-.002*AGL
    NUMBER OF ROTOR SLOTS
    S2=1.25*S1
    IS2=S2
 23 S2=IS2
    SMIN=.8*S1
    IF(S2-SMIN)10,26,26
 26 DIFS=ABS(S2-S1)
    IF(DIFS)21,22,21
 22 IS2=IS2-1
    GO TO 23
 21 IF(DIFS-1)24,22,24
```

```
 24 IF(DIFS-2)25,22,25
 25 IF(DIFS-IP)226,22,226
226 IF(DIFS-2*IP)27,22,27
 27 IF(DIFS-3*IP)28,22,28
 28 IF(DIFS-5*IP)29,22,29
 29 IF(DIFS-IP-1)30,22,30
 30 IF(DIFS-IP+1)31,22,31
 31 IF(DIFS-IP-2)32,22,32
 32 IF(DIFS-IP+2)33,22,33
 33 YRS=3.14159*RDIA/S2
    PRINT 1300,AC,S2,YRS,SMIN,SLTNI
    IF(YRS-.02)22,35,35
 35 CIB=.85*6.*CI1*TS/S2
 34 BARA=CIB/DELB
    WRS=YRS*1000./2.
    TWR=WRS
    DRB=BARA/(WRS-1.)
    DRS=DRB+3.
    BLTH=SLTH+.05
    BT2=1500.*FLUX*POL/(S2*SLTNI*TWR)
    PRINT 700,BT2
700 FORMAT(2X,@BT2=@,F12.5//)
    IF(BT2-1.7)93,93,22
 93 CIE=S2*CIB/(3.14159*POL)
    ERAR=CIE/DELB
    DE=SQRT(ERAR)+3.
    TE=ERAR/DE
    DEO=RDIA-.002*DRS
    DEI=DEO-.002*DE
    DEM=(DE/+DEI)/2.
    RSID=RDIA-.002*DRS-DCS
    RSID=RDIA-.002*DRS-.002*DCS
    PRINT 1400,AGL,RSID,RDIA
    PERFORMANCE EVALUATION
    MAGNETIC CIRCUIT CALCULATIONS
    CGCS=1./(1.+3.5*AGL/WSO)
    CGCR=1./(1.+3.5*AGL/WRS)
    CGCD=1./(1.+3.5*AGL/(2.*WD*1000.))
    GCFS=YSS/(YSS-CGCS*WSO*001)
    GCFR=YRS/(YRS-CGCR*WRS*.001)
    GCFD=SLTH/(SLTH-CGCD*WD*ND)
    GCFT=GCFS*GCFR*GCFD
    EAGL=GCFT*AGL
    ATG=800.*1.36*BAV*EAGL
    WTS=(3.14159*(DIA+.002*DSS/3.)/S1)-.001*WSS
    AST=S1*WTS*SLTNI/POL
    BTSS=1.36*FLUX/AST
    WRT=(3.14159*(RDIA-.004*DRS/3.)/S2)-.001*WRS
    ART=S2*WRT*SLTNI/POL
    BTRS=1.36*FLUX/ART
    PRINT 1100,BTSS,BTRS,EASL,ATG
    K=0
 37 K=K+1
    GO TO (38,39,40),K
 38 FD=BTSS
    GO TO 41
```

```
39 FD=BCS
   GO TO 41
40 FD=BTRS
   GO TO 41
41 IF(FD-.6)42,42,43
42 AT=91.8*FD+45.
   GO TO(50,51,52),K
43 IF(FD-1.)44,44,45
44 AT=200.*FD-20.
   GO TO(50,51,52),K
45 IF(FD-1.45)46,46,47
46 AT=6.44*EXP(3.2*FD)
   GO TO(50,51,52),K
47 IF(FD-1.7)48,48,49
48 AT=.0052*EXP(8.1*FD)
   GO TO(50,51,52),K
49 AT=.687*EXP(5.23*FD)
   GO TO(50,51,52),K
50 SATST=AT
   GO TO 37
51 SATSC=AT
   GO TO 37
52 SATRT=AT
   ATST=SATST*DSS*.001
   ATRT=SATRT*DRS*.001
   SCPATH=3.14159*(DIA+.002*DSS+DCS)/(3.*POL)
   ATSC=SATSC*SCPATH
   RCPATH=3.14159*(RDIA-.002*DRS-DCS)/(3.*POL)
   ATRC=SATSC*RCPATH
   TAT=ATG+ATST+ATRT+ATSC+ATRC
   CIM=(.427*POL*TAT)/(AKW*TS)
:  IRON LOSS
   TWM=3.14159*(DIA+.001*DSS)/S1-.001*WSS
   WTST=.001*DSS*DENI*S1*TWM*SLTNI
   BTSM=3.14159*FLUX/(2.*AST)
   IF(BTSM-1.6)53,53,54
53 SPLST=1.3*BTSM**2
54 SPLST=1.3*BTSM**3
   LIST=SPLST*WTST
   WTCI=3.14159*(OD-DCS)*DCS*SLTNI*DENI
   SPLC=1.3*BCS**2
   PRINT 1400,WTST,WTCI,TAT
   LIC=SPLC*WTCI
   TIL=2.*(LIST+LIC)
   FWL=10.*RKW
   NLL=TIL+FWL
   CIL=NLL/(3.*ES)
   CINL=SQRT(CIM**2+CIL**2)
   ANLL=NLL
   PRINT 1500,CIM,CIL,CINL,ANLL,DELB
:  COPPER LOSS
   SCML=SLTH+1.15*3.14159*DIA/POL+.12
   SCLP=2.*SCML*TS
   RS=.021*SCLP/CONA
   SCLOS=3.*RS*CI1**2
```

```
      RB=SPRB*BLTH/BARA
      BCLOS=S2*RB*CIB**2
      RE=SPRE*3.14159*DEM*1./ERAR
      ECLOS=2.*RE*CIE**2
      RCLOS=BCLOS+ECLOS
      TCLOS=SCLOS+RCLOS
      PROT=S2*RE+2.*RE
      TFR=6.*TS*AKW/S2
      RSR=TFR**2*RROT/3.
      PRINT 1400,RS,RROT,RSR
      EFF=RKW*1000./(1000.*RKW+NLL+TCLOS)
      PRINT 130,EFF
  130 FORMAT(2X,@EFF=@,F15.6/)
      IF(EFF-.92)55,56,56
   55 DELTA=DELTA-.4
      IF(DELTA-4.)82,9,9
   82 DELTA=DELTA+.4
   56 CONTINUE
      RM=ES/CIL
      XM=ES/CIM
      PFNL=CIL/CINL
      SLIP=RCLOS/(1000.*RKW+RCLOS+FWL)
      LEAKAGE REACTANCE
      H1=SQRT(ZSS*CONA*AX)
      H2=DSS-H1-H3-H4
      PSS=4.*3.14159*(H1/(3.*WSS)+H2/WSS+H3/(WSS+WSO)+H4/WSO)
     1/(1000.*10000.)
      PRS=4.*3.14159*(DRS/(3.*WRS)+.75/WRS+3.5/(WRS+3.)+.5/3.)
     1/(1000.*10000.)
      RPRS=PRS*AKW**2*S1/S2
      SSLR=400.*3.14159*TS**2*SLTH*PSS/(POL*QS)
      RSLR=400.*3.14159*TS**2*BLTH*RPRS/(POL*QS)
      OP=4.*(3.14159*DIA)**2/(YSS*POL*1000.*10000.)
      OLR=400.*3.14159*TS**2*OP/(POL*QS)
      QR=S2/(3.*POL)
      XZ=5.*XM/54.*(1./(QS**2)+1./(QR**2))
      XS=SSLR+XZ+.5*OLR
      XR=RSLR+.5*OLR
      PRINT 120,XS,XR
  120 FORMAT(2X,@XS=@,F15.5,6X,@XR=@,F15.5//)
      FULL LOAD POWER FACTOR
      G1=RM*XM**2/(RM**2+XM**2)
      G2=RM**2*XM/(RM**2+XM**2)
      G3=((RSR*G1/SLIP-XR*G2)*(RSR/SLIP+G1)+(RSR*G2/SLIP+XR
     1G1)*(XR+G2))/((RSR/SLIP+G1)**2+(XR+G2)**2)
      G4=((RSR/SLIP+G1)*(RSR*G2/SLIP+XR*G1)-(XR+G2)*(RSR*G1
     1/SLIP-XR*G2))/((RSR/SLIP+G1)**2+(XR+G2)**12)
      PFFL=(RS+G3)/(((RS+G3)**2+(XS+G4)**2)**.5)
      PRINT 110,PFFL
  110 FORMAT(2X,@PFFL=@,F12.6//)
      IF(PFFL-.8)60,61,61
   60 DELTA=DELTA+.4
      IF(DELTA-8.)9,9,61
   61 CONTINUE
      DEEP BAR CALCULATIONS
      THETA=.001*DRB*SQRT(3.14159*20./SPRB)
```

```
      P=CMPLX(-ALPHA,BETA)
      A=1.+P
      B=SINH(2.*THETA)-P*SIN(2.*THETA)
      BIMP=(BLTH/(1000.*WRS))*CSQRT(3.14159**2*20.*SPRB*A*B/
     1(COSH(2.*THETA)-COS(2.*THETA)))
      BRS=REAL(BIMP)
      SRROT=S2*BRS+2.*RE
      SRSR=TFR**2*SRROT/3.
      SXR=AIMAG(BIMP)
      XRST=AKW**2*SXR*S1/S2
      PRINT 1200,BRS,SRSR,XRST
C     TORQE RATIO
      C1=1.+RS/RM+XS/XM
      TFL=3.*ES**2*RSR/(SLIP*((RS+C1*RSR/SLIP)**2+(XS+C1*XR)
     1**2))
      TST=3*ES**2*SRSR/(2.*C1*(RS+(RS**2+(XS+C1*XR)**2)**.5))
      TRT1=TST/TFL
      TMAX=3.*ES**2/(2.*C1*(RS+(RS**2+(XS+C1*XR)**2)**.5))
      TRT2=TMAX/TFL
      PRINT 140,TRT1,TRT2
  140 FORMAT(2X,@TRT1=@,F8.3,8X,@TRT2=@,F8.3//)
      IF(TST-TFL)57,59,59
   57 DELB=DELB+.5
      IF(DELB-9.)34,34,58
   58 DELB=DELB-.5
   59 IF(TRT2-2.)57,90,90
   90 CONTINUE
      CIST=ES/((RS+C1*SRSR)**2+(XS+C1*XRST)**2)
      CIFL=ES/((RS+C1*RSR/SLIP)**2+(XS+C1*XR)**2)
      STCR=CIST/CIFL
      PRINT 1600,PFNL,SLIP,TRT1,TRT2,STCR
   63 CONTINUE
C     TEMPERATURE RISE
      SSO=3.14159*OD*SLTH
      OHL=SLTH+.025*(.001*ES+3.+YSS/4.)
      SSI=3.14159*DIA*OHL
      SSD=3.14159*(OD**2-DIA**2)*(2+ND)/4.
      SPS=3.14159*DIA*SYN
      SCI=.033/(1.+.1*SPS)
      SCD=.15/(.1*SPS)
      SLOS=SCLOS*SLTH/SCML+TIL
      STRISE=SLOS/(SSO/SCO+SSI/SCI+SSD/SCD)
      RSO=3.14159*RDIA*BLTH
      RSD=3.14159*(RDIA**2-RSID**2)*(2+ND)/4.
      RPS=3.14159*RDIA*SYN
      RCO=.033/(1.+.1*RPS)
      RCD=.15/(.1*RPS)
      RTRISE=(RCLOS+FWL)/(RSO/RCO+RCD/RCD)
      PRINT 1700,STRISE,RTRISE
      IF(STRISE-75.)64,64,55
   65 DELTA=DELTA-.2
      IF(DELTA-4.)88,9,9
   88 DELTA=DELTA+.2
   64 IF(RTRISE-75.)66,66,67
   67 DELB=DELB-.3
      IF(DELB-4.5)89,34,34
```

```
 89 DELB=DELB+.3
 66 CONTINUE
    X(I,5)=BT1
    X(I,6)=BT2
    X(I,7)=EFF
    X(I,8)=PFFL
    X(I,9)=TRT1
    X(I,10)=TRT2
    X(I,11)=STRISE
    X(I,12)=RTRISE
    WTRI=DENI*SLTNI*(3.14159*(RDIA**2-RSID**2)/4.-S2*DRS*WRS/1000000.)
    TIC=CI*(WTST*WTCI+WTRI)
    WTSW=CONA*6.*SCML*TS*DENC/1000000.
    WTRW=DENC*(S2*BARA*BLTH+2.*3.14159*ERAR*DEM)/1000000.
    TCW=CC*WTSW+CR*WTRW
    TC=TIC+TCW
    E(I,L)=TC
    PRINT 400,TC
400 FORMAT(2X,@TC=@,F12.5//)
1000 CONTINUE
    F(I)=SQRT(E(I,1)**2+E(I,2)**2+E(I,3)**2+E(I,4)**2+E(I,5)**2)
1100 FORMAT(5E15.6)
1200 FORMAT(5E12.5)
1300 FORMAT(5E15.6)
1400 FORMAT(4E18.8)
1500 FORMAT(5E15.6)
1600 FORMAT(5E12.5)
1700 FORMAT(5F12.5)
  10 RETURN
    END
```