'COMPUTER-AIDED DESIGN OF ASYNCHRONOUS MACHINE'

BY

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Nothingness

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A. A. Jimoh
(Ass. Lecturer)

C O N T E N T

			Page
List of Plates			ix
List of Figures			x
List of Tables			xiii
List of Symbols			xv
Synopsis			xxiv
Original Contributions			xxv
CHAPTER 1:	I N T R O D U C T I O N		
	1.1	A Digital Computer	2
	1.2	Design Problems	5
	1.3	Role of Computer in Designs	6
CHAPTER 2:	SPLIT - PHASE INDUCTION MOTOR.		
	2.1	INDUCTION MOTOR	10
	2.2	Split - Phase Motor	12
	2.3	Other Single - Phase Motors	15
CHAPTER 3:	REVIEW OF INDUCTION MACHINE WINDINGS.		
	3.1	Winding Specification Items	21
	3.2	Single - Layer Winding	25
	3.3	Double - Layer Winding	32
	3.4	Fractional Pitch or short-chorded Winding ..	37

	3.5	Fractional - slot Winding	41
CHAPTER	4:	THEORY AND PERFORMANCE CALCULATION METHODS.	
	4.1	Production of a Rotating Field	42
	4.2	Cross-Field Theory	45
	4.3	Revolving-Field Theory	46
	4.4	Combined-Winding Performance Calculations	53
CHAPTER	5:	BASIC MOTOR CONSTANTS.	
	5.1	Air-Gap MMF and Flux Waves of a single-phase Winding ..	59
	5.2	Magnetic Circuit and saturation Factor	64
	5.3	Leakage Reactance	64
	5.4	Resistance	69
	5.5	Losses	73
CHAPTER	6:	FITTING EQUATIONS INTO DESIGN CURVES.	
	6.1	Flow Diagram of Procedures Used	75
	6.2	Method of Fitting Equations	77
	6.3	The Graphs (Fitted)	79
CHAPTER	7:	D^2L SEPARATION CHART	
	7.1	Existing Methods	126
	7.2	Chart for Separating D_1 and L from D_1^2L	128
CHAPTER	8:	COMPUTER AIDED DESIGN ANALYSIS OF A SINGLE-PHASE INDUCTION MACHINE	
	8.1	Aspects of Machine Design	132
	8.2	Volume of Active Materials	132
	8.3	The Stator Punching	132

8.4	The Rotor Punching	137
8.5	Magnetic Circuit Calculations	137
8.6	Main Winding	142
8.7	Rotor Cage	144
8.8	Running Performance Calculations	146
8.9	Auxiliary Winding	146
8.10	Combined Winding Performance Calculations	152
8.11	Design Analysis Program	153
CHAPTER 9:	CONCLUSION	
9.1	Suggestions for Further Works	169
APPENDIX 1:	CALCULATION SHEET FOR MOTOR PERFORMANCE BY REVOLVING-FIELD THEORY	172
APPENDIX 2:	CALCULATION SHEET FOR COMBINED WINDING PERFORMANCE	173
APPENDIX 3:	LINEAR LEAST-SQUARE CURVE FITTING	175
A 3.1	Least Square Theory	175
A 3.2	Method of Performing Linear Least Squares Fit ...	176
APPENDIX 4:	ITERATION SCHEME FOR FORMULAE NOT REDUCIBLE TO LINEAR	180
APPENDIX 5:	SHIRPLEY'S METHOD FOR INVERTING A MATRIX	182
APPENDIX 6:	PROGRAM FOR FITTING CURVE OF OUTPUT CONSTANT FOR POLYPHASE INDUCTION MACHINES	183
APPENDIX 7:	PROGRAM FOR FITTING CURVE OF AMPERE CONDUCTOR FOR POLYPHASE INDUCTION MACHINES	186
APPENDIX 8:	PROGRAM FOR FITTING CURVE OF OUTPUT CONSTANT FOR SPLIT-PHASE AND CAPACITOR START INDUCTION MOTORS	189
APPENDIX 9:	PROGRAM FOR FITTING CURVE OF CORE-PATH SHORTENING FACTOR (2-POLES)	192

APPENDIX 10: PROGRAM FOR FITTING CURVE OF CORE-PATH SHORTENING FACTOR (4 - POLES) 195

APPENDIX 11: PROGRAM FOR FITTING CURVE OF CORE-PATH SHORTENING FACTOR (6 - POLES & OVER).. 198

APPENDIX 12: PROGRAM FOR FITTING CURVE OF LOHYS ORDINARY 201

APPENDIX 13: PROGRAM FOR FITTING CURVES OF FUNDAMENTAL-FREQUENCY LOSSES 205

LIST OF SYMBOLS OR ABBREVIATIONS USED IN THE COMPUTER PROGRAMS OF APPENDIXES 6 - 13 210

APPENDIX 14: DISTRIBUTION FACTOR AND HARMONIC CONTENT OF CONCENTRIC WINDING 211

APPENDIX 15: CALCULATING SHEET PERFORMANCE OF A SPLIT-PHASE INDUCTION MOTOR 212

APPENDIX 16: PROGRAM FOR DRAWING D^2L SEPARATION CHART (2-POLES) 213

APPENDIX 17: PROGRAM FOR DRAWING D^2L SEPARATION CHART (4 - POLES).. 215

APPENDIX 18: PROGRAM FOR DRAWING D^2L SEPARATION CHART (6-POLES).. 217

LIST OF SYMBOLS OR ABBREVIATIONS USED IN THE COMPUTER PROGRAMS OF APPENDIXES 16 - 18 219

APPENDIX 19: DESIGN ANALYSIS PROGRAM 220

LIST OF SYMBOLS OR ABBREVIATIONS USED IN THE COMPUTER PROGRAMS OF APPENDIX 19 248

APPENDIX 20: TABLE OF WIRE USED 262

REFERENCES 263

LIST OF PLATES

Plate			Page
I	A	Squirrel - Cage Rotor	12a
II	A	4 - Pole Single - Phase Concentric Winding.	29a
III	A	Mush Winding.	31a

LIST OF FIGURES

Figure		Page
1.	A Simple Block Diagram of a Digital Computer	4
2.	Flow Diagram of Design Analysis	4
3.	Flow Diagram of Design Synthesis	8
4.	Flow Diagram of Design Optimization	8
5.	Split-Phase Motor	14
6.	Reactor - Start Motor	14
7.	Capacitor - Start Motor	16
8.	Two - Value Capacitor Motor (Capacitor and Transformer)	16
9.	Two - Value Capacitor Motor (two Capacitors)	18
10.	Shaded - Pole Induction Motor	18
11.	Types of coil	22
12(a)	Circular Diagrams of a Concentric Winding 48-slots, 4-poles, 3-phase Induction Motor	26
12(b)	Developed Diagrams of concentric Winding 48-slots, 4-poles, 3-phase Induction Motor	27
13.	Developed Diagram for a Single-Phase 2-pole Motor with 24 - Slots	30
14(a)	Developed Diagram of a 3 - phase, 2- pole, full-pitch, lap winding (star connected)	34
14(b)	Developted Diagram of a 3 - phase, 2 - pole, full-pitch, Wave winding	36
15.	Developed Diagram of a 3 - phase, 2 - pole, 18 - slots, 2 layer chorded winding	38
16.	Production of a Rotating Field	43

Figure		Page
17.	Resolution of a Stationary Pulsating Vector into two constant-maguitude revolving vectors	46
18.	Production of a stationary sinusoidally pulsating wave by two constant - magnitude sine waves moving in opposite directions	48
19.	Coupled circuits representing the single-phase induction motor, according to the revolving-field theory	48
20.	Conventional equivalent circuit according to revolving field theory	51
21.	Simplified form of the equivalent circuit	51
22.	Schematic representation of a 1 - ∅ induction motor with windings in quadrature	54
23.	Equivalent circuit of figure 22 according to revolving field thecry	54
24.	The mmf wave of a full-pitch coil	60
25.	The mmf wave of a chorded coil	60
26.	The mmf wave of a concentric coil	62
27.	Method of specifying stator-slot dimensions	62
28.	Flow diagram of procedures used	76
29.	Flow diagram of linear square curve fitting	78
30.	Output constant for Polyphase Induction Machines	82
31.	Ampere conductors for polyphase Induction Machines	88
32.	Approximate output constant for split-phase & Capcitor start Induction Motors for Continuous duty	91
33.	Flux distribution pattern in concentric winding design, 2 - pole case	94
34.	Core path shortening factor curves	96
35.	Manetization curve for Lohys Ordinary	102

Figure		Page
36.	Slot constants for flat-bottom Trapezoidal slots	107
37.	Fitting of slot constants for flat-bottom trapezoidal slots..	108
38.	Slot constants for round-bottom slots.	107
39.	Fitting of slot constants for round-bottom slots	110
40.	Fitting of slot constants for round-bottom slots	112
41.	Belt leakage constant	118
42.	Fitting of belt leakage constant..	115
43.	Speed at maximum torque, single-phase Induction motor	118
44.	Fundamental-Frequency losses in induction mtors..	118
45.	D^2L separation chart; 2-pole Machine	Inset
46.	D^2L separation chart; 4-pole Machine	Inset
47.	D^2L separation chart; 6-pole Machine	Inset
48.	Flow diagram for the plotting of the D_1^2L separation charts . ..	130
49.	Flow diagram for volume of active materials	133
50.	Stator punching design	134
51.	Flow diagram for stator punching design	135
52.	Rotor punching design	136
53.	Flow diagram for rotor lamination	139
54.	Flow diagram of magnetic circuit calculations	140
55.	Flow diagram for main winding design	143
56.	Flow diagram of rotor cage design	145
57.	Flow diagram of auxiliary winding design	151

LIST OF TABLES

Table		Page
1.	'..'.:"V V'.[1] nation for 3 •- phase, 4 - pole, 48 slots tfonoont-:c.o ling	..28
2.	Slot Allocation Ta le for single - Phase concentriz Winding ..	31
3.	Slot Allocation for 3 - phase, 2 - polos, 12 slots Double Layer Windings	
4-,	Coil -Gtaap for One-PhaGO of a \'ave Winding	.35
5,	Coil - Group for *One* Phase of a 3-phase, 4 - poles, 24 slots Wave Winding ..	.37
6,	Slot Allocation Ttih> for a 3 - phase, 2 - poles, 18 sloes Double - Layer Winding with Fractional Pitch »	.39
7,	Magnetio - Circuit Calculations for Induction Motors	.65
8,	Fitting of Output Constant for Polyphase Induction Machines ,.	87
9,	Pitting of ampere -» conductor •• <• •• ««•	90
10.	Fitting of Output constant for Split-phase induction motors •«•	93
11.	Fitting of core-path Shortening factor (2-pole Machines)•• ••	90
12.	Fitting of core-path shortening factor (4—pole Machines)$_M$ ••	99
13.	Fitting of core-path shortening factor (6-pole & over) ,. ••	100
14-	Fitting of Magnetization curve for Lohys Ordinary Tiatenial ...	104
15«	Fitting of slot constant for flat-bottom Trapezoidal slots ,.	106
16.	Fitting of slot constant for round-bottom slots	.113
17«	Fitting of Belt - Leakage cons cant •• ., •• •••	116
18.	Fitting of speed at maximum torque, single-phase induction motors	119
19.	Fitting of Fundamental-Frequency Iron Losses in Induction motors	122
20.	Stator Punching	.137

21. Rotor Punching 141

22. Motor Constants for Locked-Rotor Conditions 148

2'j>. List of Inputs for the Program 154

24. Input Parameters to the Progra in Appendix 19 for the case study 157

A6.1 Input to computer Program of appendix 6 185

A7.1 Input to Computer program of appendix 7 188

A8,1 Input to computer program of appendix 8 . . . . . -|^-|

A9»1 Input to computer program of appendix 9 . . . . . 19^

A10.1 Input to computer program of appendix 10 . . . . . -j^y

A11.1 Input to computer program of appendix 11 200

A12.1 Input to computer program, of appendix 12 203

A13^1 Input to computer program of appendix 13 207

LIST OF SYMBOLS

CHAPTER 2

e	–	Instantaneous Value of an induced electromotive force.
N	–	Number of turns. (or North pole).
ϕ	–	Magnetic flux.
t	–	Time variable.
l	–	length.

CHAPTER 3.

χ	–	Time-phase displacement of a.c. winding phases.
m	–	Number of phases.
N	–	North pole
p	–	Number of pole-pairs
q	–	Number of slots per pole per phase
S	–	Number of slots. (or South pole).
X	–	Distance in slots between beginnings of two adjacent phases.
y	–	Pole-pitch, in slots.
Z	–	Coil-pitch, in slots.

CHAPTER 4

a - Ratio of effective conductors in auxiliary winding to effective conductors in main winding.

E_b - Voltage induced in stator winding by forward component of air-gap flux.

E_{ba} - Voltage induced in auxiliary winding by its own backward field.

E_{bm} - Voltage induced in main winding by its own backward field.

E_f - Voltage induced in stator winding by forward component of air-gap flux.

E_{fa} - Voltage induced in auxiliary winding by its own forward flux.

E_{fm} - Voltage induced in main winding by its own forward flux.

f - Frequency.

ϕ - Time phase angle between I_m and I_a.

I - Primary current

I_a - Current in auxiliary winding

I_{2b} - Rotor current induced by backward field, in terms of stator winding.

I_{2f} - Rotor current induced by forward field, in terms of stator winding.

I_m - Current in main winding.

K_p - $X_m/(X_m + x_1)$.

K_r - K_p^2

N - Speed.

N_s - Synchronous Speed

r_1 - Stator winding resistance.

r_2 - Secondary resistance, referred to primary.

R_b - Apparent resistance to backward field.

R_f - Apparent resistance to forward field.

R_T - Apparent total resistance of main winding.

R_{Ta} - Apparent total resistance of auxiliary winding.

s - Slip

t - Time variable.

T - Total torque developed.

T_b - Torque developed by backward field.

T_f - Torque developed by forward field.

V_a - Voltage impressed in auxiliary phase.

V_m - Voltage impressed in main phase

w - Angular velocity

x_1 - Stator winding leakage reactance.

X_o - $X_m + x_1$.

X_2 - Rotor leakage reactance.

X_b - Apparent reactance to backward field.

X_f - Apparent reactance to forward field.

X_m - Reactance due to mutual flux linking stator and rotor windings.

X_T - Apparent total reactance of main winding.

X_{Ta} - Apparent total reactance of auxiliary winding.

z_1 - $r_1 + jx_1$ - primary leakage impedance.

z_{1a} - $r_{1a} + jx_{1a}$ - primary leakage impedance of auxiliary winding.

Z_b - Apparent impedance to backward field.

Z_f - Apparent impedance to forward field.

CHAPTER 5

a_o - Coefficient of constant term of Fourier's series.

a_n - Coefficient of sine component of nth term of Fourier's series.

A_r - Cross-section of a ring.

A_b - Cross-section area of a single rotor bar.

ACT - Weighted average coil throw, in number of slots.

α - Skew in electrical degrees.

b_n - Coefficient of cosine component of nth term of Fourier's series.

B_g - Air-gap density.

C - Total number of series - connected conductors.

C_1, C_2, C_3 - Number of conductors in slots 1, 2, 3.

D_i - Internal diameter of resistance rings.

D_r - Mean diameter of the end ring.

h - Actual mmf, or turns, of a single coil.

K_g - Weight in Kilogram.

K_ϕ - Flux factor.

K_{w1} - Distribution factor for the fundamental.

K_{wn} - Distribution factor for the nth harmonic.

K_{s1} - Stator slot constant.

L - Length of stack.

m - Number of phases.

p.f. - Power factor.

R_{sp} - Specific resistance of conductor.

SK - Skew distance.

x_1 - Stator winding leakage reactance.

X_{bolt} - Bolt-leakage reactance.

X_{end} - End leakage reactance.

X_{skew} - Skew leakage reactance.

X_{slot} - Stator - slot leakage reactance.

X_{zz} - Zig-zag leakage reactance.

CHAPTER 6

B - Core flux density, Tesla.

B_g - Air-gap flux density, Tesla.

B_m - Maximum flux density, Tesla.

C_o - Output constant.

D_1 - Stator bore diameter.

E_{rms} – R.M.S. value of induced e.m.f.

f – Frequency.

f_b – Form factor = 1.11.

ϕ – Flux, except in section 6.3.6 where it was defined as on figure 36.

F – A constant in equation for slot constants for round-bottom slots.

H – Ampere turns per metre.

KVA – Power.

KW, Watts – Real power.

K_{w1} – Winding factor of fundamental.

L – Axial length.

m – Number of phases.

N – Number of turns.

η – Efficiency.

p – Number of pole-pairs.

pf – Power factor.

P_{CL} – Fundamental-frequency iron losses, Watts/m^3.

Q – Ampere Conductor.

r_2 – Secondary resistance, referred to primary.

S_{po} – Ratio of the speed at the maximum torque to the synchronous speed.

x – Total leakage reactance.

CHAPTER 7

D_1 – Stator bore diameter.

L – Axial length.

N_s – Synchronous Speed.

U – Peripheral velocity.

y – Pole-pitch, cm.

CHAPTER 8

A – Net Slot-winding area.

d – Diameter of the wire over the insulation.

n – Total number of wires in the slot.

Z_L – Locked rotor impedance.

X – Short-circuit reactance.

a	
ϕ	
I_n	
I_m	
K_r	
r_1	As defined for Chapter 4.
r_2	
s	
X_o	
X_1	
X_m	
s	

SYNOPSIS

Computer, its role in design, and the general electric machines design problems are briefly described at the beginning, to give a general introduction to the subject. Brief descriptions of various types of single-phase induction motors, a family of asynchronous machines, immediately followed. Later in the thesis, induction machine windings are reviewed. This is immediately followed by a brief presentation of the cross-field theory, and quantitative presentations of the revolving field theory and combined winding performance theory; all of single-phase induction machines. Brief literature review of the basic motor constants, including magneto-motive force and flux waves, magnetic circuit and saturation factor calculations, leakage reactances, resistances, and losses, are made. Given detail treatment are the innovative equations which arose from the fitting of graphs used in the design of some electric machines. A new chart for separating the bore diameter (D_1) and the axial length (L) from their D_1^2L product is fully presented. At the end of the presentation procedures in computer-aided design analysis of a single-phase induction machine are discussed. This discussion is summarized in a computer program for the design of a split-phase induction machine. The whole work ends with conclusion and suggestions for further works.

ORIGINAL CONTRIBUTIONS

The major aims of this project are:

(i) to make a general and detail study of machine design principles with particular reference to the single-phase induction machines,

(ii) to investigate the use of a digital computer in (i),

(iii) produce and test a computer-aided design program,

(iv) to acquire an in-depth understanding of windings, and

(v) thereafter present a write-up that enables an in-depth understanding of the subject by students and interested others, especially those who may be interested in its physical realisation in this country.

Though there exist many literatures on this subject (see references) but none particularly presented detail descriptions of the aboves. Practical experiences, which are definately not obtainable in any book or article, are quite necessary for a succesful execution of this project. However, the whole work is original despite lack of practical experiences, and with those literatures serving as references only.

Of more innovative approach are the following:

1. The explanations of the construction of winding diagrams for three-phase concentric and distribution, lap and wave, windings with the aid of tables 1, 3, 4, 5, and 6, as fully explained in Chapter 3. Tables 1, 3, 4, 5, and 6 are innovations, and so are the ideas behind them, and their use. It is believed that these

tables are easy to form and winding diagram construction and understanding are easier through them.

2. The chart, fully described in Chapter 7, for separating the main dimensions, bore diameter (D_1) and axial length (L), from their D_1^2L product is an innovation. The idea behind it is an original contribution. This chart idea unified all the existing and possible methods of separation of D_1 and L from D_1^2L. It also gives a clearer understanding of the problem and allows for easy imagination of the physical structure of a machine. Furthermore, in computer-aided design it simplifies and economize computer usage in optimal design of the main dimensions since only possible range, obtainable from the chart, is used.

3. The idea of using equation, in place of storing datas of selected points into the memory of the computer and using interpolation formula to obtain values of a point in-between two selected points, as a means of representing a graph in computer-aided design of machine is an original contribution. The following equations, which resulted from this idea, are innovations and are fully discussed in Chapter 6:

(a) Output constant for polyphase induction machines,

$$C_o = 2060 - 970\, e^{-0.013P}$$

(b) Ampere Conductor,

$$Q = 29303.35 - 11484.05\, e^{-0.0184P}$$

(c) Output constant for split-phase and capacitor start induction motor for continuous duty,

$$C_o = 429.7 - 332.35\ e^{-3.54P}$$

(d) Core-path Shortening factors,

(i) 2-pole machine: $K_c = 1.87\ (1 + 0.0346\ e^{2.69B})$

where B is the maximum core flux density in **tesla.**

(ii) 4-pole machine: $K_c = 1.686\ (1 + 0.029\ e^{2.33B})$

(iii) 6-pole and over: $K_c = 1.62\ (1 + 0.0081\ e^{2.83B})$

(e) Slot constant for flat-bottom trapezoidal slots (see article 6.3.6)

(f) Slot constant for round-bottom slots (see article 6.3.7)

(g) Belt-leakage constant,

$$K_B = \frac{11.25}{N_{sp}} + 0.48$$

where $N_{sp}=(S_1 + S_2)/4p$; average number of slots per pole.

(h) Speed at maximum torque, single-phase induction motors,

$$S_{po} = 0.7 + 0.3\ e^{-1.69\,f/x}$$

(i) Fundamental-frequency losses (see article 6.3.10).

However, it is believed that this method, apart from being equally accurate as the existing one, has the advantages of economising the use of computer in terms of storage, time, and cost. More advantages like the ease of use and valuability of the resulting equation in other areas are possible as well.

All other works in this project, including the planning, writing, and running of all the computer programs, and the flow diagram of figure 28 in Chapter 6, showing the procedure followed in fitting equations to graph points are very satisfactory contribution.

CHAPTER 1

INTRODUCTION

Computer-aided design of electric machines is as old as the invention of electrical machine itself. This is because at least abacus, which is a device that computes, was already in use by then. Hence, in its ordinary sense computer-aided design of electric machines is simply the application of any device that can compute in the electrical machinery design process. Though in this age of electronics the computer we are concerned with here is by no means any kind of a device that computes, such as an abacus, slide rule, adding machine, or desk calculator, but the more sophisticated and advanced type: the modern high speed electronic devices that have come into use since about 1945. This device is basically of two different types: analog and digital. In brief, an analog computer can be defined as a machine which accepts analogous inputs, processes analogously, and gives output in analogous form. While a digital computer accepts digit as inputs, processes digital data, and gives out answers in digital form.

Designing an electric machine involves an appropriate utilization of the theory and performance characteristics, calculations, using the knowledge from existing designs, reading of graphs, approximating, trial-and-error practice, judicious guessing, and choosing between options, in order to obtain its dimensions and electrical particulars

to satisfy given specifications, such as kilowatt, speed, temperature rise, and conditions of services, at the minimum possible cost. Hence, without conputer a designer's work is by all means tedious, time consuming, and error prone.

In the last three decades, since early 1953[1] to be fairly specific, computer has been proved to be not only capable of taking over most of the designer's job but also performing the designer's job with high accuracy within the shortest possible time. It also gives the best possible design at the minimum possible cost; a subject referredto as design optimization. Other uses of a computer in design, apart from design analysis, design determination (synthesis), and design optimization, are in studying new problems as well as in improving solutions of old problems.[3,4,5] Hence, it is safe to say that by computer-aided design of electric machines we are referring to electrical machinery design automation - one feeds in his specifications at the input and obtains the design parameters, with its performances, at the output.

1.1 A Digital Computer

Figure 1 shows a simple block diagram of a digital computer. It has a memory capability to store data and instructions. It performs these instructions many of which are arithmetic in nature. It must also be able to display the solutions to the problems which it computes and be able to accept data and instructions from humans prior to their execution and use.

The arithmetic unit performs the operations of addition, substraction, multiplication, and division. It also performs certain logical operations too. The instruction control unit of the computer obtains the instructions which are stored in the memory, interprets the instructions, and sequences the operation of the rest of the machine to perform the instruction.

The main memory unit contains the instructions and the data which are being processed by the control unit and arithmetic unit. The sequence of instructions which the control unit executes is called a program. A program is written by a programmer and placed in a form which is interpretable by a computer, such as punched cards. Once the entire program has been stored in the computer's memory and the data on which it is to operate are also inserted, the computer processes the information according to the instructions of the program at an electronic speed determined primarily by the rate at which it can fetch instructions and data from its main memory. The memory is also used to remember intermediate results obtained from computations during the execution of the program.

The input unit reads the instructions and data into the main memory of the computer where they are stored until they are processed. The unit reads only in a medium which is compatible with the computer. Some input devices are punched-card readers, punched-paper-tape readers, magnetic character readers, optical character readers,

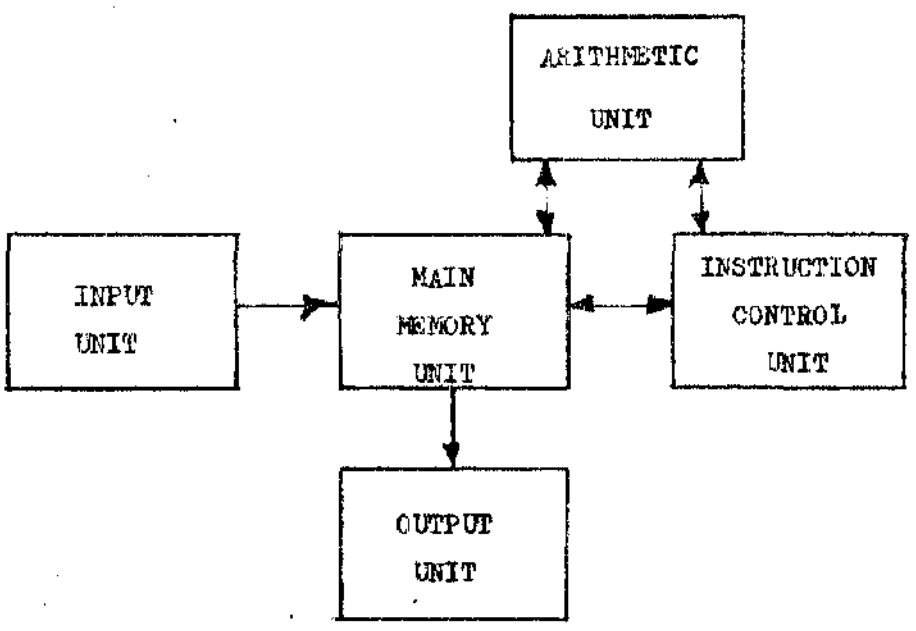


FIGURE 1: A simple block diagram of a Digital Computer.

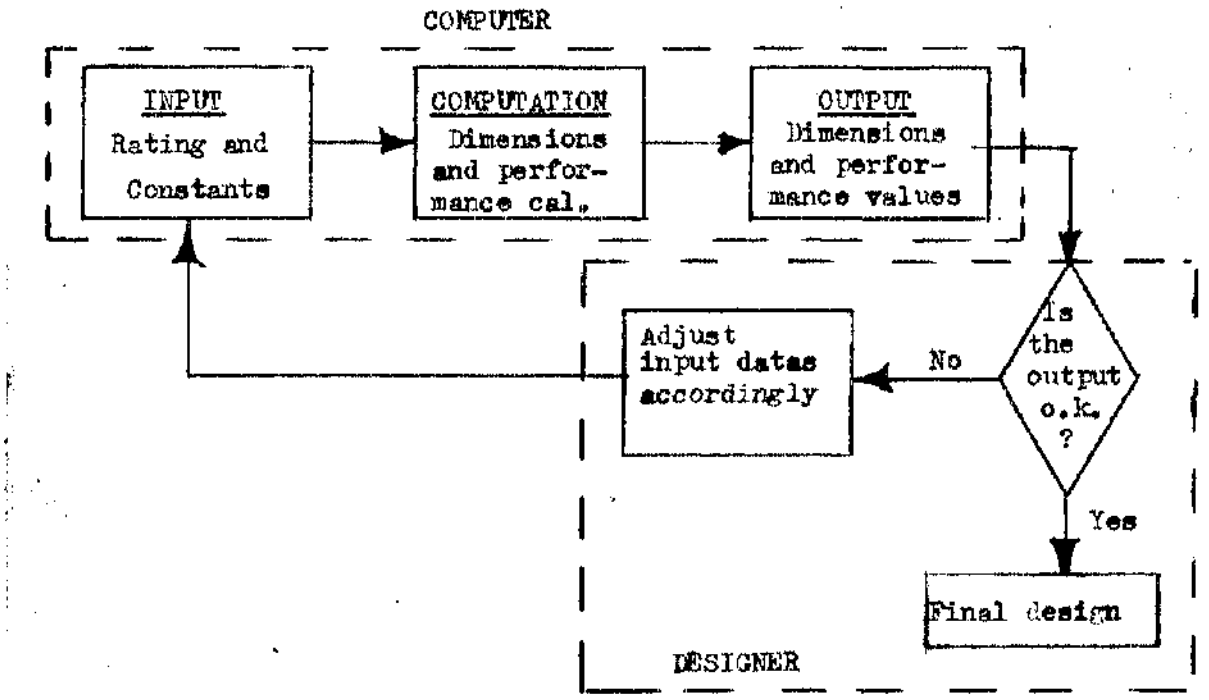


FIGURE 2: Flow diagram of Design Analysis.

and typewriters. The output unit presents the results of the computation to the user in a form compatible with the user and not as electric signals in binary code as it is represented within the machine. Some common output devices are card-punching machines, magnetic-tape units, typewriters, oscilloscopes, and high-speed line printers.

All the foregoings are the hardware components of the machine. The instructions and communications within them are carried out in machine language. Due to the unpleasantness involved, programmers do not write program in machine language, rather higher languages - like FORTRAN, PASCAL, COBOL, etc - are used. FORTRAN is found most suitable for engineering problems. However, to enable computer execute instructions written in any of these languages, service routines, which are themselves computer programs in machine language, are included as part of the computer to help in converting these higher languages into the machine language and vice versa. They are referred to as the software components of the computer. An example is a compiler.

1.2 Design Problems.

The general problems to be solved in the design of most electrical machines including transformer are:

(i) The magnetic circuit, its geometrical dimensions and the magnetic loading (ϕf).

(ii) The electric circuit, its conductor size and the electric loading (NI).

(iii) Performance calculations and the adequate adjustment of (i) and (ii) above to meet the specifications.

(iv) Insulation of the machine, suitable vent and other thermal designs (to enable adequate cooling of the machine so that its temperature rise is within specified value) and other mechanical designs.

To succesfully carry out all these there is need for an adequate knowledge of the theory and performance characteristics of the machine to be designed. The experience of the designer and knowledge of existing designs are also required to start the design by guessing almost accurately certain initial values. Usually the designer comes up with an initial design at first and obtains the final design by a cut-and-try process.

1.3 Role of Computer in Designs

The role of computer in design can be grouped into four: design analysis, design determination (synthesis), design optimization, and design problem study. In design analysis, [1,3,13,14] programs which analyse each of many aspects of the machine to be designed are written. These programs are relatively simple, and therefore a library of many such programs can be prepared in a relatively short time. Furthermore, these analysis programs make the computer serve as an aid to the designer, by enabling larger calculations and more accurate methods to be used and by disposing off quickly, routine and tedious calculations. Greater accuracy and reliability are also achieved. An analysis program accepts

as input data the specifications, including the machine ratings and other constants based on the designer's experience, and gives as output the dimensions and various performance values. Usually a final design is obtained after repetitive running of the program with various adjustments, based on the last result, made on the input data. This role of computer in design is as illustrated in Figure 2.

Design synthesis[1,3,13,14] entails a more involved program which includes design analysis but furthermore makes the computer to do the designer's part in figure 2. It also determines the design of relatively small components of the machine. Here, the designer feeds into the computer, together with sufficient input datas, the performance specifications of the product to be designed. The program then proceeds to obtain first an initial trial design then calculates the performance constants as in design analysis. However, it then compares them with the specified performance values and proceeds to go back and make changes in the trial design and recalculate until the design meets the specifications. This is illustrated in Figure 3.

The third role of computer in design, design optimization[1,3,13,14,15] involves a program that does not only design the machine to specifications as in design synthesis, but optimizes the individual design in the process. Hence, a design so obtained, an optimum design, meets all performance requirements and other limitations at minimum cost (which include losses).

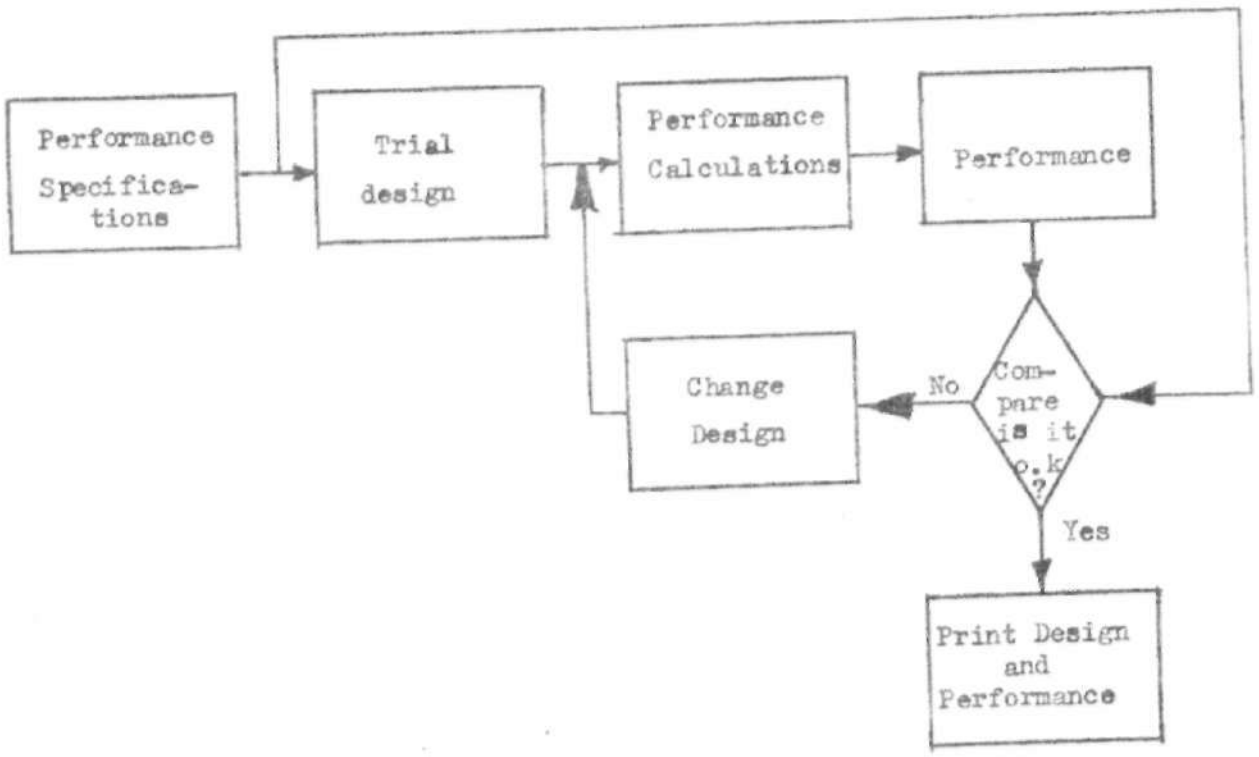


FIGURE 3: Flow Diagram of Design Synthesis.

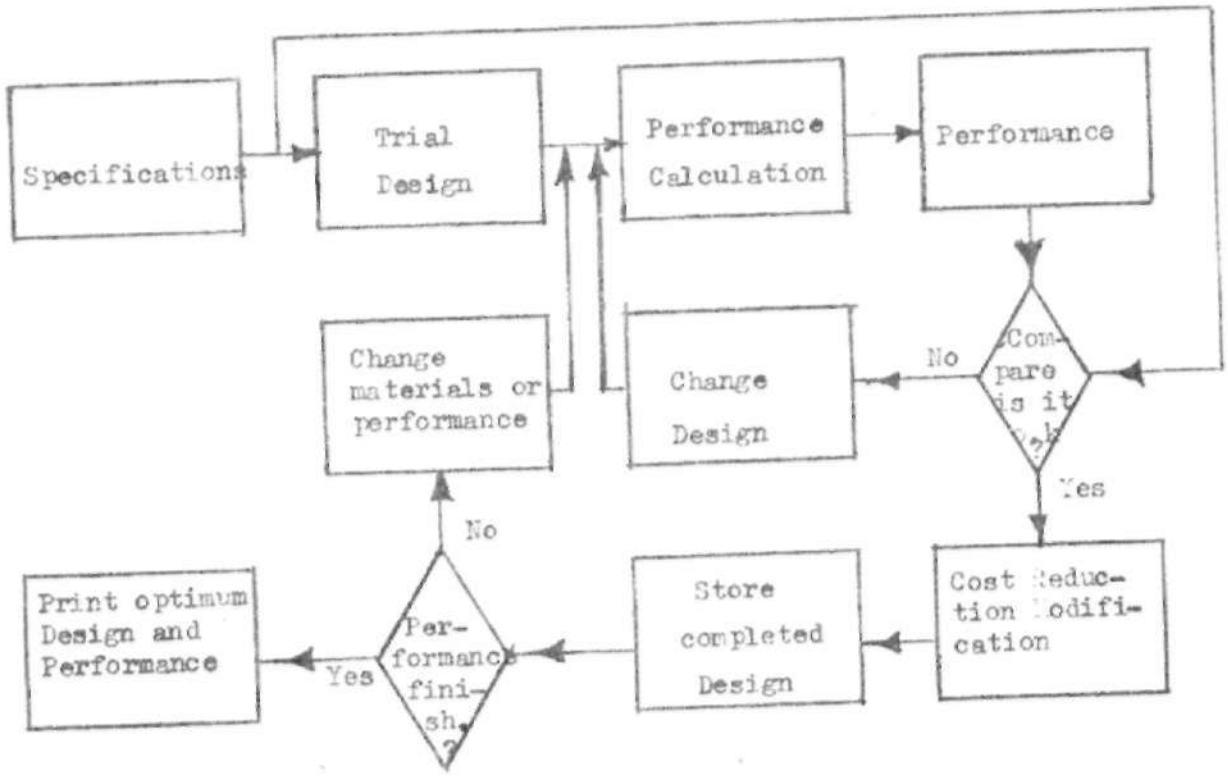


FIGURE 4: Flow diagram of Design Optimization.

This is difficult, quite involving, and liniting. The problems here include definition of variables and their permissible values, setting of objectives, adequate definition of cost, and then nininization of this cost function. The block diagram of Figure 4 illustrates an approach.

The last role of computer in design involves the use of computer in investigating ways of improving an existing method of solving certain problems in design, or design process in general, and in studying problems confronting design generally in order to obtain more accurate and more reliable designs and better economic use of computer in design as well. One aim of this study is to achieve this.

CHAPTER 2

SPLIT-PHASE INDUCTION MOTOR

The induction motor is the most widely used and most popular of all alternating current motors, It is simple in construction and it is a most desirable type of industrial motor due to its ruggedness and ability to stand rough usage. Polyphase motors are self-starting, reliable, and are essentially constant speed; even though they are sometimes used for varying-speed or for multispeed applications.

Single-phase induction motors, especially fractional kilowatt sizes exceed polyphase motors both in production and usage. Single-phase motors unlike polyphase, are not self-starting; hence various methods and devices are used to start them. The special starting circuit may be cut out entirely or left wholly or partly in the circuit when the motor is up to speed. This variety of starting arrangements form the basic differences between the various types of single-phase induction motors like split-phase, capacitor-start, two-value, permanent-split, shaded-pole, repulsion-start, and repulsion-induction motors.

2.1 Induction Motor.

The induction motor derives its name from the fact that the currents flowing in the secondary member (usually the rotor) are induced by currents flowing in the primary member (usually the stator). More accurately, the

secondary currents are induced by the action of the magnetic fields set up in the machine by the stator winding. This action is better explained by Faraday's law, which states that, when there is relative motion between the magnetic field and a coil situated in that field, there will be an e.m.f. induced in that coil, whose magnitude is equal to the time rate of change of flux linkage between the field and the coil. That is, if ϕ is the flux, and N is the number of turns in the coil, then the induced e.m.f.,

$$e = - \cdot \frac{N d\phi}{dt} \qquad \ldots\ldots (2.1)$$

A corollary of Faraday's law is

$$e = Blv \qquad \ldots\ldots (2.2)$$

where B is the constant flux density, and l is the effective length of the coil cutting the flux, and v is the velocity of coil moving through the constant flux at right angles to the direction of flux.

Most induction motors use a squirrel-cage rotor for the secondary, because this type is lowest in cost and highest in reliability; it requires no slip rings and has no brushes to wear out or to cause radio interference. Polyphase motors sometimes use wound rotors, with slip rings and brushes; this arrangement permits control of speed and torque by use of external rheostats for special applications. Single-phase induction motors generally use a squirrel-cage rotor. Single-phase motors may use a repulsion-type rotor which carries a drum winding similar to that of a d-c machine.

Squirrel-cage construction is the most popular. The "winding" consists of individual conductors in each of the slots; these individual conductors are all severally joined to end rings, there being one end ring at each end of the rotor. (See Plate I). These conductors may be of copper, brass, aluminium, or of any other conductor material; the end rings may likewise be of almost any current-carrying material, depending upon the characteristics desired. The conductors may be brazed, soldered, or welded to or cast integral with the end rings at either end. Modern practice favours the die-casting process. Usually aluminium or some alloy of aluminium or magnesium is used. This type of rotor is known as a squirrel-cage rotor because of the resemblance, of the current-carrying conductors and end rings to the cylindrical cages used for exercising pet squirrels. If the iron laminations are removed, the resemblance becomes at once apparent.

2.2 Split-Phase Motor.

A split-phase motor is a single-phase induction motor equipped with an auxiliary winding, displaced in magnetic position from and connected in parallel with the main winding. Unless otherwise specified, the auxiliary circuit is assumed to be opened when the motor has attained a predetermined speed.

Figure 5 shows a schematic representation of a split-phase induction motor. There are two separate and distinct windings on the stator, a main or running winding and an auxiliary, or starting, winding. Each

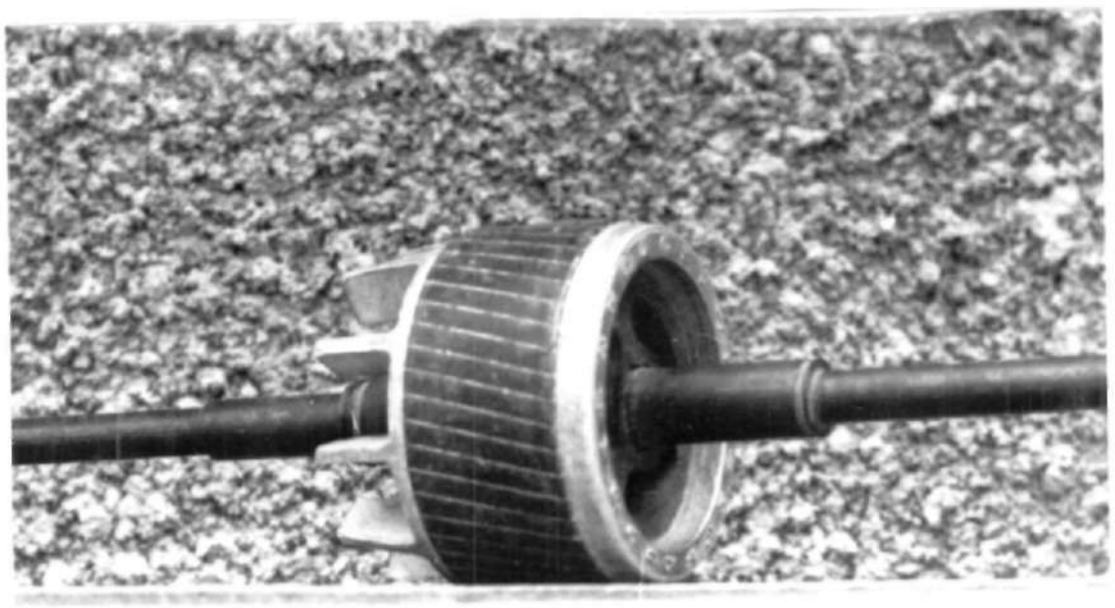


PLATE I: A Squirrel - Cage Rotor.

winding is a conplete circuit in itself. Ordinarily, but not necessarily, the windings are displaced in space by 90 electrical degrees. The rotor is usually of squirrel-cage construction.

For purposes of starting, both windings are connected to the common power source. The essence of the auxiliary winding is to produce a rotating flux at standstill - which is necessary for starting the motor. The two conditions necessary for the production of this rotating flux are that the axis of the starting winding has to be displaced in space with respect to the axis of the main winding, and the current in the starting winding has to be out of time phase with the current in the main winding. In split-phase induction motor, the latter is satisfied by making the main winding to have a relatively low resistance and high reactance, while the starting winding has a high resistance and low reactance. This results in an angle of about 30 degrees between the currents in the two windings.

A starting switch opens the circuit of the auxiliary winding when the rotor attains a speed of 75 to 80 per cent of synchronous speed. This is because at this speed the motor can develop almost as much torque on the main winding alone as it can on both windings, but beyond, less torque is developed with the auxiliary winding in the circuit. Another reason for the switch is to prevent the motor from drawing an excessive amount of watts from the line and burning out the starting winding.

This motor found its use in washing machines, oil burners, fans and blowers, refrigerators, centrifugal pumps, wood working tools, business

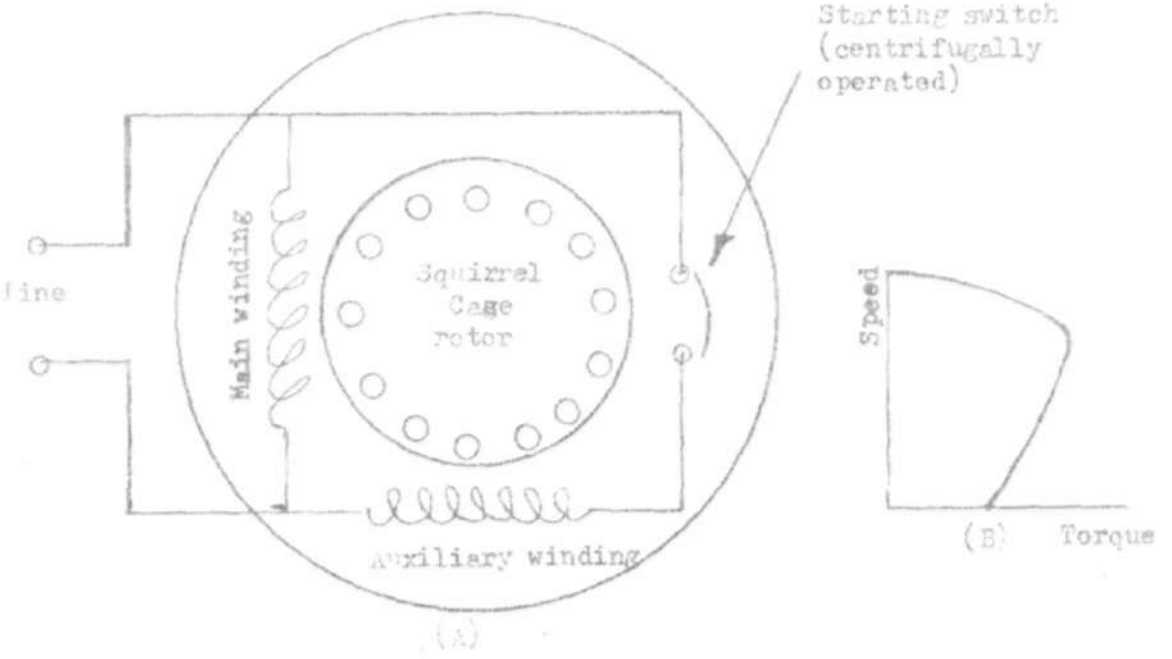


FIGURE 5: Split-phase motor, (a) Schematic representation, (b) Speed-Torque relationship.

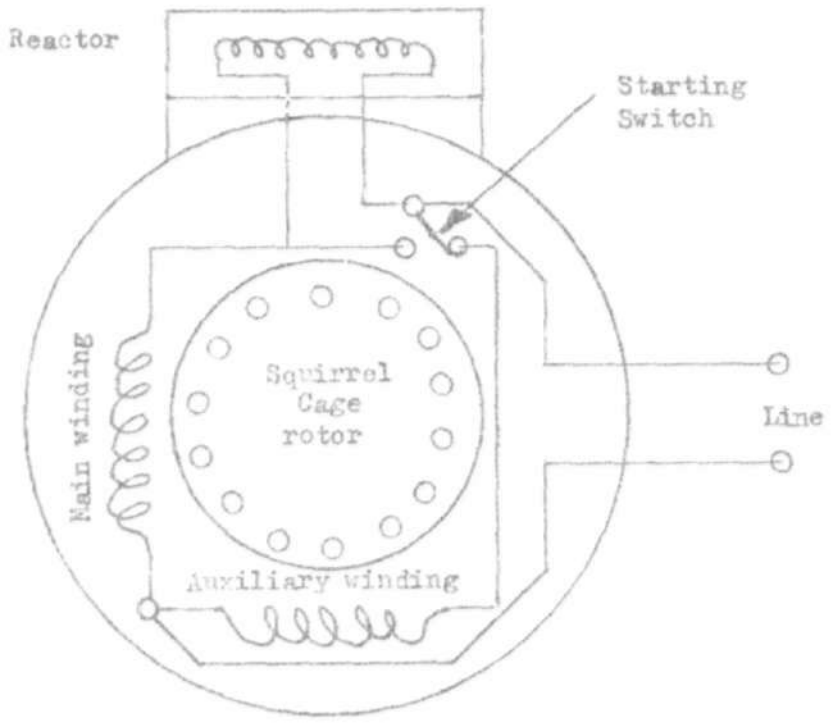


FIGURE 6: Schematic representation of a reactor-start motor.

machines, bottle washers, churns, automatic musical instruments, buffing machines, grinders, and many other devices and appliances which require moderate torques.

2.3 Other Single-Phase Motors.

Other types of single-phase induction motors are either modified forms of split-phase induction motor by the addition of one or more components to improve the performance, either at start or at run, for other various applications or single-phase induction motor which is modified for starting by another method other than that by the production of rotating flux.

2.3.1 Resistance-Start Motor:

This is a split-phase motor with a resistor connected in series with the starting "winding" to increase the angle between the currents of the main and starting windings and the starting torque. The resistance must be cut out together with the starting winding at about 70 per cent of the synchronous speed.

2.3.2 Reactor-Start Motor:

This is a split-phase motor with a reactor connected in series with the main winding to obtain the same effect as when a resistor is connected in series with the auxiliary winding. This reactor must be short-circuited, or otherwise made ineffective, when the starting winding circuit is opened by the centrifugal switch. A schematic diagram of such a motor is as shown in Figure 6.

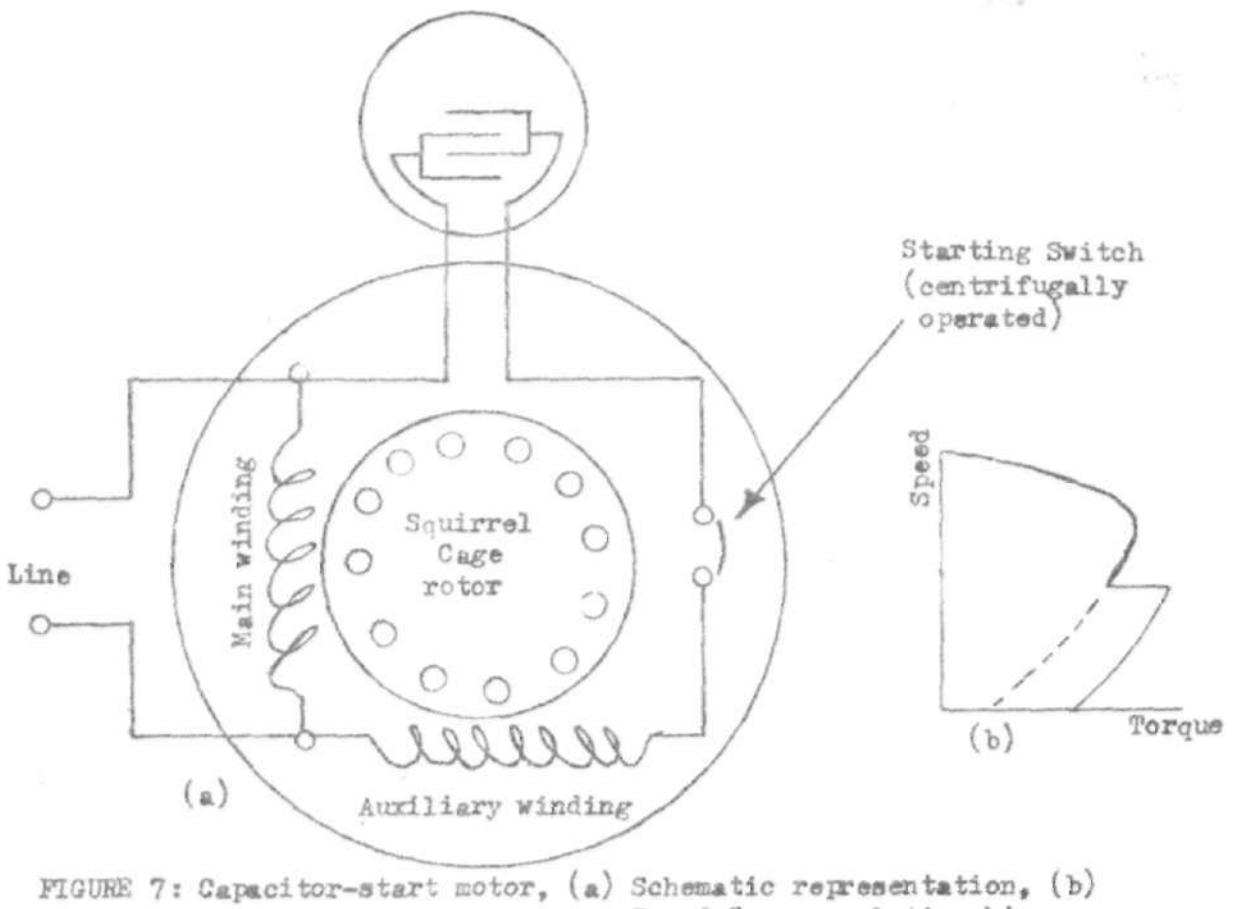


FIGURE 7: Capacitor-start motor, (a) Schematic representation, (b) Speed-Torque relationship.

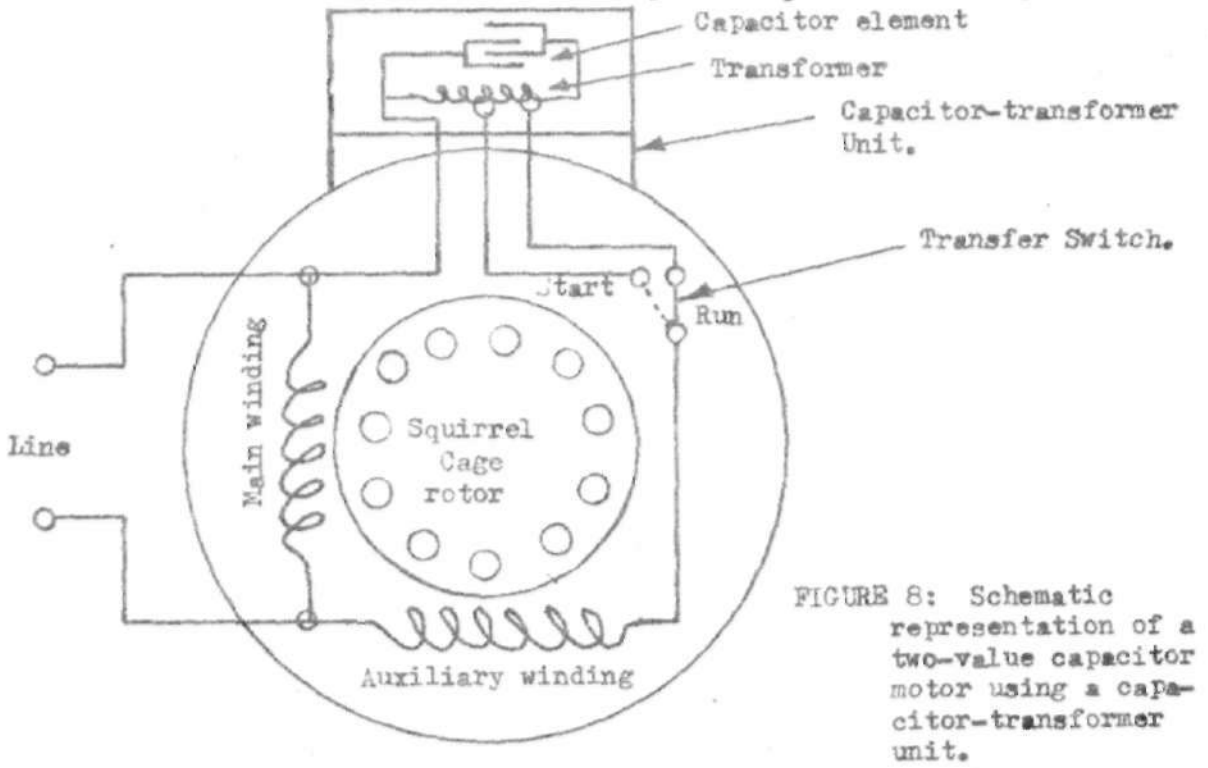


FIGURE 8: Schematic representation of a two-value capacitor motor using a capacitor-transformer unit.

2.3.3 Capacitor-Start Motor:

A capacitor-start motor is a single-phase induction motor with a main winding arranged for direct connection to a source of power and an auxiliary winding connected in series with a capacitor. A capacitor-start motor is a capacitor motor in which the capacitor phase is in the circuit only during the starting period. Here, the capacitor causes the current in the starting winding to lead the terminal voltage and the angle between the currents of the main and auxiliary windings to increase considerably and may approach 90 degrees. The starting torque increases considerably too. Figure 7 shows a schematic representation.

2.3.4 Permanent-Split Capacitor Motor:

This is a capacitor motor having the same value of capacitance for both starting and running conditions. Here, the starting winding and the capacitor are designed for permanent operation, giving an unbalanced 2-phase motor. It has a small starting torque of about 35 to 50 per cent of the rated torque.

2.3.5 Two-Value Capacitor Motor:

This is a capacitor motor using different values of effective capacitance for the starting and running connections. The use of different values of capacitance for starting and running here enables the 2-phase motor described in 2.3.4 to develop high starting torque and at the same time have a satisfactory running performance. The two major types of two-value capacitors, capacitor-transformer type and two

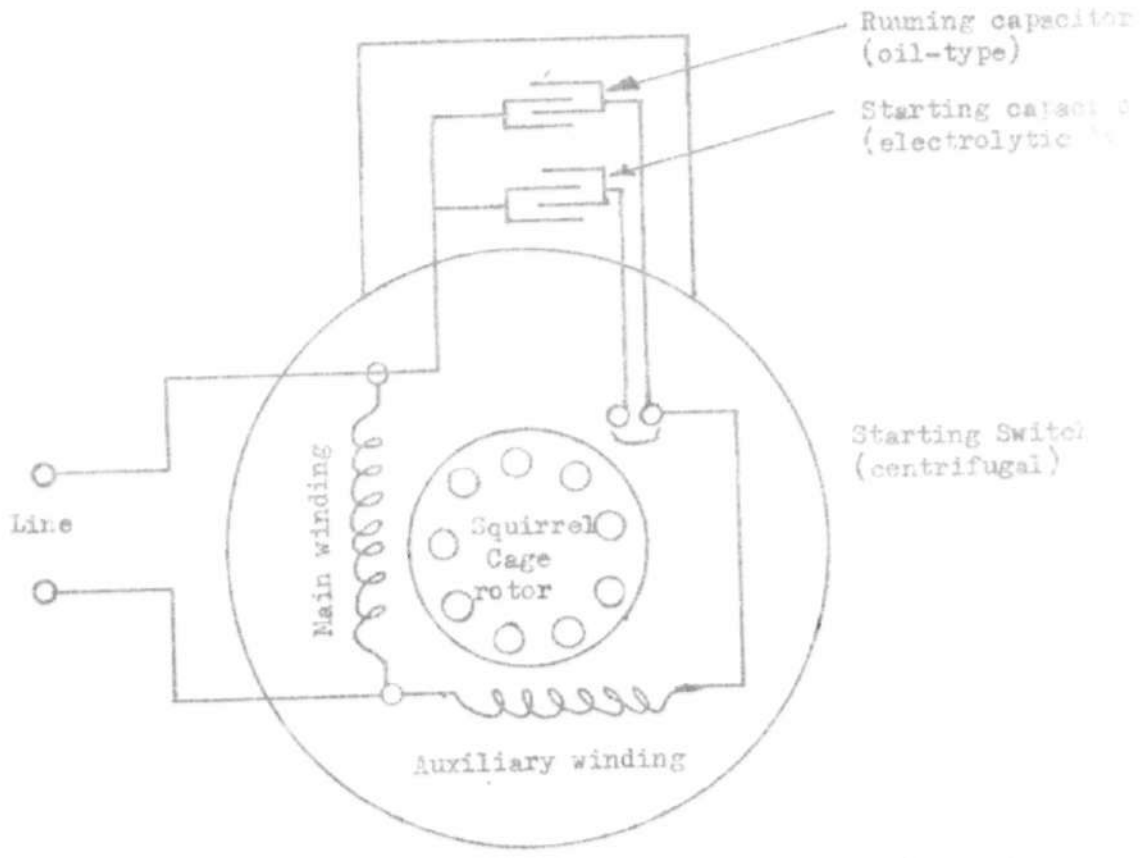


FIGURE 9: Schematic representation of a two-value capacitor motor using two capacitors.

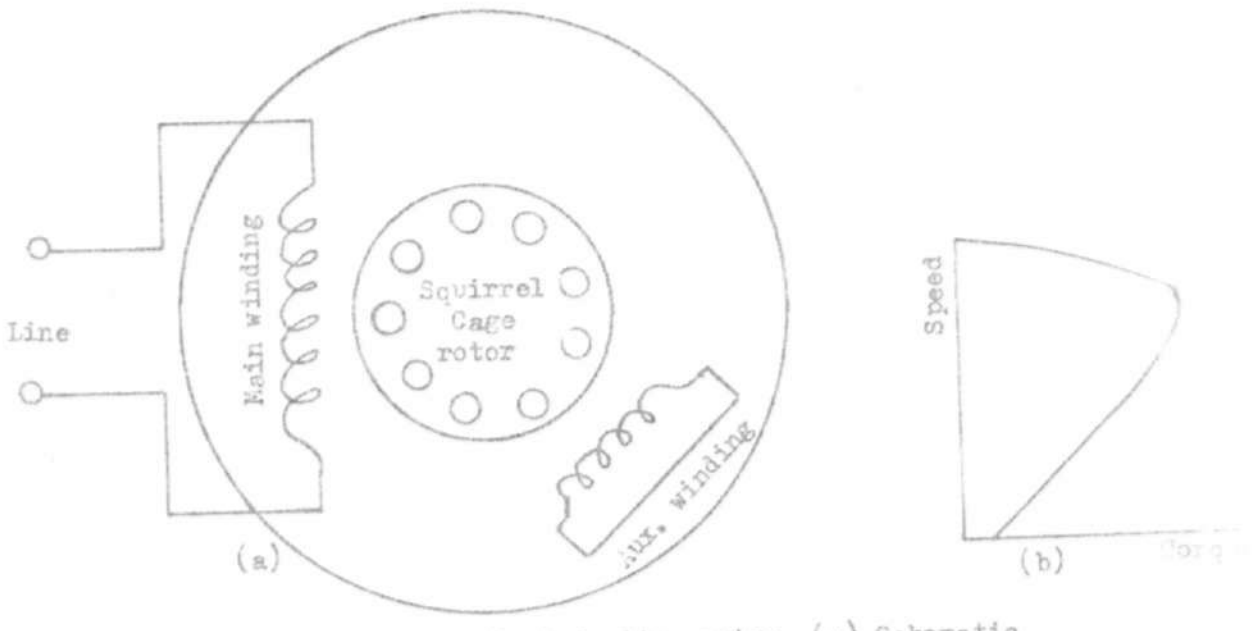


FIGURE 10: Shaded-pole induction motor, (a) Schematic representation, (b) Speed-Torque relationship.

capacitors type, are as shown in Figures 8 and 9 respectively. The last two motors, permanent-split and two-value, develop a more uniform torque and are, therefore, quieter than the others, previously described, which produce a pulsating torque resulting in vibration and noise under certain conditions.

2.3.6 Shaded-Pole Motor:

A shaded-pole motor is a single-phase induction motor provided with an auxiliary short-circuited winding or windings displaced in magnetic position from the main winding. The main winding is usually a concentrated single-phase winding placed on salient poles. Around a portion of each pole a copper strap (called shading coil) is placed, thus forming a short circuit. The rotor is of the squirrel-cage type. The method of production of starting torque here depends upon the production of a periodic shift in the pole flux across the pole faces by means of the shading coils. This motor is schematically represented in Figure 10.

2.3.7 Repulsion-Start Induction Motor:

A repulsion motor is a single-phase motor which has a stator winding arranged for connection to the source of power and a rotor winding connected to a commutator. Brushes on the commutator are short-circuited and are so placed that the magnetic axis of the rotor winding is inclined to the magnetic axis of the stator winding. This type of motor has a varying speed characteristic.

A repulsion-start induction motor is a single-phase motor having the same windings as a repulsion motor, but at a predetermined speed

the rotor winding is short-circuited or otherwise connected to give the equivalent of a squirrel-cage winding. This type of motor starts as a repulsion motor but operates as an induction motor with constant-speed characteristics.

2.3.8 Repulsion-Induction Motor:

A repulsion induction motor is a form of repulsion motor which has a squirrel-cage winding in the rotor in addition to the repulsion motor winding. A motor of this type may have either a constant-speed or varying-speed characteristic.

CHAPTER 3

REVIEW OF INDUCTION MACHINE WINDINGS

Winding may be defined as the arrangement of a group of coils in a machine in such a way that they constitute an electric circuit through which the working e.m.f. is induced, armature winding, or through which the magnetic fluxes are created, field winding. In induction machines conductors are arranged in series pairs to form turns, then coils (one of which may have one or more turns), which are situated in slots, punched uniformly round the air gap surface of stator and rotor, and then a winding by arranging and connecting these coils in a way to give a pre-specified phase grouping. Actually, the problem of winding is to arrange and connect the coils in the several slots to obtain the required phase-groupings. Before describing the various types of induction machine windings, items that specify a winding shall first be briefly defined.

3.1 Winding Specification Items

(a) Types of coil: This could either be concentric, lap, or wave. These are illustrated in figures 11 (a), (b), and (c) respectively.

(b) Layers: This could either be single or double. In a single-layer winding each coil-side occupies a whole slot, whereas in a double-layer winding one coil-side lies in the upper position in a first slot while the other occupies the lower position in a second slot spaced at a pole-pitch or less from the first.

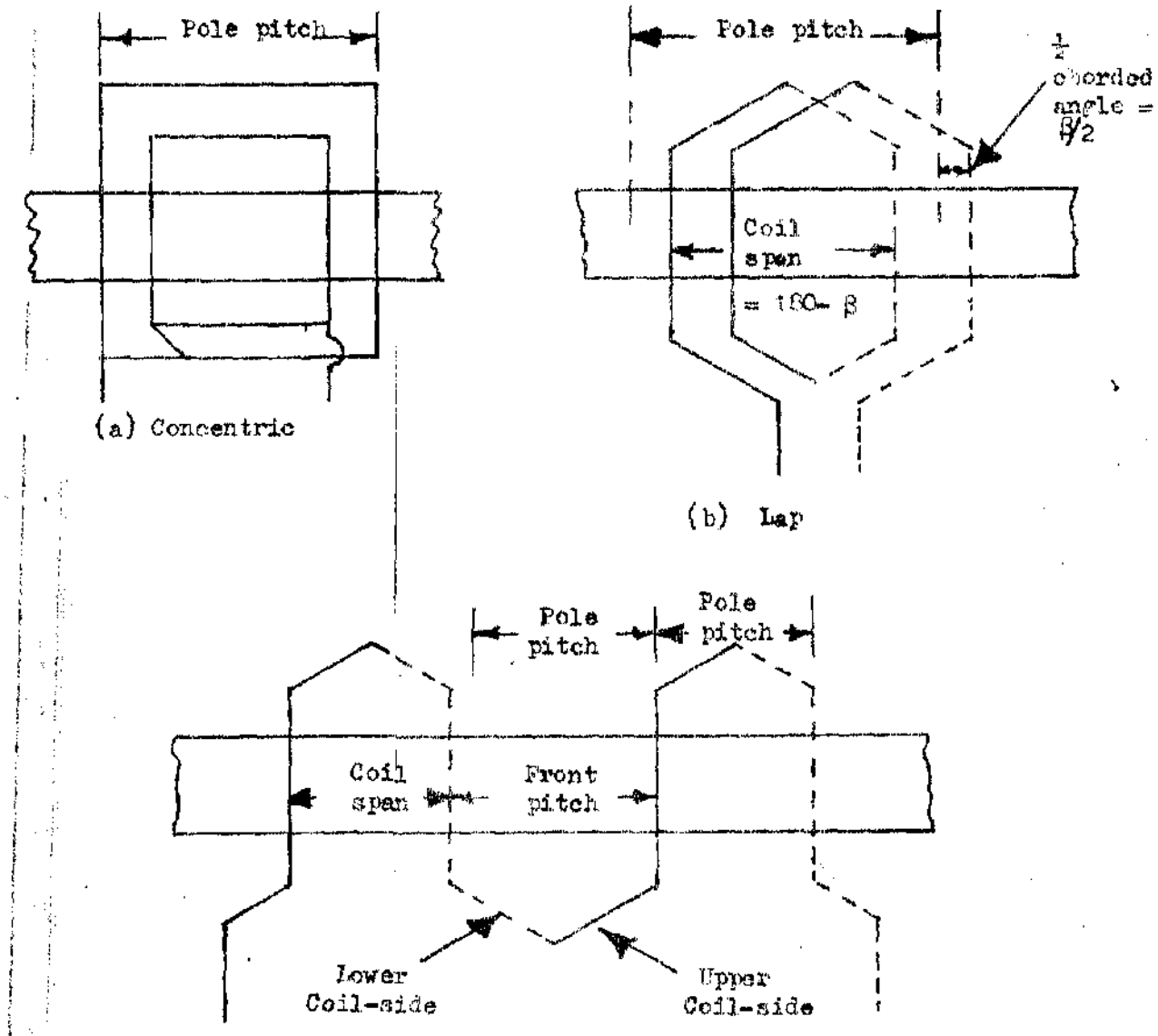


FIGURE 11: Types of Coil.

(c) Phase-spread: The requirements of an a.c. winding are that it shall produce a symmetrical m-phase system of e.m.f.'s of identical magnitude, wave-shape and frequency, and displaced in time-phase by $\gamma = 2\pi/m$ electrical radians. This is secured by having identical windings for all phase-groups, and arranging the groups with an effective space displacement of $2\pi/m$ electrical radians. Hence phase-spread is either $2\pi/m$ or π/m electrical radians.

(d) Slotting: This could either be integral or fractional. Windings with a whole number of slots per pole (i.e. y = number of slots S divided by number of poles 2p is an integer) are called integral-slot windings. The arrangements in which y is fractional are termed fractional-slot windings.

(e) Coil-span: This is the spacing of coil-sides; figure 11. When coil-sides are spaced by exactly a pole-pitch they are said to be of "full-pitch". The pitch of a coil may be greater or - more often - less than a pole-pitch, in which case it is described as "short-pitched" or "chorded". The latter is usually done to reduce the amount of copper in the end-connections and to reduce or suppress certain harmonics in the phase e.m.f.

(f) Coil Group: There is one coil group per pole pair per phase and each coil group is made up of 2 or more single coils usually connected in series. Each coil must have one or more turns. To connect coils to form a coil group, the last turn of the first coil of a coil group is connected to the first turn of the second coil of the same coil group, and so on, until all coils are connected together.

(g) Circuits: A circuit is formed by connecting the coil groups of a phase either in series or parallel. The latter is done only when windings are required for large currents and low e.m.f.s. For series connection of coil groups of a phase two coil ends which carry current in opposite directions should be connected together. For parallel connection of the coil groups, ends carrying current in the same direction have to be connected together.

(h) Coils: The coils may have one turn or several. In the former case single-turn coils require only one conductor in each layer, but this will generally be laminated to facilitate bending in the end-windings and to reduce eddy current losses. These coils form bar-windings, and are commonly found in low-voltage machines with large phase currents. Machines with small numbers of poles and low values of flux per pole require a relatively large number of turns per phase: this is true also of high-voltage machines. However, the choice of coil depends on the number of turns per phase required to generate the e.m.f., the current rating, and the number of parallel circuits obtainable.

(i) Pole-pitch and Slot Angle: Let the following be defined thus:

S - the number of slots in the stator or rotor

2p - the number of poles

n - the number of phases

y - the pitch of the winding

The pole-pitch of the winding, $y = S/2p$. The coil-pitch or coil-throw is the number of slots between two coil sides of a coil. The coil-pitch, Z, is equal to the pole-pitch for a full-pitch winding. For short-chorded winding Z is greater than or less than y.

The short-chording angle, $\beta = 180\ (1 - Z/_y)$ electrical degrees

The slot angle (slot-pitch), $\alpha = 360\ P/S$ electrical degrees

The number of slots per pole per phase, $q = S/2pm$.

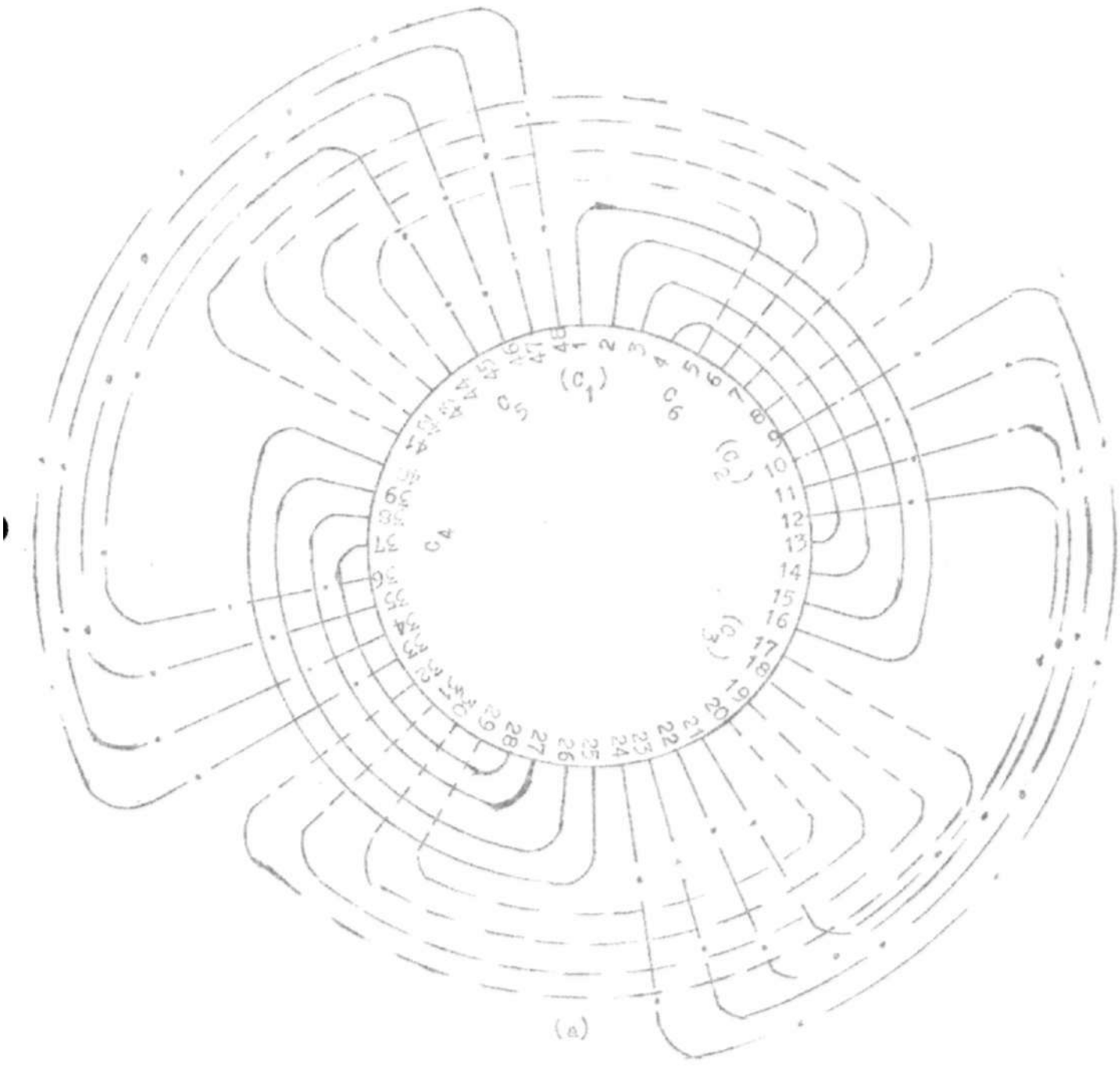
Distance in slots between beginnings of two phases for phase sequence $\gamma = \gamma/\alpha = X$ slots. For the beginning of phase I at slot 1, beginning of phases II and III must be at slots 1 + X and 1 + 2X respectively.

3.2 Single-Layer Windings.

3.2.1 Three-Phase Concentric Winding.

Concentric winding are so named because all the coils for a single pole have a common center and different pitches, or throws, for each individual coil.

A 3-phase concentric winding is best understood by an example. Figure 12 shows the circular and developed diagrams of a concentric winding for a 3-phase, 4-poles induction motor with 48-stator slots. In the diagram, four coils, connected in series, make up a coil group. Each coil consists of several turns and the cross-over from one coil to the next is indicated by a short slanted line.



(a)

FIGURE 12(a): Circular diagrams of a Concentric Winding, 48- slots 4-poles 3-phase Induction Motor.

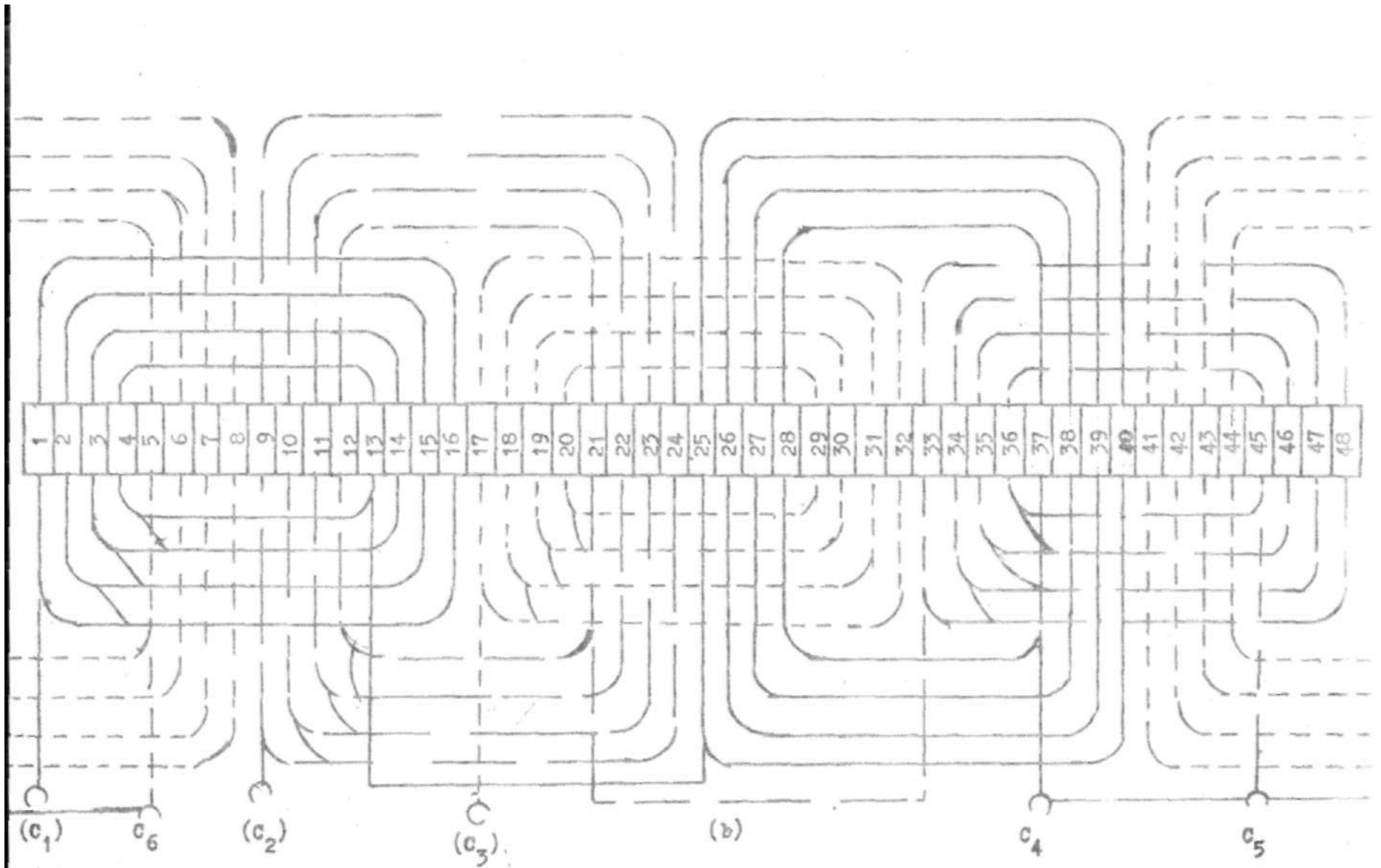


FIGURE 12(b): Developed diagrams of a Concentric Winding, 48-slots 4-poles 3-phase Induction Motor.

Procedure in constructing the diagram is as follows:

(i) $S = 48$; $2p = 4$; $m = 3$. Given.

(ii) Hence, from (i) $q = S/_{2pm} = 48/(4 \times 3) = 4$

(iii) With the slots allocated numbers serially from 1 to 48, and with the number of slots per pole per phase, $q = 4$, known, construct table 1 as shown. An asterisked number signifies the starting slot for a phase. It will be seen that the first number of the first North polarity for each phase is chosen.

(iv) If current flows in the upward direction in the North pole, it flows in the downward direction in the South pole. Also there is a coil

TABLE 1: Slot Allocation for 3-phase, 4-pole, 48 slots Concentric Winding.

POLE-PAIR	POLE	PHASE	POLARITY	SLOTS/CONDUCTORS)
		I	N	* 1 2 3 4
1	1	III	S	5 6 7 8
		II	N	* 9 10 11 12
	2	I	S	13 14 15 16
		III	N	* 17 18 19 20
		II	S	21 22 23 24
2	3	I	N	25 26 27 28
		III	S	29 30 31 32
		II	N	33 34 35 36
	4	I	S	37 38 39 40
		III	N	41 42 43 44
		II	S	45 46 47 48

group per pole-pair per phase. Then, for example, a coil group for phase I and pole-pair 1 is formed by concentrically joining the conductors in the North pole to those of the South pole thus:

N ⟶ 1 ⟶ 16 ⟶ 2 ⟶ 15 ⟶ 3 ⟶ 14 ⟶ 4 ⟶ 13 ⟶ S

On the whole the total number of coil groups should be mp = 2 x 3 = 6; 2 for each phase. Hence, the coil group for Phase I and pole-pair 2 is:

N ⟶ 25 ⟶ 40 ⟶ 26 ⟶ 39 ⟶ 27 ⟶ 38 ⟶ 28 ⟶ 37 ⟶ S

Then by joining these two coil groups together either in series or parallel a phase group circuit is formed.

Similar procedure could be performed for the other two phases resulting in six terminals; C1 and C4 for phase I, C2 and C5 for phase II, and C3 and C6 for phase III. These terminals could be connected to form either a star or delta connection.

The pole-pitch $y = 48/_4 = 12 = (13 - 4) + (14 - 3) + (15 - 2) + (16 - 1)/4$, the arithmetic mean of the pitches of the coils in a group.

3.2.2 Single-Phase Concentric Winding (Plate II).

This is just a single phase of the three-phase winding discussed in 3.2.1, except that in single-phase induction motors there are two single-phase windings, the main winding and the starting winding. However, there is no need for a special procedure here since the diagram is simply constructed for the given distributions. For example a single-phase 2-pole motor with 24 slots having the following distributions:

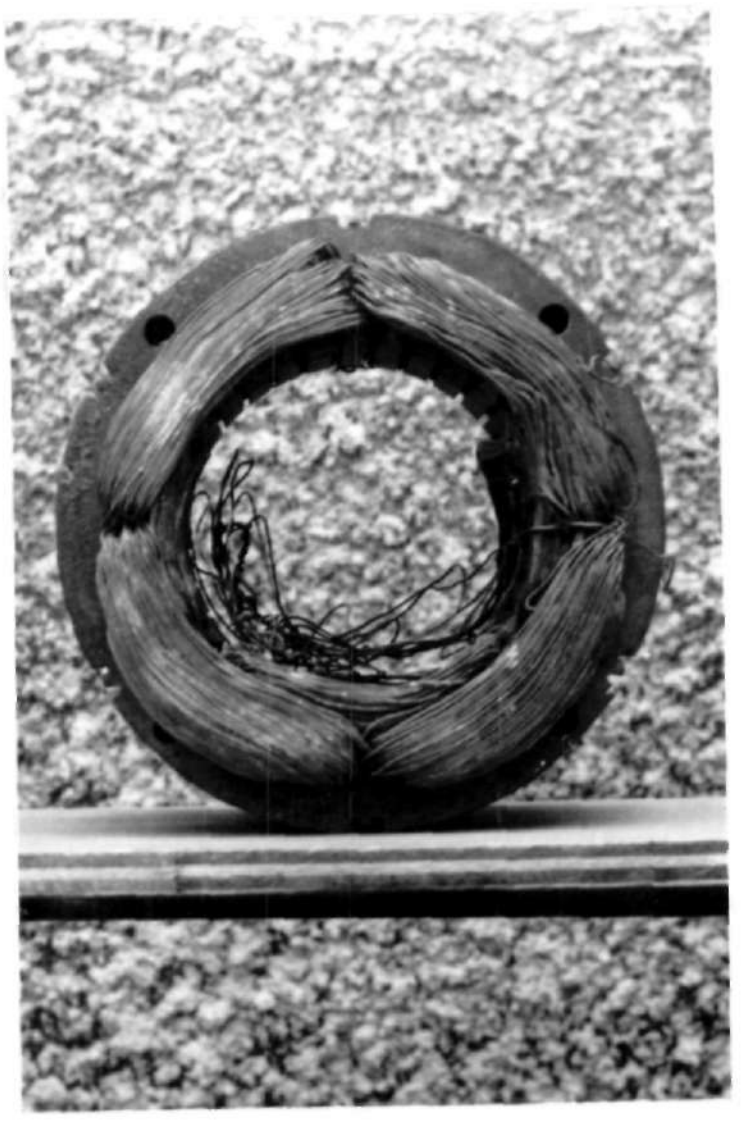


PLATE II: A 4 - Pole Single - Phase

Concentric Winding.

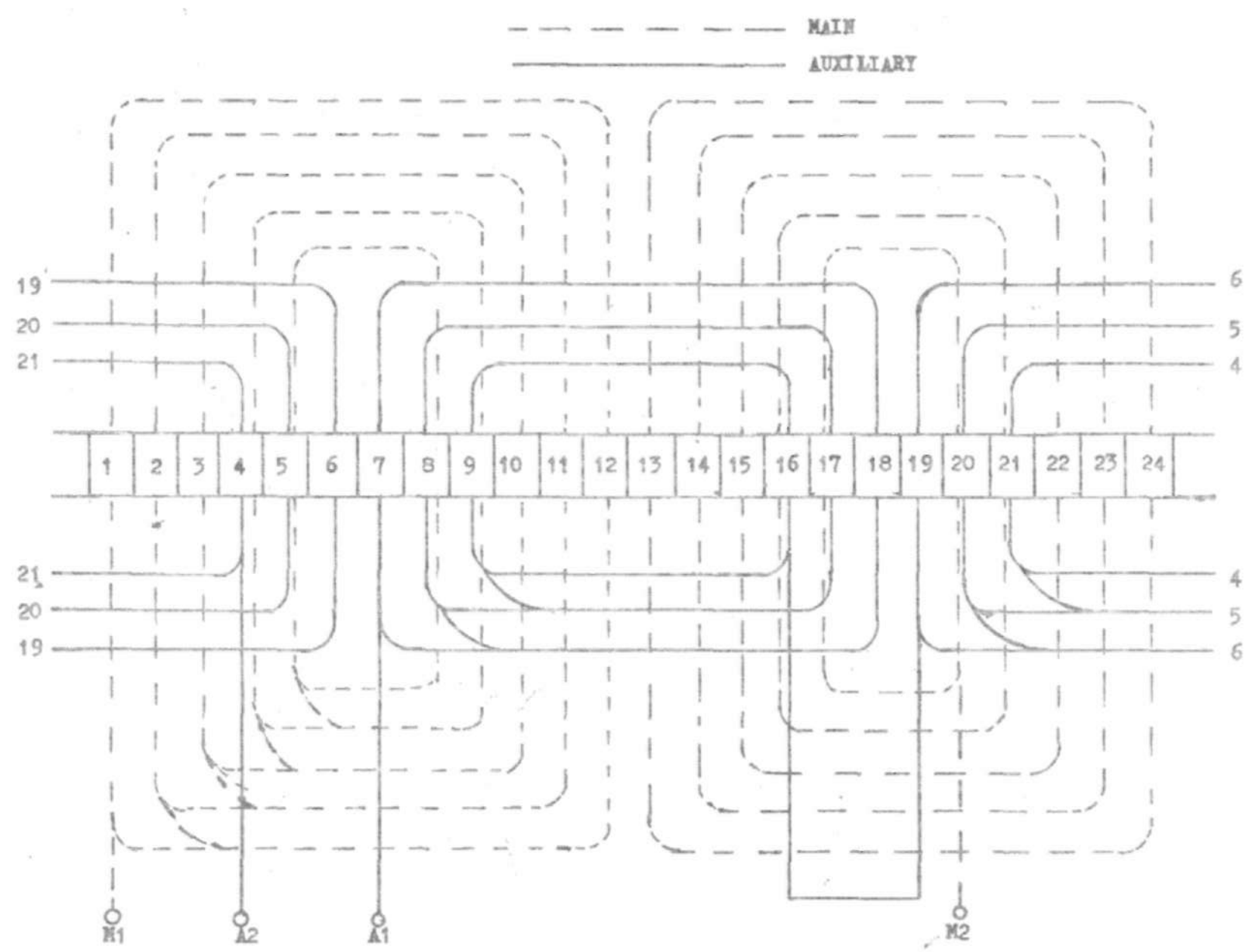


FIGURE 13: Developed diagram for a single-phase 2-pole motor with 24-slots.

Slots:-	1	2	3	4	5	6	7	8	9	10	11	12
Main:-	1	1	1	1	1	X	X	1	1	1	1	1
Auxilliary:-	1	1	1	X	X	X	X	X	X	1	1	1

will be drawn as in Figure 13 according to table 2. The main winding is displaced in phase from the auxiliary winding by β electrical degrees. In practice, $\beta = 90$, but there are designs in which β is either less or more than 90 electrical degrees.

TABLE 2: Slot Allocation Table for Single-Phase Concentric Winding.

SLOT NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
MAIN	1	1	1	1	1			1	1	1	1	1	1	1	1	1	1			1	1	1	1	1
AUX.				1	1	1	1	1	1							1	1	1	1	1	1			

3.2.3 Windings with Equal-Span Coils.

Equal-Span coil winding is the name applied to windings consisting of coils wound with an identical pitch. These windings have the advantage that their pitch can be shortened. Three types can be identified: mush (plate III), involute, and chain or imbricated windings. Each differ from the other by the way the end connection is arranged. The difference in the arrangement of the end connection is achieved by altering the mode of formation of the coil groups or, and, shortening the pitch.[17,18].

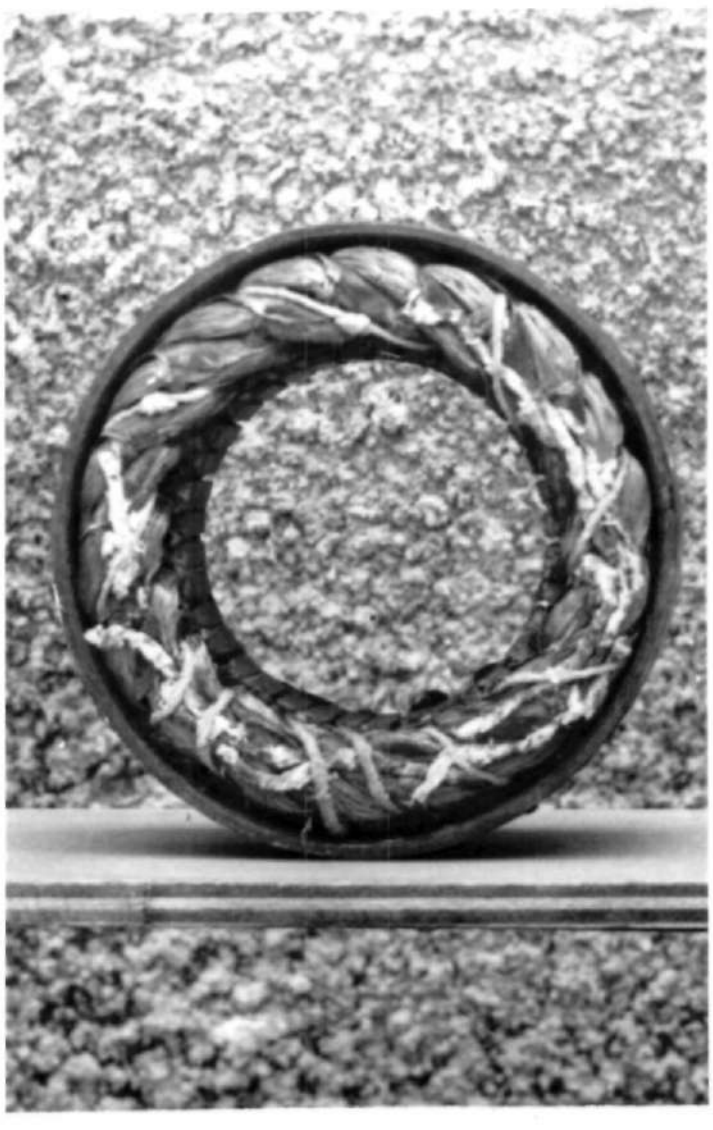


PLATE III: A mush Winding.

3.3 Double-Layer Windings

3.3.1 Three-Phase Distributed Windings.

Distributed windings are so called because they have more than one slot per phase per pole. For example a 3-phase, 2-pole induction machine with 12 slots will be as shown in Figure 14(a) for a full-pitch lap winding, and Figure 14 (b) for a full-pitch wave winding. Procedure for the construction of these diagrams is as follows:-

(i) S = 12, 2p = 2, m = 3. Given.

(ii) With the slots allocated numbers serially from 1 to 12, and with the number of slots per pole per phase, q = S/2pm = 12/6 = 2, known, table 3 is constructed as shown. An asterisked number signifies the starting slot for a phase. It will be seen that the first number of the first North pole for each phase is chosen. The bracketed numbers are repetition of the unbracketed ones but with slash superscript. Those without slashes represents the top layer of the slots and those with slashes represents the botton layers.

TABLE 3: Slot Allocation for 3-phase, 2-poles, 12 slots Double-Layer Windings

POLE- PAIR	POLE	PHASE	POLARITY	SLOTS
1	1	I	N	*1(1') 2 (2')
		III	S	3 (3') 4 (4')
		II	N	*5 (5') 6 (6')
	2	I	S	7 (7') 8 (8')
		III	N	*9 (9') 10 (10')
		II	S	11(11') 12 (12')

(iii) The pole-pitch = $S/_{2p}$ = $12/_{2}$ = 6. A full-pitch will have the coil-span of all the coils equal to the pole-pitch. Hence, 6 in this case.

(iv) Lap Winding: For example for phase I, the starting slot is 1. 1 + 6 = 7, then a coil is formed by connecting a conductor in slot 1 to a conductor in slot 7. Since it is a double layer winding the top layer of slot 1 will be connected to the botton layer of slot 7. Hence, a coil is 1 - 7'. Similarly, 2 + 6 = 8, then another coil is 2 - 8'. To form a coil group, these two coils are joined together as shown in the diagram. Hence, a coil group is:

N ⟶ 1 ⟶ 7' ⟶ 2 ⟶ 8' ⟶ S

A closer study will show that this arrangement obeys the polarity (or the direction of flow of current). The second coil group is formed similarly by connecting the conductor in the bottom layer of slot 1 to that in the top layer of slot 7, and the conductor in the bottom layer of slot 2 to that in the top layer of slot 8 thus,

N ⟶ 1' ⟶ 7 ⟶ 2' ⟶ 8 ⟶ S

By connecting these two coil groups either in NSNS (series) or NNSS (parallel) a phase group circuit can be formed. The diagram shows a series connection.

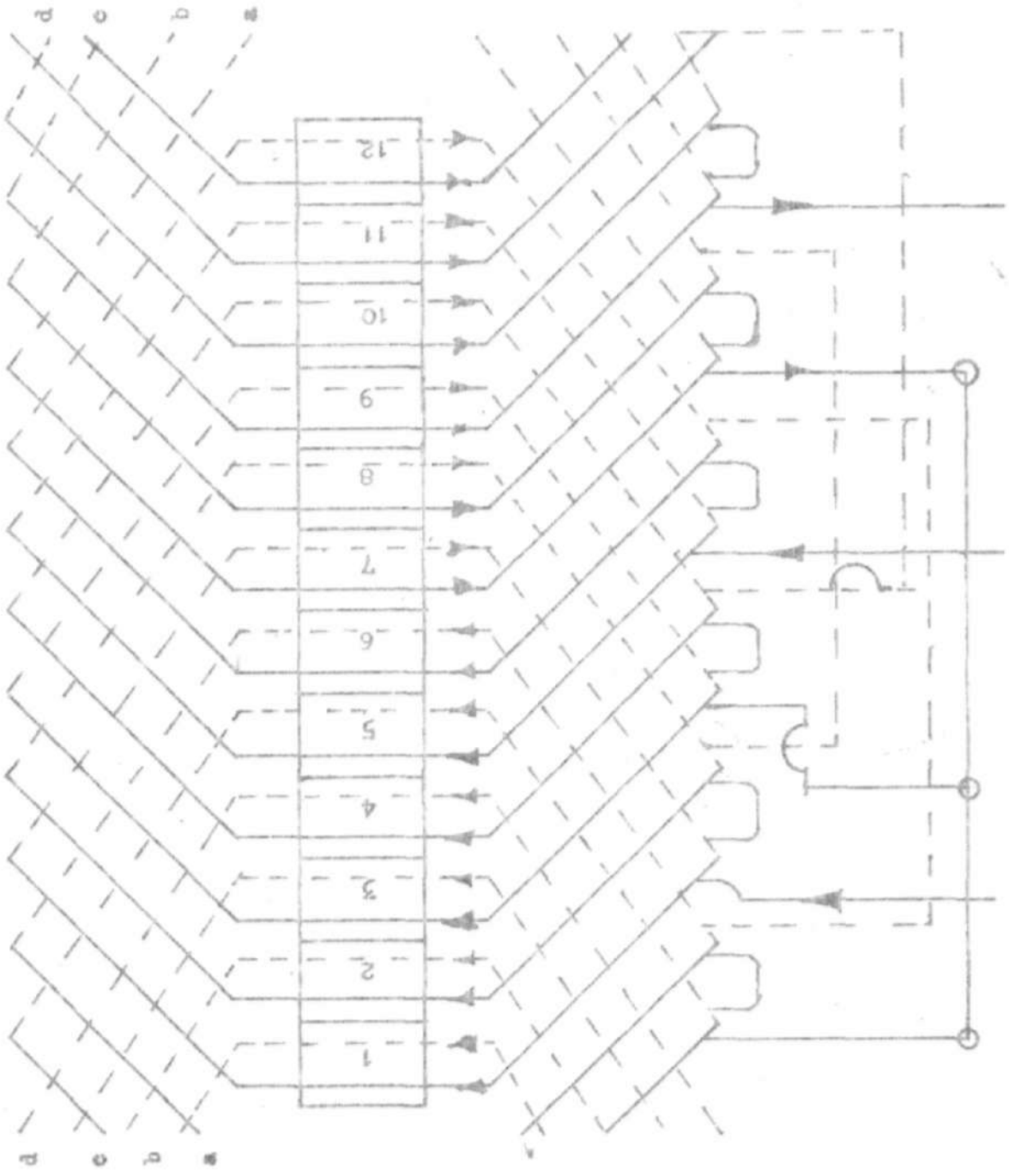


FIGURE 14(a): Developed diagram of a 3-phase, 2-pole, full-pitch, lap winding (Star Connected).

The same process can be repeated for the other 2 phases. Thus resulting in six terminals which could be connected in star or delta. Figure 14 (a) shows a star connection.

(v) Wave Winding: To construct a wave winding table 4, for phase I only, will have to be constructed from table 3. Hence, for

TABLE 4: Coil-Group for One Phase of a Wave Winding

POLE GROUP / COLUMN	1 ⟶ 2	2 ⟶ 1
1st	S ⟶ 1 ⟶ 7'	E ⟵ 7 ⟵ 1'
2nd	2 ⟶ 8'	8 ⟵ 2'

phase I group circuit the connection should be:-

START ⟶ 1 ⟶ 7' ⟶ 2 ⟶ 8' ⟶ 2' ⟶ 8 ⟶ 1' ⟶ 7 ⟶ END

The same table could be constructed for other phases. For further understanding of how to construct table 4 another example is considered. For example table 5 shows a phase I group circuit connection for a 3-phase, 4-poles induction machine with 24 slots.

FIGURE 14(b): Developed diagram of a 3-phase, 2-pole, full-pitch, wave winding.

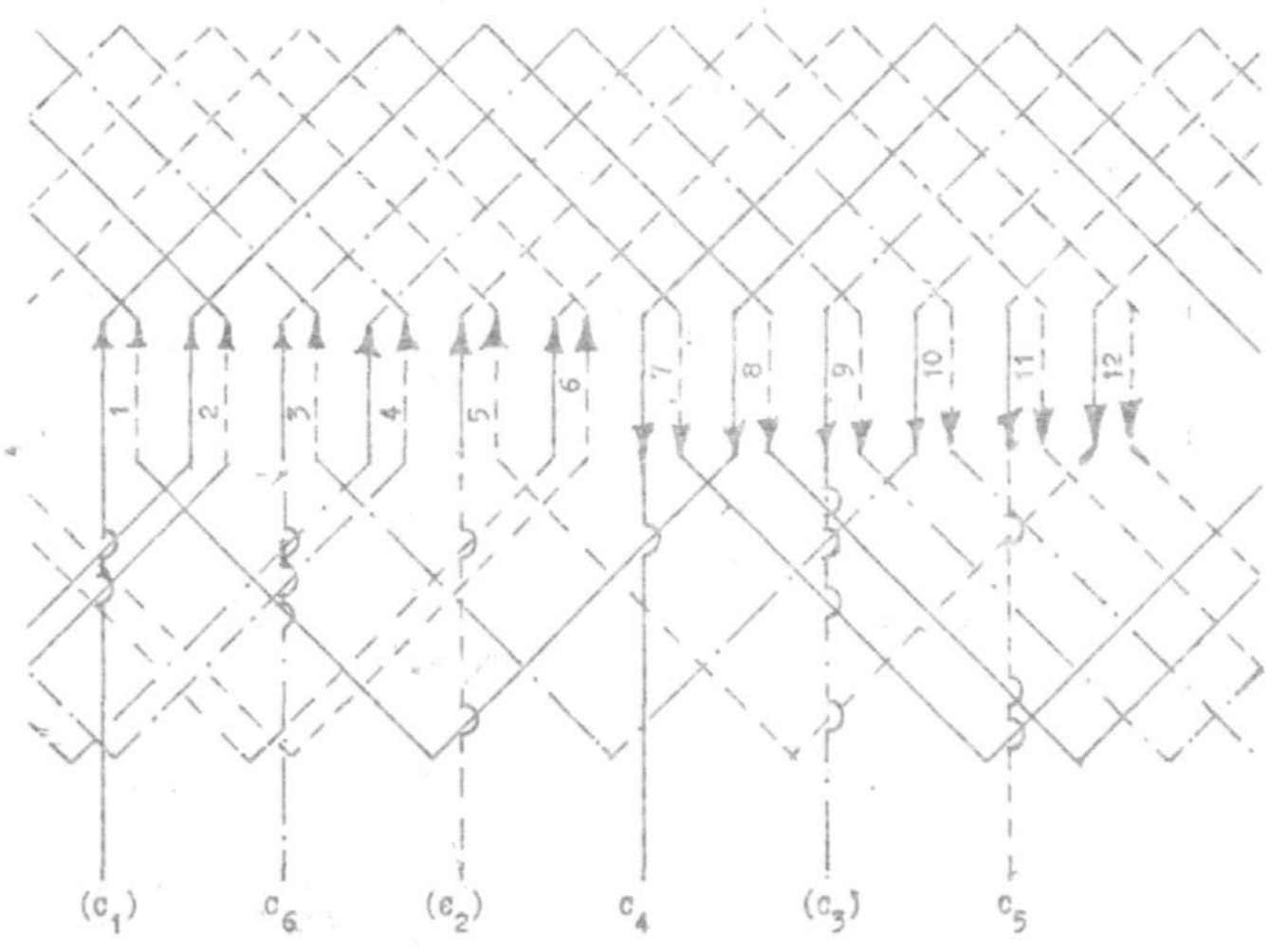


TABLE 5: Coil Group for One phase of a 3-phase,4-poles, 24 slots Wave Winding.

POLE GROUP / COLUMN	1 → 2 3 → 4	2 → 3 4 → 1
1st	S ← - - → 1 - → - 7'	E ← - 7 ← - 13' 13 → - 19' 19 - ← - 1'
2nd	2 → - 8' 14 → - 20'	8 - ← 14' 20 - ← 2'

3.4 Fractional Pitch or Short-Chorded Winding.

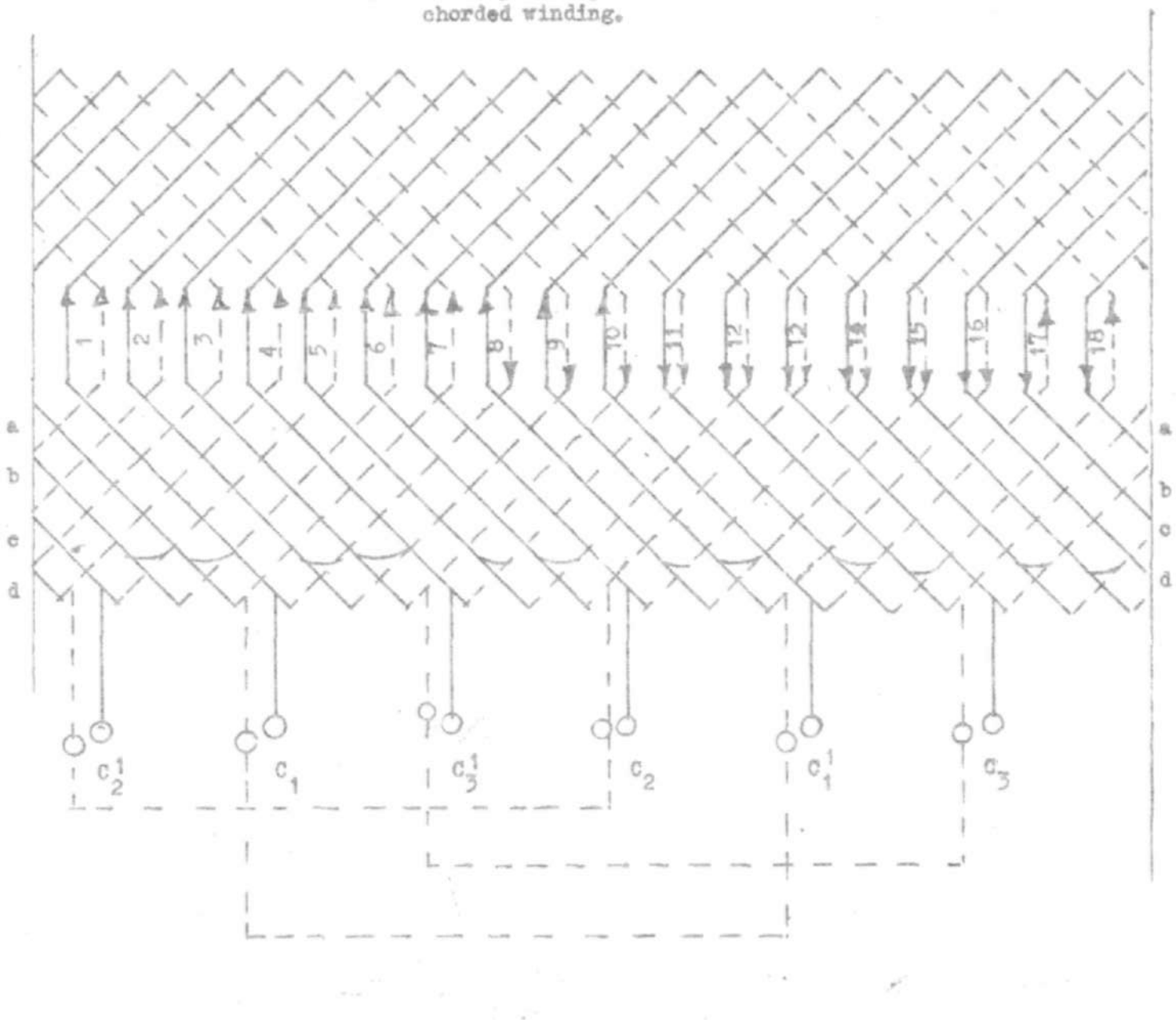
This is best understood by considering an example. Consider a 3-phase, 2-pole induction machine with 18 slots. The winding diagram is as shown in Figure 15. Procedure is as follows:-

(i) Given: S = 18; 2p = 2; m = 3.

(ii) $q = S/2pm = 18/6 = 3$

(iii) Pole-pitch, $y = 18/2 = 9$. For full-pitch, the coil-pitch = 9.

FIGURE 15: Developed diagram of a 3-phase, 2-pole, 18 slots, 2 layer chorded winding.



But to reduce harmonic content of the winding and hence the machine, the winding is short-chorded by 2 slots so that the coil pitch becomes 9 – 2 = 7. Hence, $\beta = 180\ (1 - 7/9) = 40$ degrees.

$$\text{Cos } \beta/2 = 0.94$$

(iv) Construct table 6. Slot angle, $\alpha = 360/S = 360/18 = 20^{o}$

Hence, distance in slots between beginnings of any two phases for phase sequence of 120 degrees $= 120/20 = 6$ slots. For the beginning of phase I at slot 1, beginning of phases II and III must be at slots 1 + 6 = 7 and 7 + 6 = 13 respectively. They are asterisked in the table.

TABLE 6: Slot Allocation Table for a 3-phase, 2-poles, 18 slots Double-Layer Winding with Fractional Pitch.

POLE-PAIR	POLE	PHASE	POLARITY	SLOTS
1	1	I	N	*1 (1') 2 (2') 3 (3')
		III	S	4 (4') 5 (5') 6 (6')
		II	N	*7 (7') 8 (8') 9 (9')
	2	I	S	10 (10') 11 (11') 12 (12')
		III	N	*13 (13') 14 (14') 15 (15')
		II	S	16 (16') 17 (17') 18 (18')

(v) The theoretical slot allocation (for full pitch coil) is shown in the table. However, because of short chording, some slots will accomodate

coil sides of different phases. That is, the bottom of a slot may be used for one phase, whilst the top is used for another phase. In such slots, currents will flow in opposite direction. This occurrence is common in short-chorded designs. In fractional pitch windings, the number of slots in which currents flow are in opposite directions is usually given as 2p (pole pitch - coil pitch). Here the slots are 8, 9, 17 and 18.

(vi) Taking the top coil side of slot 1 as the beginning of phase I, the coil's other coil side will lie in the bottom of slot 1 + 7 = 8. The coil is then denoted by 1 - 8'. That is and in general, in two-layer winding, one coil side lies in top of one slot, and the other in the bottom part of another slot one coil pitch away. The construction using parallel lines is as shown in Figure 15.

For 3 slots per pole per phase, the last turn from 8' will be connected to the first turn on top of slot 2 whose bottom coil side is in slot 9 (denoted 2 - 9'). The last turn from 9' is connected to top of first turn in slot 3 the bottom of which is in slot 10 (the coil is 3 - 10'). Thus we have passed through and connected three coils ($q = 3$) in series to form the coil group with two ends coming out at 1 and 10'.

Since the full pitch is 9 slots, then the next coil group with respect to phase I must start at 1 + 9 = 10. The bottom of coil whose top is at slot 10 must be in 10 + 7 = bottom of slot 17. Accordingly, the coils which make up the coil group are 10 - 17' to 11 - 18' to 12 - 1'.

By connecting these two coil groups either in NSNS (series) or NNSS (parallel) a phase group circuit can be formed. The diagram shows a series connection.

The same process can be repeated for the other 2 phases. Thus resulting in six terminals which could be connected in star or delta.

Single-phase motors can be wound in two layer winding also. This usually offers better performance characteristics and involves the main and auxiliary windings respectively.

3.5 Fractional-Slot Windings.

These are windings in which the slots per pole per phase are expressed as a whole number plus a fraction. For example a 3-phase, 8-poles induction motor with 36 slots has $q = 36/(8 \times 3) = 1\frac{1}{2}$. In induction motors, such cases usually arise when stators with the same number of slots are wound for more than one number of poles. For a given number of slots in the stator, the slots per pole per phase in one winding will turn out to be a whole number, and in another winding a fractional number.

The fractional-slot winding differs from the integral-slot winding in that it must be composed of coil groups with different numbers of coils and each phase must occupy the same number of slots, otherwise the winding would be unbalanced.

Detail treatment are found in already published works.[9,17,19,20]

CHAPTER 4

THEORY AND PERFORMANCE CALCULATION METHODS.

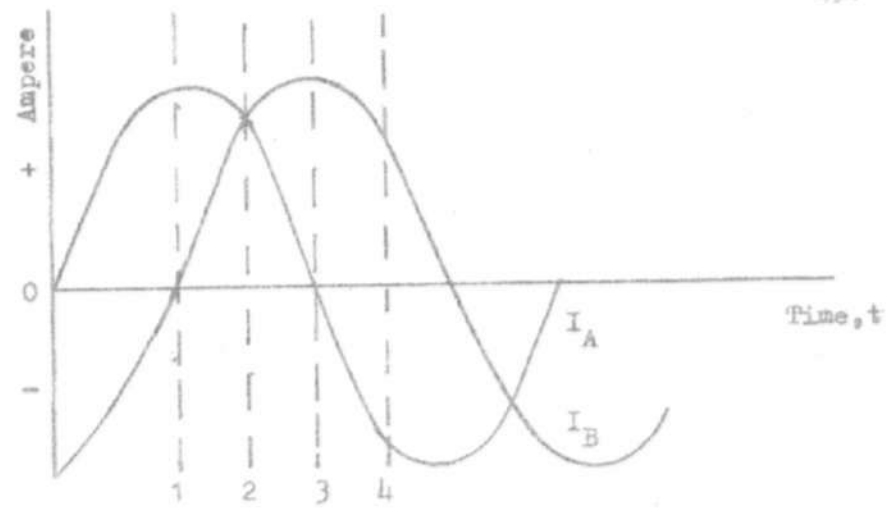
While polyphase induction motors are explained and analysed by a single theory, the revolving field theory, the single-phase induction motors are analysed by two, the cross-field theory and the revolving field theory. These theories are useful for qualitative and quantitative analysis of single-phase induction machines.

Veinott, in his book[1], presented a quantitative and qualitative treatment of these theories. His quantitative treatment led to methods for calculating the running and combined-winding (main and auxilliary)performances of a single-phase induction motor from its characteristic constants, which may be derived by calculation or from test. These methods, due to their simplicity and thoroughness, are quite suitable for use in computer-aided design, and are therefore adopted with suitable modification in this work.

However, both theories are equally good and give the same overall answers. Therefore, a theory used in a particular work is a matter of choice. In this work, the revolving theory is chosen, and hence, shall be given a better treatment.

4.1 Production of a Rotating Field.

Imagine two coils, A and B, placed in quadrature to each other. The cross-sectional view is as shown in Figure 16. Let each be a distinct



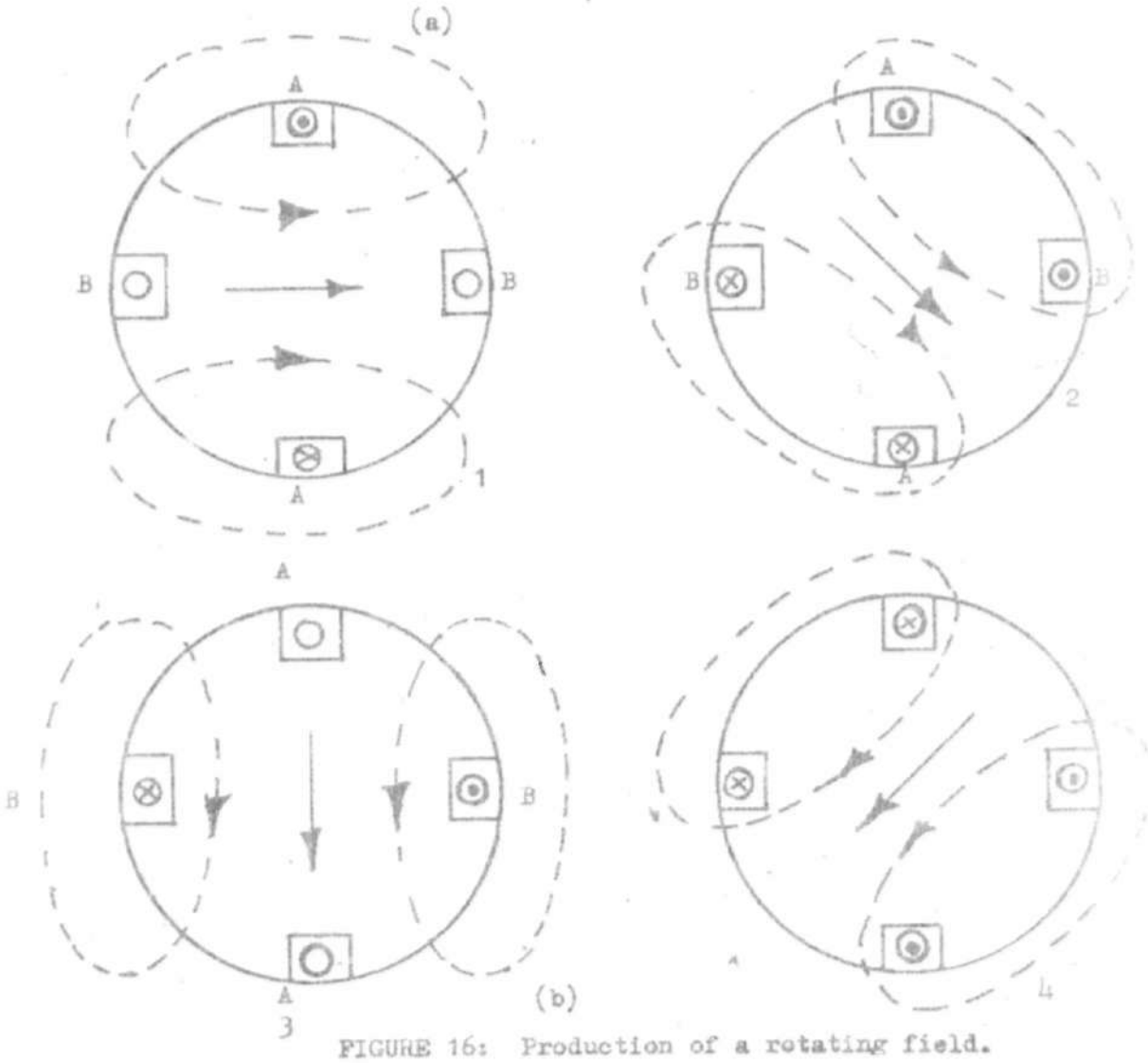


FIGURE 16: Production of a rotating field.

circuit that is supplied with current from separate sources. Let these two currents, I_A and I_B, be sinusoidal, equal in magnitude and frequency but 90 degrees out of phase in time. Such currents are represented by sine curves in Figure 16 (a), where instantaneous values of the currents I_A and I_B are shown.

The four views shown in Figure 16 (b) are drawn to represent the instantaneous currents (1, 2, 3, and 4 in Figure 16 (a)) in the two coils and the corresponding instantaneous resultant fields set up by them at each of the four different instants of time. The dotted lines represent the field and the arrows on them, the directions. The dot on the cross-sectional view of the coil indicates that the current is flowing directly toward the observer, while a cross indicates that it is flowing away from the observer.

A close observation of the four views shows that the resultant field rotates through 45° for a time lapse from 1 to 2, and another 45° for 2 to 3, and so on. Hence, the field will make one complete revolution in one cycle of current. Thus, a rotating magnetic field has been set up by the structure and the two conditions necessary for this are: (1) two separate circuits (made of coils) located 90 electrical degrees apart in space; (2) two phases, or sources of a-c voltages, equal in magnitude and displaced by 90 degrees in time.

4.2 Cross-Field Theory

The structure in 4.1 is a two-phase induction motor if in place of the coils we have two separate phase windings. If currents are supplied to the windings as in 4.1, there will be two component fields that are stationary in space, but pulsating in amplitude with time, and these two component fields combine in such a way as to produce a single field which remains substantially constant in amplitude, but rotates at a uniform speed.

If one of the phase windings in the two-phase motor is removed or open-circuited. We shall be left with a single-phase induction motor. A current through this single winding on the stator will set up only one stationary pulsating field component with fixed axis. Since the other field component is absent there will be no rotating field, hence no torque and no tendency to start.

Somehow if starting is achieved and the rotor revolves at synchronous speed the windings of the rotor will revolve through the stator field (the stationary pulsating field), voltage will be induced in it due to the cutting of flux lines. This induced voltage is in phase with the stator flux and magnetizing current since it is directly proportional to flux density at constant speed. The induced voltage in the rotor winding implies current flowing in the winding and hence the setting up of a field component whose axis is in space quadrature with that of the stator field. This axis is known as the cross-field axis. Hence, satisfying one of the conditions necessary for the production of a rotating field.

The second condition, that the cross-field should also be in time quadrature with the main field (the stator field), is satisfied by thinking of the rotor winding as mostly inductive, hence the impedance is mostly reactive so that any current flowing in it would lag behind the voltage induced in it by about 90 degrees.

4.3 Revolving-Field Theory

The revolving field theory of single-phase induction motor is developed from the fact that the sum of two uniformly rotating vectors, equal in magnitude and rotating in opposite directions, is equal at all instants of time to a stationary vector which merely pulsates in magnitude. For example, Figure 17 shows two vectors of constant magnitude F/2, revolving in opposite directions at an angular velocity w. At time t = 0, they are both horizontal in the same direction, hence having resultant F. At time t = t, they take positions wt radians above and wt radians below horizontal, as shown. The vector sum is F cos wt which is a vector which remains stationary in space but pulsates in magnitude sinusoidally with time.

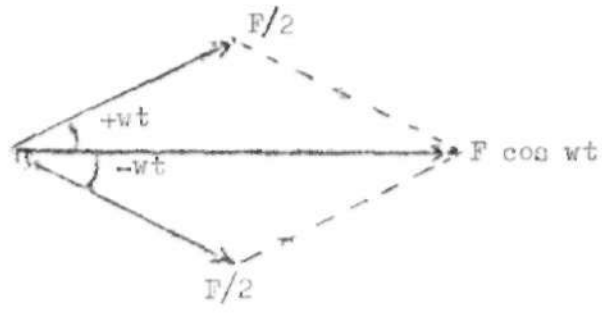


Figure 17. Resolution of a stationary pulsating vector into two constant-magnitude revolving vectors.

For a practical application, the magnetic flux in the air gap of the induction motors at any instant varies sinusoidally in space around the periphery. Figure 18 shows two oppositely revolving sine waves, equal in magnitude. The one moving in the positive direction is labeled the "forward wave", and the one moving in the negative direction, the "backward wave". At zero, the centers of the two waves both coincided with the Y-axis; at time t = t, they have each moved away from this position by the angles +wt and -wt. Now, let

f_{xf} = height of forward wave at point x

f_{xb} = height of backward wave at point x

f_x = height of resultant wave at point x

Then,

$$f_{xf} = \frac{F}{2} \cos (x - wt) = \frac{F}{2} (\cos x \cos wt + \sin x \sin wt) \quad ...(4.1)$$

$$f_{xb} = \frac{F}{2} \text{Cos} (x + wt) = \frac{F}{2} (\text{Cos } X \text{ Cos } wt - \sin X \sin wt) \quad ...(4.2)$$

$$f_x = f_{xf} + f_{xb} = F \text{ Cos } X \text{ Cos } wt. \quad .....(4.3)$$

f_x is maximum when X = 0 and t = 0, and it is equal to F. At t = 0 f_x = F Cos X. Hence, any stationary pulsating sine wave can be resolved into two counterrevolving sine waves, each having a constant magnitude of half the magnitude of the stationary wave.

4.3.1 Equivalent Circuit for Single-Phase Induction Motor

A single-phase induction motor has a single stator winding which has both resistance, r_1, and reactance, x_1. The resistance r_1 is responsible for the copper loss in the winding, while x_1 is due to leakage flux which

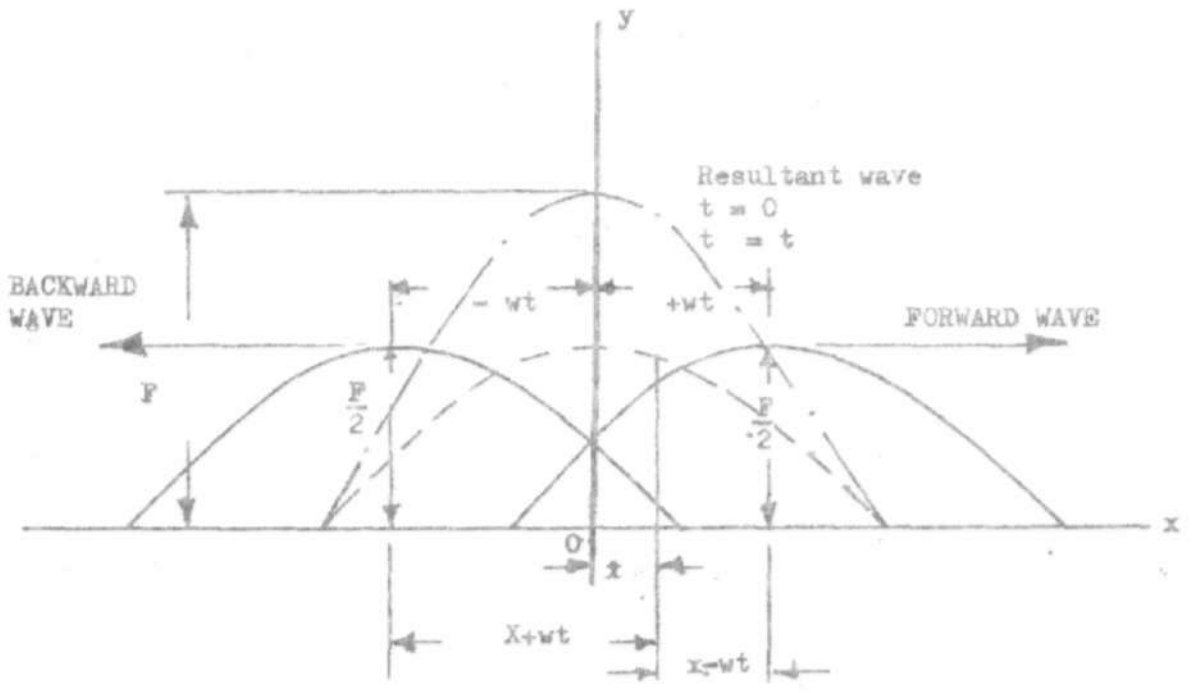


FIGURE 18: Production of a stationary sinusoidally pulsating wave by two constant-magnitude sine waves moving in opposite directions.

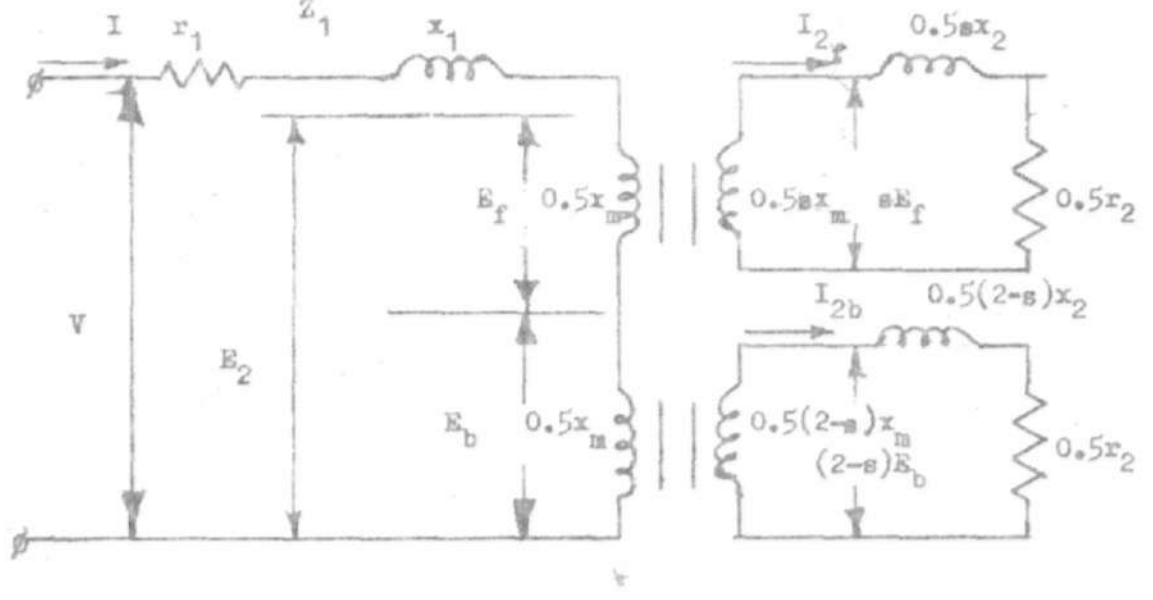


FIGURE 19: Coupled circuits representing the single-phase induction motor, according to the revolving-field theory.

links only the primary winding. The mutual flux, which crosses the air gap and links the secondary winding, is X_m.

Now, applying the revolving field theory, since the actual pulsating air-gap flux is resolved into two equal counterrevolving fields, half the voltage induced by the air-gap flux is due to the forward field and half to the backward field. Hence half the mutual reactance should be charged to the forward and half to the backward field. This is shown in Figure 19.

Now consider the rotor circuits when the rotor is revolving at a speed giving a slip of s with respect to the forward field. The voltage actually induced is sE_f at a frequency of sf, and the reactance in the circuit is $0.5sX_2$, where X_2 is the rotor leakage reactance at line frequency f. The slip of the rotor with respect to the backward field is 2-s. Hence the voltage induced in this circuit is $(2-s)E_b$ at a frequency of (2-s)f, and reactances are multiplied by 2-s. Mutual reactances, of course, are also multiplied by s and 2-s, as shown.

For the primary of Figure 19,

$$V = Ir_1 + jIx_1 + j(I - I_{2f})(0.5X_m) + j(I - I_{2b})(0.5X_m) \qquad (4.4)$$

$$= Ir_1 + j\,Ix_1 + E_f + E_b = Iz_1 + E_2 \qquad (4.5)$$

For the forward-field rotor circuit,

$$I_{2f} = \frac{sE_f}{0.5\,(r_2 + jsX_2)} = \frac{E_f}{0.5\left[(r_2/s) + jX_2\right]} \qquad (4.6)$$

For the backward-field rotor circuit,

$$I_{2b} = \frac{(2-s)\,E_b}{0.5\left[r_2 + j(2-s)X_2\right]} = \frac{E_b}{0.5\left[r_2/(2-s) + jX_2\right]} \qquad (4.7)$$

Hence, from (4.5), (4.6), and (4.7) the classical revolving-field theory equivalent circuit can be drawn as shown in Figure 20.

Power transferred across the air gap = Power input - stator losses (4.8)

= Secondary input (4.9)

From Figure 20, secondary input power = $I_{2f}^2 \left(\frac{0.5r_2}{s}\right) + I_{2b}^2 \left(\frac{0.5r_2}{2-s}\right)$ (4.10)

Obviously, secondary output = secondary input - secondary I^2r losses (4.11)

Hence, secondary Output = $0.5\, I_{2f}^2 \frac{r_2}{s} - 0.5\, I_{2f}^2 r_2 + 0.5\, I_{2b}^2 \frac{r_2}{2-s} -$

$0.5\, I_{2b}^2 r_2$ (4.12)

$= 0.5\, \frac{I_{2f}^2 r_2}{s}(1-s) - 0.5\, \frac{I_{2b}^2 r_2}{2-s}(1-s)$ (4.13)

But Torque = output watts/ $\frac{2\pi N}{60}$ (4.14)

N is the speed and N_s is the synchronous speed

For slip s,

$$N = N_s (1-s)$$

$$\therefore \text{ Torque (N.m)} = \frac{1}{2\pi N_s (1-s)/60} \times \left[0.5\, \frac{I_{2f}^2 r_2 (1-s)}{} - 0.5\, \frac{I_{2b}^2 r_2 (1-s)}{2-s}\right] \qquad (4.15)$$

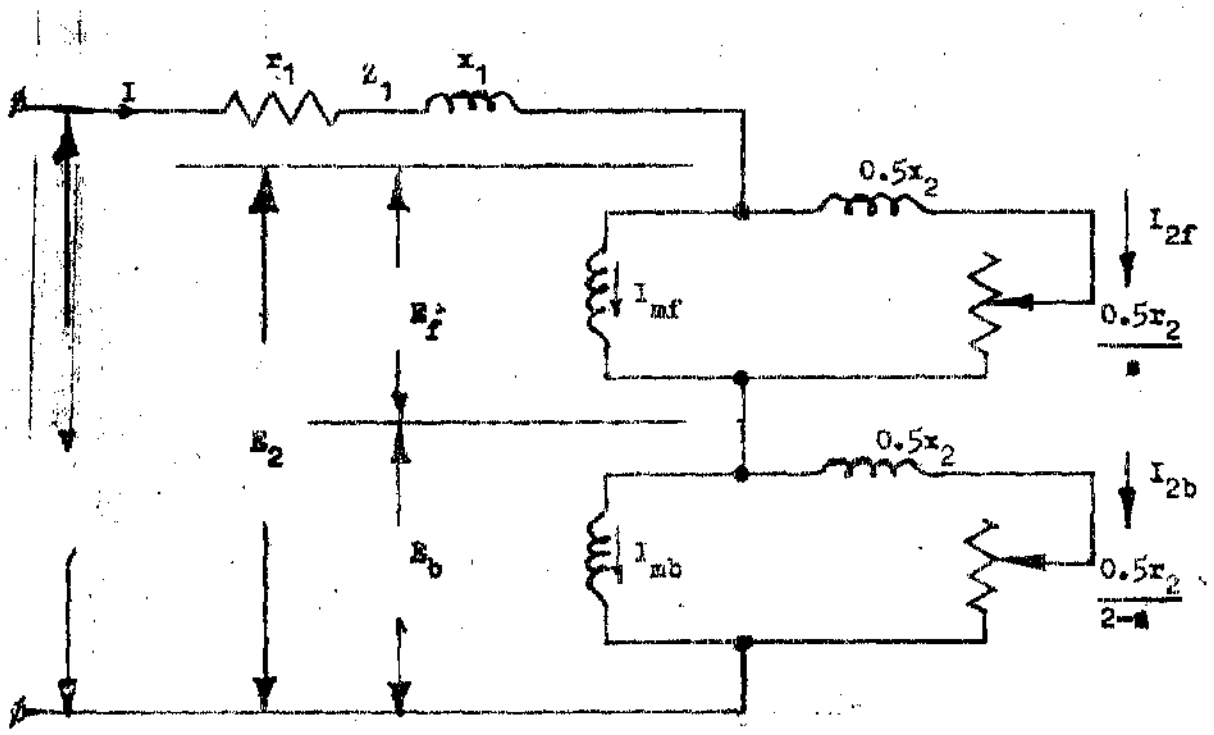


FIGURE 20: Conventional equivalent circuit according to revolving field theory.

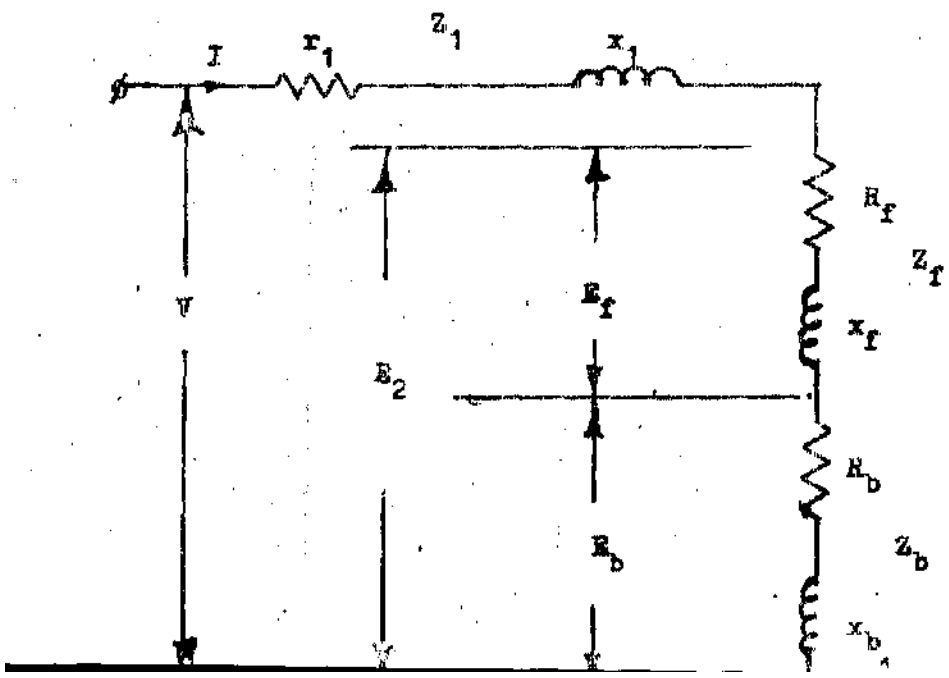


FIGURE 21: Simplified form of the equivalent circuit.

$$\therefore \text{ Torque (synch. Watts)} = \text{Torque (N.m)} \times \frac{2\pi N_s}{60}$$

$$= \frac{0.5\, I_{2f}^{2} r_2}{s} - \frac{0.5\, I_{2b}^{2} r_2}{2 - s} \qquad (4.16)$$

which are the copper losses in the two adjustable resistors of Figure 20. These are the forward and backward torques in synchronous watts.

Currents I_{2f} and I_{2b} represent, in stator terms, the currents induced by the forward and backward fields in the rotor bars at frequencies of sf and (2-s)f, respectively. These currents set up revolving mmfs with each revolving in space at synchronous speed, one forward, one backward. These must be overcome by stator currents which flow in the stator at fundamental frequency. The latter are I_{2f} and I_{2b} in Figure 20.

4.3.2 Running Performance Calculations [1]

A running performance calculating method for the single-phase motor based on the revolving-field theory as exemplified by the circuit of Figure 20 can be developed. The easiest way to do this is to reduce the two parallel branches to equivalent series circuits, so that the whole becomes a simple series circuit, as shown in Figure 21. For the condition that $X_1 = X_2$, it is found that,

$$R_f = \frac{0.5\, K_r\, r_2/s}{\left[(r_2/X_o)/s\right]^2 + 1} \qquad (4.17)$$

$$X_f = \frac{0.5\, X_o K_p \left[(r_2/X_o)/s\right]^2 + 0.5\, K_p X_2}{\left[(r_2/X_o)/s\right]^2 + 1} \qquad (4.18)$$

$$R_b = \frac{0.5\ K_r\ r_2/(2 - s)}{\left[(r_2/X_o)/(2 - s)\right]^2 + 1} \qquad (4.19)$$

$$X_b = \frac{0.5\ X_o K_p \left[(r_2/X_o)/(2 - s)\right]^2 + 0.5 K_p X_2}{\left[(r_2/X_o)/(2 - s)\right]^2 + 1} \qquad (4.20)$$

where $K_p = X_m/(X_m + x_1)$ (4.21)

and $K_r = K_p^2$ (4.22)

Appendix 1 shows a calculation sheet, as used by Veinott[1], suitable for routine performance computations.

$T_f = I^2 R_f$ and $T_b = I^2 R_b$, hence total Torque $T = T_f + T_b$

4.4 *Combined-Winding Performance Calculations.*

Figure 22 shows the schematic diagram of a single-phase induction motor with two windings in space quadrature. Using the revolving field theory the equivalent circuit of the joint operation of the windings in quadrature is as shown in Figure 23.

In this case there are two single-phase windings on the stator, each winding sets up a forward field and a backward field, making four revolving components in all. When the windings are in space quadrature, there is no mutual reactance between the stator windings in the ordinary sense, that is, by transformer action. However, each of the four revolving component fields must of necessity induce a voltage in each stator winding. In each stator winding the sum of these voltages plus the stator leakage-impedance drop must equal the applied voltage. These conditions will determine the primary currents in the respective windings.

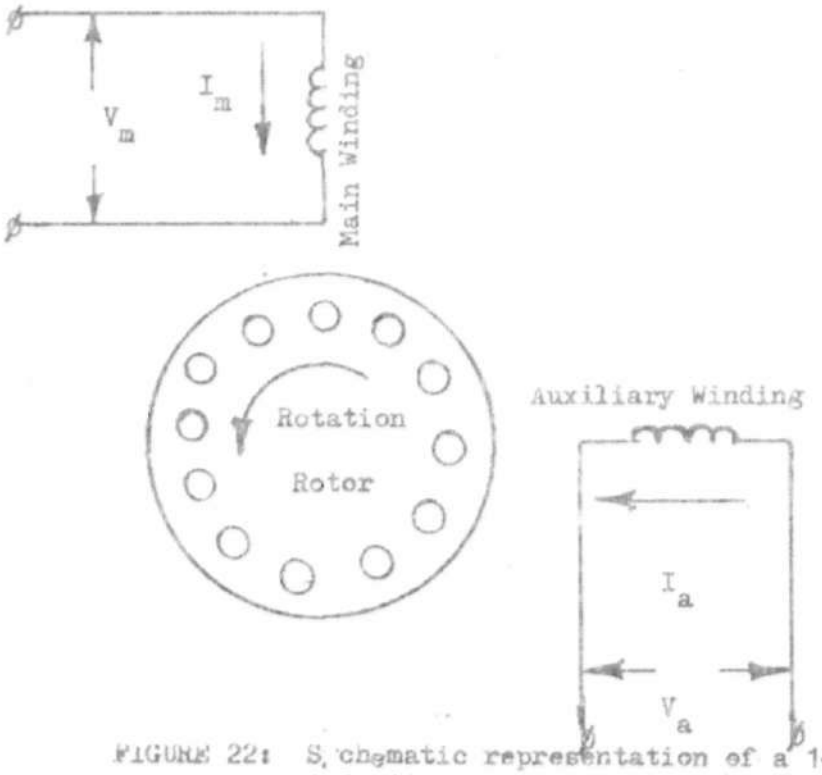


FIGURE 22: Schematic representation of a 1-ϕ induction motor with windings in quadrature.

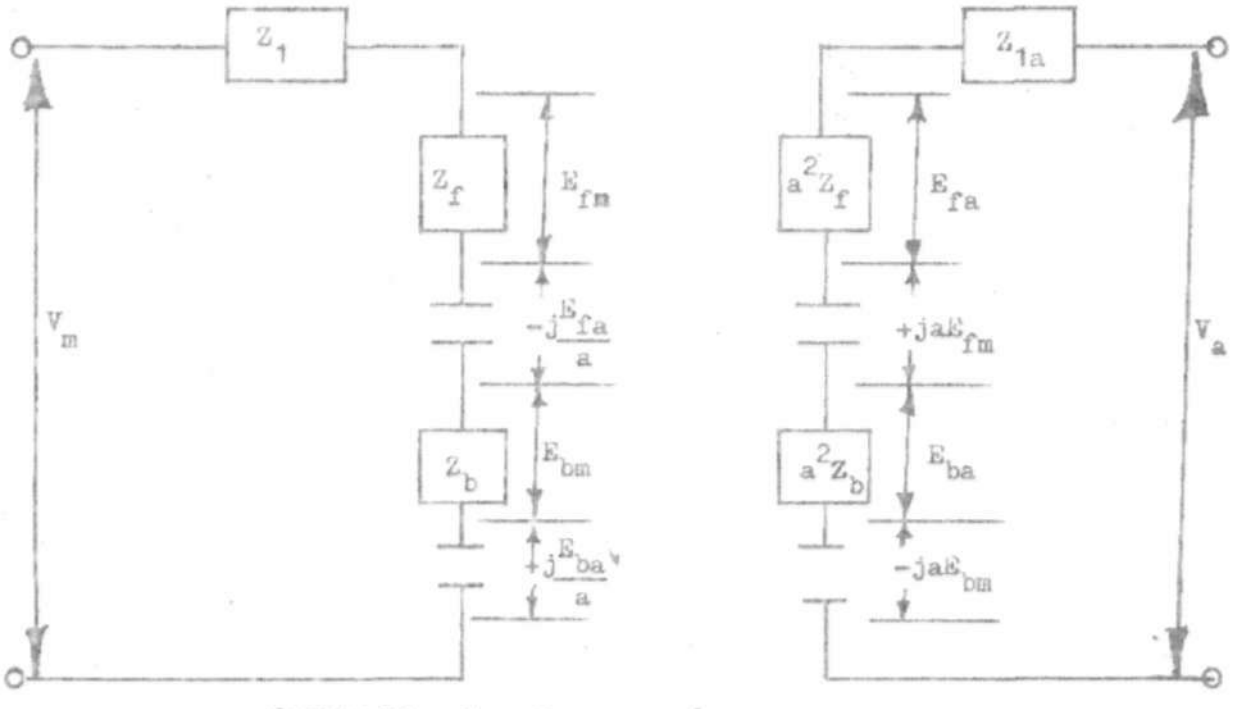


FIGURE 23: Equvalent circuit of figure 22 according to revolving-field theory.

Voltages induced in the main phase by the two component revolving fields set up by the main phase itself are

$$E_{fm} = I_m Z_f \tag{4.23}$$

$$E_{bm} = I_m Z_b \tag{4.24}$$

Likewise, the field components which are set up by the auxiliary winding induce the following voltages in the auxiliary winding

$$E_{fa} = I_a a^2 Z_f \tag{4.25}$$

$$E_{ba} = I_a a^2 Z_b \tag{4.26}$$

where a *is the ratio of effective turns in the auxiliary winding to effective turns in the main winding.*

Since main winding has $1/a$ times as many turns as the auxiliary winding; and since voltage induced in the main winding by the forward-revolving field lags 90 degrees in time phase behind E_{fa}, while that induced by the backward-revolving field leads 90 degrees ahead of E_{ba}. Then, voltages induced in the main winding by the auxiliary fields are: by the forward field:

$$-j\frac{E_{fa}}{a} = -jaI_a Z_f \tag{4.27}$$

by the backward field:

$$+j\frac{E_{ba}}{a} = +jaI_a Z_b \tag{4.28}$$

Similarly, voltages induced in the auxiliary winding by the main-winding fields are:

by the forward field: $+jaE_{fm} = +jaI_m Z_f$ (4.29)

by the backward field:

$$-jaE_{bm} = -jaI_m Z_b \tag{4.30}$$

Hence, voltage in the two circuits are,

$$V_m = I_m Z_1 + I_m Z_f - jaI_a Z_f + jaI_a Z_b + I_m Z_b \tag{4.31}$$

and

$$V_a = I_a Z_{1a} + I_a Z_f a^2 + jaI_m Z_f + I_a a^2 Z_b - jaI_m Z_b \tag{4.32}$$

If $R_T = r_1 + R_f + R_b$; $X_T = x_1 + X_f + X_b$

$R_{Ta} = r_{1a} + (R_f + R_b)a^2$, $X_{Ta} = X_{1a} + a^2 (X_f + X_b)$

then, total impedance of main winding, at any slip s is,

$$Z_T = R_T + j X_T \tag{4.33}$$

and, total impedance of auxiliary winding, at any slip s is

$$Z_{Ta} = R_{Ta} + j X_{Ta} \tag{4.34}$$

substituting (4.33) and (4.34) in (4.31) and (4.32), we have

$$V_m = Z_T I_m - ja (Z_f - Z_b) I_a \tag{4.35}$$

$$V_a = +ja(Z_f - Z_b) I_m + Z_{Ta} I_a \tag{4.36}$$

solving (4.35) and (4.36) simultaneously, we have

$$I_m = \frac{V_m Z_{Ta} + j V_a a (Z_f - Z_b)}{Z_T Z_{Ta} - a^2 (Z_f - Z_b)^2} \tag{4.37}$$

$$I_a = \frac{V_a Z_T - j V_m a (Z_f - Z_b)}{Z_T Z_{Ta} - a^2 (Z_f - Z_b)^2} \tag{4.38}$$

These are the primary current in each winding.

To determine torques developed by the forward and backward fields. The magnitudes of these fields in terms of main-winding volts are from (4.31) and (4.32)

Voltage induced in the main winding by resultant forward field,

$$= (I_m - jaI_a)Z_f \qquad (4.39)$$

Voltage induced in the main winding by resultant backward field,

$$= (I_m + jaI_a)Z_b \qquad (4.40)$$

$$(I_m - jaI_a)^2 = \text{Real}_f + j\ \text{Imaginary}_f$$

$$\text{Real}_f = I_m^2 + (aI_a)^2 + 2aI_mI_a \sin\phi \qquad (4.41)$$

$$Z_f = R_f + j\ X_f,$$

hence,

$$T_f \text{ (synchronous watts)} = \text{Real}_f \times R_f$$

$$= \left[I_m^2 + (a\ I_a)^2 + 2aI_mI_a \sin\phi\right]R_f \qquad (4.42)$$

$$(I_m + jaI_a)^2 = \text{Real}_b + j\ \text{Imaginary}_b$$

$$\text{Real}_b = I_m^2 + (a\ I_a)^2 - 2a\ I_mI_a \sin\phi \qquad (4.43)$$

$$Z_b = R_b + j\ X_b,$$

hence,

$$T_b \text{ (synchronous watts)} = \text{Real}_b \times R_b$$

$$= \left[I_m^2 + (aI_a)^2 - 2aI_mI_a \sin\phi\right]R_b \qquad (4.44)$$

Total torque,

$$T(\text{synchronous watt}) = T_f - T_b$$

$$= \left[I_m^2 + (aI_a)^2\right](R_f - R_b) + (2aI_mI_a \sin\phi)(R_f + R_b) \quad (4.45)$$

secondary I^2r losses at slip s are:

$$\text{due to forward field} = s\,T_f \quad (4.46)$$

$$\text{due to backward field} = (2 - s)T_b \quad (4.47)$$

Appendix 2 shows a calculation sheet, as used by Veinott[1] suitable for combined winding performance based on this theory.

CHAPTER 5

BASIC MOTOR CONSTANTS

5.1 Air-Gap MMF and Flux Waves of a single-Phase Winding

Any periodic, finite, single-valued function, f(x), can be expanded into a trigonometric series of the form:

$$f(x) = \tfrac{1}{2}a_o + a_1\sin X + a_2\sin 2X + \ldots + a_n\sin nX + b_1\cos X + b_2\cos 2X + \ldots + b_n\cos nX \quad \text{-----(5.1)}$$

Such a series is known as a Fourier series. The coefficients are evaluated thus:

$$a_o = \frac{1}{\pi}\int_0^{2\pi} f(x)\,dx \quad \text{----------(5.2)}$$

$$a_n = \frac{1}{\pi}\int_0^{2\pi} f(x)\sin(nx)\,dx \quad \text{----------(5.3)}$$

$$b_n = \frac{1}{\pi}\int_0^{2\pi} f(x)\cos(nx)\,dx \quad \text{----------(5.4)}$$

5.1.1 MMF Wave of a Full-Pitch Coil

If there is one full-pitch coil per pole, excited with a current to produce a mmf of h, the mmf wave is a series of rectangles as shown in figure 24. Applying the above Fourier series theorem, it will be found that the series of the mmf wave of this single coil is,

$$f(x) = \left[\frac{4h}{\pi}\ \sin x + \tfrac{1}{3}\sin 3x + 1/5\sin 5x + \ldots\right] \quad \text{-----(5.5)}$$

5.1.2 MMF Wave of a Chorded Coil

If the throw of the coils in figure 24 is reduced to an angle β and if the centers of the coils are left in the centers of the poles, the height h of the mmf wave will not be changed, but the area will be reduced along the X-axis, as shown in figure 25. The Fourier series for the mmf wave can be found to be,

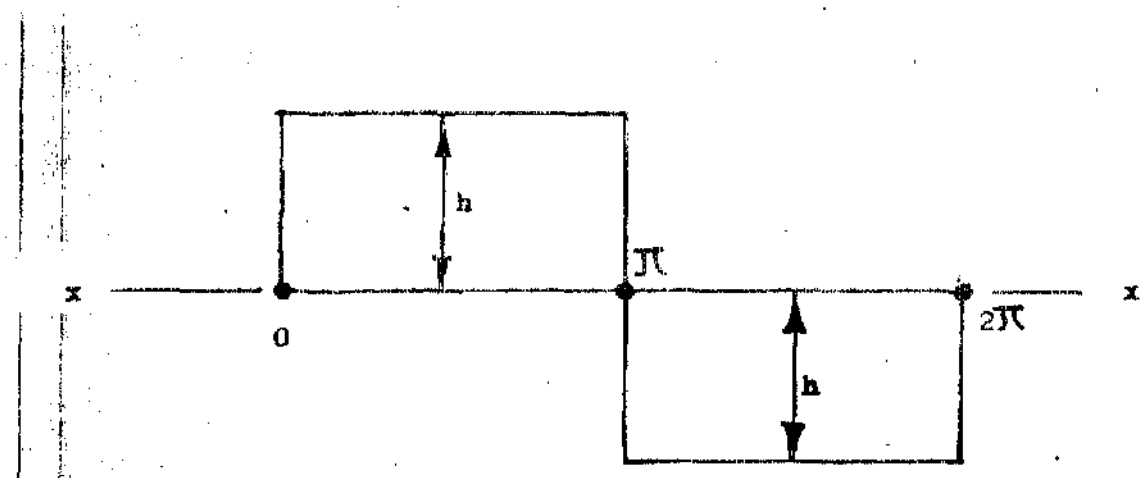


FIGURE 24: The mmf wave of a full-pitch coil

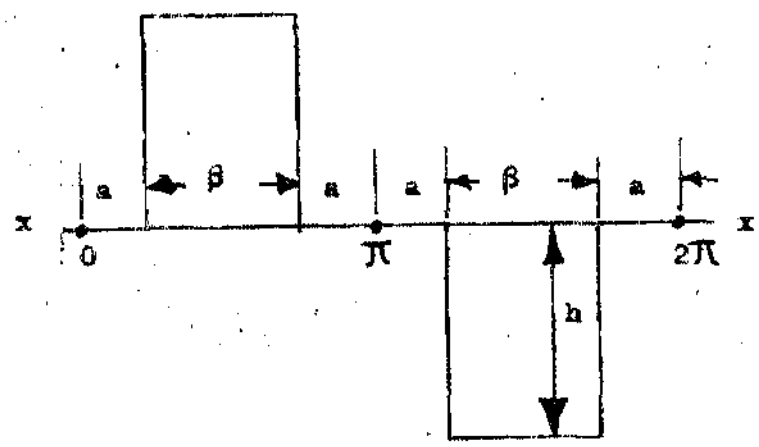


FIGURE 25: The mmf wave of a chorded coil.

$$f(x) = \frac{4h}{\pi} \sin\frac{\beta}{2} \sin x - \frac{1}{3}\sin^3\frac{\beta}{2}\sin 3x \ldots \pm\frac{1}{n}\sin^n\frac{\beta}{2}\sin(nx) \text{ ---------(5.6)}$$

where $\pm$ appear, + is used if $n = 4r+1$, and - is used if $n = 4r-1$, where r is any whole number.

The first terms in equations (5.5) and (5.6) are referred to as the fundamental of the mmf wave, while other terms are the harmonics. For example, if $n = 3$, then the term corresponding to $n = 3$ is the 3rd harmonic of the mmf wave.

5.1.3 MMF Wave of a Concentric Coil

As previously discussed in Chapter 3, a concentriccoil is made up of a number of elemental coils having different pitches, but all having a common center. The mmf wave of each elemental coil is a series of rectangles, as in figure 25, but when they are added together, the resultant mmf wave takes on a stair-step appearance, as shown in figure 26.

The fundamental wave for the group is obtained by adding the fundamentals for each of the elemental coils, by applying the first term of equation (5.6), the Coefficient of the fundamental wave is,

$$a_1 = \frac{4}{\pi}(C_1\sin B_1 + C_2\sin B_2 + C_3\sin B_3) \text{ ------(5.7)}$$

Similarly, for the nth harmonic,

$$a_n = \pm\frac{4}{n\pi}(C_1\sin nB_1 + C_2\sin nB_2 + C_3\sin nB_3) \text{ ------(5.8)}$$

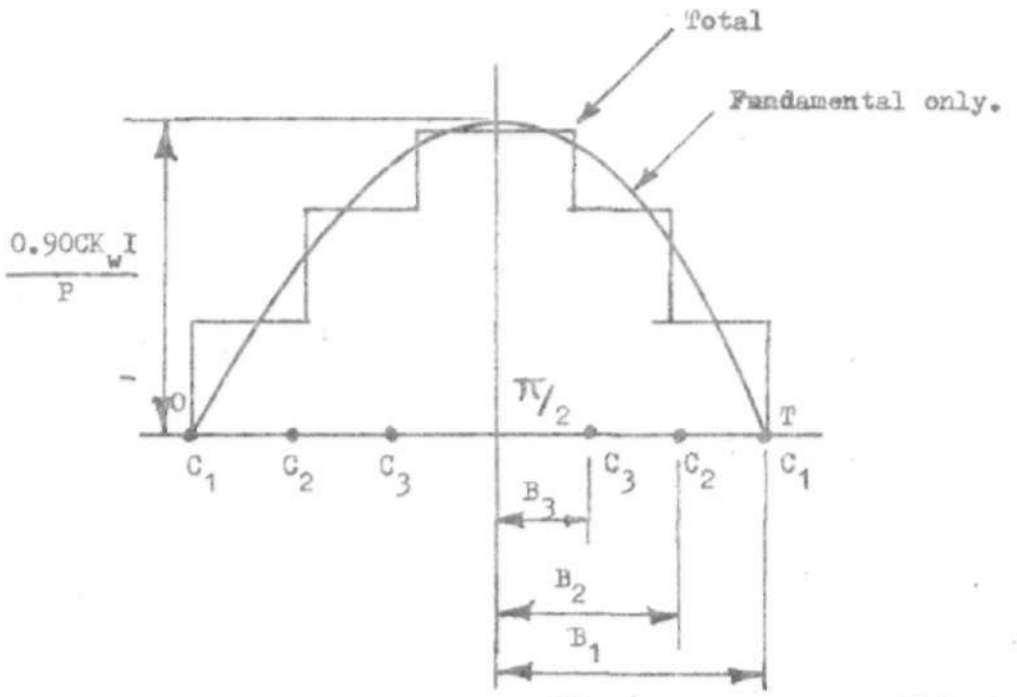


FIGURE 26: The mmf wave of a concentric coil.

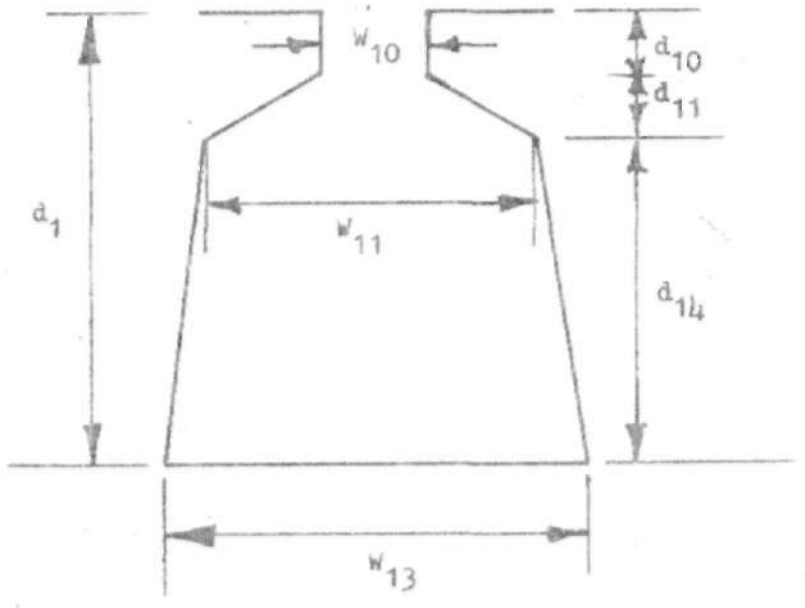


FIGURE 27: Method of specifying stator-slot dimensions.

5.1.4 Distribution Factors of a Concentric Winding

If the concentric coil of figure 26 were replaced by a single full-pitch coil having the same total number of conductors, the amplitude of the nth harmonic would be, from equation (5.5)

$$a_n = \frac{4}{n\pi}(C_1 + C_2 + C_3) \quad \text{------} \quad (5.9)$$

Distribution factor for the nth harmonic is defined as,

$$K_{wn} = \frac{\text{Amplitude of nth harmonic of mmf wave for actual coil}}{\text{Amplitude of nth harmonic of a full-pitch coil of same total conductor.}}$$

Hence, dividing (5.8) by (5.9)

$$K_{wn} = \frac{C_1 \text{ Sin } nB_1 + C_2 \text{ Sin } nB_2 + C_3 \text{ Sin } nB_3}{C_1 + C_2 + C_3} \quad \text{------} \quad (5.10)$$

and, for the fundamental,

$$K_{w1} = \frac{C_1 \text{ Sin } B_1 + C_2 \text{ Sin } B_2 + C_3 \text{ Sin } B_3}{C_1 + C_2 + C_3} \quad \text{------} \quad (5.11)$$

Let C = total number of series-connected conductors in machine, and

P = number of pole-pairs, hence,

$$C_1 + C_2 + C_3 = \frac{C}{4P} \quad \text{------} \quad (5.12)$$

Then, substituting (5.12) in (5.10) and (5.11) we have,

$$\frac{CK_{wn}}{4P} = C_1 \text{ Sin } nB_1 + C_2 \text{ Sin } nB_2 + C_3 \text{ Sin } nB_3 \quad \text{---} \quad (5.13)$$

and (5.13) in (5.8) gives,

$$a_n = n\frac{\pi}{4}\cdot\frac{CK_{wn}}{4P} = \frac{CK_{wn}}{nP\pi} \qquad \text{--------} \quad (5.14)$$

For fundamental, n = 1 in (5.14), hence,

$$a_1 = \frac{CK_{w1}}{P\pi} \qquad \text{------} \quad (5.15)$$

It is usual to express the nth harmonic in per unit with respect to the fundamental; thus,

$$\text{Per - unit } n^{th} \text{ harmonic} = \frac{a_n}{a_1} = \frac{K_{wn}}{nK_{w1}} \qquad \text{----} \quad (5.16)$$

5.2 Magnetic Circuit and Saturation Factor

Table 7 shows a typical schedule for calcultaing magnetic circuit values and the saturation factor. The derivations and explanations of some terms and formulae in the table can be found in already published works[1,6,7,8,9,12,18,19,20].

5.3 Leakage Reactance

This is considered as being made up of five components: (1) slot leakage (stator and rotor); (2) zig-zag leakage; (3) end leakage; (4) belt leakage; and (5) skew leakage. Each one of these is computed separately and the whole added together to obtain the total leakage reactance. However, definition and formulae for evaluating each will be presented here. Readers who are interested in the derivations and detail explanations are referred to already published works.[1,6,7,8,9,12,18,19,20].

5.3.1 Slot Leakage Reactance

Slot leakage reactance refers to the leakage due to flux crossing the slots within the slots themselves and thereby linking the conductors that set up this flux. If L is the length of stack and C_n the total

TABLE 7

Magnetic - Circuit and Saturation Factor Calculations
(all dimensions in cm)

	Stator	Rotor
Outer Diameter	D_o	D_2
Internal Diameter (Bore)	D_1	D_b
Stack Length, L	L_1	L_2
Slots	S_1	S_2
Tooth pitch	$\lambda_1 = \pi D_1/S_1$	$\lambda_2 = \pi D_2/S_2$
Tooth face	$t_{10} = \lambda_1 - W_{10}$	$t_{20} = \lambda_2 - W_{20}$
Tooth width	t_1	t_2
Depth of Yoke	d_{y1}	d_{y2}
Carter factor	$K_1 = \frac{\lambda_1(5g+W_{10})}{\lambda_1(5g+W_{10}) - W_{10}^2}$	$K_2 = \frac{\lambda_2(5g+W_{20})}{\lambda_2(5g+W_{20}) - W_{20}^2}$
Slot Opening	W_{10}	W_{20}

Number of Poles	2P	Gap constant	$K = K_1 \times K_2$
Air gap	$g = (D_1 - D_2)/2$	Pole pitch	$\lambda_p = \pi(D_2+g)/2p$
Volts/phase	V	Frequency (Hz)	f
Flux per pole	$\phi = 0.45016 V K_\phi / f C K_{w1}$	Eff. cond./phase	CK_{w1}
Stacking factor	F	Core path shortening factor	K_{c1} or K_{c2} (from equation)
K_ϕ	$1-(I_m r_m (P.f.)/V)$	ir gap flux density	$\frac{4.454 \times 10^{-3} CK_{w1} I}{(2p) \lambda_g F_m}$

Magnetising reactance, $X_m = 0.04\ (CK_{w1})^2 \lambda_g f / (\pi g_e S F_m K_\phi (2p))$

(Table 7 continued)

	Area, A	Length, l	Density, B	AT/m	AT
Stator core	$2FL_1d_{y1}$	$(D-d_{y1})/4P$	ϕ/A	$K_{c1}H_{c1}$	$lK_{c1}H_{c1}$
Stator teeth	$FL_1S_1t_1/2P$	Actual, l_{t1}	$\phi/(.637A)$	H_{t1}	$l_{t1}H_{t1}$
Rotor teeth	$FL_2S_2t_2/2P$	Actual, l_{t2}	$\phi/(.637A)$	H_{t2}	$l_{t2}H_{t2}$
Rotor core	$2FLd_{y2}$	$(D_b+d_{y2})/2P$	ϕ/A	$K_{c2}H_{c2}$	$l_{c2}K_{c2}H_{c2}$
Air gap	$L\lambda_p=Ag$	$g_e = gK$	ϕ/A	$\phi/\mu_o A)$	g_eH_g
	Total Ampere turns, ΣAT				

Saturation Factor, SF_n = total $AT/(g_eH_g)$

series conductors in a slot, then the total reactance of the slot can be proved to be,

$$X_s = 2\pi f C_n^2 \times 10^{-8} (3.19 L K_{s1}) \quad \text{-----} \quad (5.17)$$

K_{s1} is known as the slot constant and it is defined as the equivalent permeance of a slot; which is a function primarily of the geometry of the slot and the arrangement of the conductors therein. Usually this is evaluated from graphs, but in this work two new equations were innovated for use in place of the graphs. Further discussion on this is made in Chapter 6.

For a single - phase concentric winding the total stator-slot leakage reactance, which is the sum of the reactances of all the slots is,

$$X_{slot} = \left[2\pi f (CK_{w1})^2 \times 10^{-8}\right] \left(6.38 \frac{L}{S_1} K_{s1} C_x\right) \quad \text{-----} \quad (5.18)$$

where C_x is an arbitrary correction factor.

$$C_x = \frac{(C_1^2+C_2^2+C_3^2)}{(C_1+C_2+C_3)^2} \frac{1}{K_{w1}^2} \frac{S_1}{6P} \quad \text{-----} \quad (5.19).$$

5.3.2 Zig-Zag Leakage Reactance

This is the reactance due to flux that crosses the air gap through a tooth face on the opposite member and returns across the gap. The total zig-zag reactance per phase can be derived as,

$$X_{zz} = K_x \left\{ \frac{1.065 mL}{S_1 g} K_{zz} \right\} \quad \text{-------} \quad (5.20)$$

where K_x is the reactance constant $= 2\pi f (CK_{w1})^2 \times 10^{-8}$ ------ (5.21)

and K_{zz} is the zig-zag constant $= \frac{(t_{10} + t_{20})^2}{4(\lambda_1+\lambda_2)}$ ----- (5.22)

where g, t_{10}, t_{20}, λ_1, and λ_2 are as defined in table 7.

m is the number of phases. m = 2 for single - phase motors.

5.3.3 End Leakage Reactance

This is the reactance due to leakage fluxes interlinking with the end turns of the primary winding and with the end rings of the rotor. A single empirical formula for end leakage reactance is,

$$X_{end} = K_x \left(\frac{1.57mD_eACT}{2pS_1}\right) \quad \text{------} \quad (5.23)$$

where D_e is the mean diameter of stator slots, and

ACT is the average coil throw. Both will be further defined in this Chapter.

5.3.4 Belt Leakage Reactance

This is a form of differential leakage reactance. Differential leakage reactance is caused by a difference in distribution between two coupled windings. When two mutually coupled windings have different distributions, it is not possible by short-circuiting one winding to reduce the air-gap flux to zero at all points because of the difference in distribution. This "differential flux" will link the short-circuited winding in such a way as to induce no net voltage in the short-circuited winding, but the same mutual flux will induce a reactance voltage in the primary winding. Hence, the primary winding does have a definite finite

value of leakage reactance, and this leakage reactance is caused by mutual flux that links both windings.

This reactance is usually computed by the empirical formula

$$X_{belt} = K_x (0.00118 m K_m K_B) \quad \text{----} \quad (5.24)$$

where, K_B is the belt leakage constant. Its evaluation is discussed in Chapter 6.

5.3.5 Skew Leakage Reactance

This is a form of differential leakage reactance which is introduced by skewing either the rotor or the stator of an induction motor. The skew leakage reactance is evaluated from either of the following formulae:

$$X_{skew} = (1 - C_{SK}^2) X_m K_p \quad \text{----} \quad (5.25)$$

or

$$X_{skew} = K_x (0.3234 m K_m K_p q) \quad \text{----} \quad (5.26)$$

where C_{sk}, skew factor, $= (\text{Sin } \frac{\alpha}{2})/(\pi\alpha/360)$, ----- (5.27)

$$K_m = A_g/(g_e SF_m(2p)), \quad \text{----} \quad (5.28)$$

$$K_p = x_1/(x_m + x_1) \quad \text{--------} \quad (5.29)$$

$$q^p = \text{skew leakage factor} = 1 - C_{sk}^2 \quad \text{-----} \quad (5.30)$$

$$\text{or approximately } q = 0.25 (\alpha/100)^2 \quad \text{-----} \quad (5.31)$$

5.4 Resistance

Primary and secondary resistances are basic constants that have to be evaluated in order to predetermine torques, currents and losses.

5.4.1 Primary Resistance Calculations

The procedure of estimating resistance and weight of wire is first evaluating, the length of a mean conductor, or LMC; then, from the results of this evaluation, the number of conductors, the wire size, and the number of parallel circuits, the resistance is then calculated with the aid of wire tables.

For the following simple cases, the procedure for calculating resistance is:

1. Windings where tested resistance values are available for a similar winding. In such a case, evaluation of the resistance usually involves a simple rationing process.

2. Mold windings where the perimeters of the various sections of the mold are accurately known. These perimeters, plus a small allowance for build-up of the coils on the molds, enable one to determine the length of a mean conductor readily.

For other cases the mean length of conductor has to be estimated. A simple process for doing this is given in the following procedure, often known as the "gamma method". For concentric windings, the first step is to evaluate the weighted-average coil throw.

If a concentric winding has C_1, C_2, C_3 number of turns distribution, then

$$ACT = \frac{C_1T_1+C_2T_2+C_3T_3}{C_1+C_2+C_3} \quad \text{---- (5.32)}$$

where T_1 is the throw of coil (in teeth enclosed) C_1 in number of slots.

The mean diameter, D_e, of the stator slots, is taken as the diameter at the centers of the wound portions of the stator slots. For example, figure 27 shows one way of specifying the dimensions of a stator slot. If the slot has a round bottom, d_1 is measured to the very bottom of the slot. It is assumed that all the slots below d_{11} contain conductors but that d_{10} and d_{11} portions contain none. Hence,

$$D_e = D_1+d_1+d_{10}+d_{11} \quad \text{---- (5.33)}$$

Length of a mean conductor is evaluated thus,

$$LMC = L_1 + \left(\frac{\pi D_e \chi}{S_1}\right) ACT \quad \text{---- (5.34)}$$

where L_1 is the stack length,

χ is 1.3 for 2-pole, 1.5 for 4-poles, 1.7 for six or more poles.

The second term of equation (5.34) is the length of one end connection.

If there are q parallel paths and if all paths are wound with wire of the same size, then the primary resistance, is given thus,

$$r_1 = \left(\frac{LMC}{100}\right)\left(\frac{C}{q}\right)\left(\frac{\text{ohms/1000meters}}{1000}\right) \quad \text{---- (5.35)}$$

The value of ohms per 1000 meters is taken from a suitable wire table at an appropriate ambient temperature (about 31°C for the tropics).

$$\text{Weight of wire} = \frac{LMC}{100} Cq \frac{K_g/1000 \text{ metres}}{1000} \quad \text{----- (5.36)}$$

5.4.2 Secondary Resistance Calculations - Squirrel - Cage Rotors

The procedure for evaluating rotor resistance in terms of the primary winding (so that it can be used in equivalent circuits) is as follows: (i) A value of bar current flowing in a single bar is assumed; (ii) the I^2r losses in all the bars are computed from the square of this assumed bar current and the ohmic resistances of the bars, the latter being calculated from their dimensions and specific resistance; (iii) the end-ring currents are calculated by summing up the currents for the bars in half a pole-pitch; (iv) end-ring losses are computed from the end-ring resistances and currents; (v) adding these two components of loss gives the total rotor I^2r losses in terms of the current in a single bar; (vi) mmf of the rotor is found in terms of rotor-bar current and equated to the mmf wave of the stator in terms of stator current, giving a relationship between rotor-bar current and stator current; (vii) total rotor I^2r is then expressed in terms of stator current.

$$\text{Ring} = \frac{63.7\ D_r}{A_r(2p)^2 x\ \%\ \text{cond.}} \quad \text{------} \quad (5.40)$$

The effect of wide resistances rings is taken into account by modifying (5.40) thus:

$$\text{Ring} = \frac{63.7\ D_r K_{ring}}{A_r(2p)^2 \%\ \text{cond.}} \quad \text{------} \quad (5.41)$$

$$\text{where } K_{ring} = p\left(1-\frac{D_i}{D_r}\right)\frac{1+(D_i/D_r)^{2p}}{1-(D_i/D_r)^{2p}} \quad \text{----} \quad (5.42)$$

5.4.3 Secondary Resistance Calculations - Wound Rotors

The rotor resistance referred to the primary is,

$$r_2 = \frac{n_p}{n_s}\left(\frac{C_p K_{w1p}}{C_s K_{w1s}}\right)^2 r_{22} \quad \text{---} \quad (5.43)$$

where the subscripts p & s denotes primary and secondary terms respectively.

r_{22} is the actual resistance in secondary winding.

The resistance increases with temperature thus:

$$R_t = R_o(1+\alpha t) \quad \text{------} \quad (5.44)$$

Where R_t is the resistance at temperature t^oC and R_o is the resistance at 0^oC, while α is a constant depending on the material.

5.5 Losses

Iron losses in induction motors fall roughly into two classes: (1) fundamental - frequency losses and (2) high frequency losses. Fundamental-frequency losses are supplied directly by the stator from the line. High-frequency losses are supplied by mechanical power developed by the rotor; that is, they act as a mechanical drag on the rotor, just as friction and windage do.

The evaluation of fundamental frequency losses is discussed in Chapter 6. High-frequency and surface losses is evaluated from the following empirical formula:

$$\text{Watts Loss} = 8.463 \times 10^{-6}\, C_{sf}\, B_g^{2.3} \left(\frac{f}{2p}\right)^{1.55} D_1^{2.05} \sqrt{S_1}\; L \left(\frac{w_{10}}{g}\right)^{1.22} \qquad (5.45)$$

where C_{sf} = 0.9, 1.4, or 2.3 depending on the grade of steel used; transformer 50, transformer 75, electrical or field respectively.

An empirical formula for friction and windage losses for sleeve-bearing fractional-horsepower induction motors for speeds up to 3600rpm is,

$$\text{Fraction Watts} = 1.25 \left(\frac{\text{Journal outer Diameter}}{2.54}\right)^3 \left(\frac{\text{rpm}}{100}\right) - \qquad (5.46)$$

Stray load loss is defined as that portion of the total loss in a machine not accounted for by the sum of friction and windage, stator I^2R loss, rotor I^2R loss, and no-load core loss.

CHAPTER 6

FITTING EQUATIONS INTO DESIGN CURVES

A computer that can read a point on a graph on its own is yet to be invented. Hence, in computer aided design of machine, means have to be provided for this. To the author's knowledge, the method employed up to date is that of storing the datas of selected points on the graph into the memory of the computer and then fetching them when needed in the design program. A point in between two points is obtained, with the aid of a program within the main program, by any of the popular interpolation formulae[11].

This method, though quite accurate, does not economize the computer usage, in terms of time, memory, and of course cost. Also its implementation is too involving, and thus the possibility of error can not be overlooked. However, it is believed that the establishment of an equation for curve overcomes these disadvantages and even offers an extra advantage of the resulting equation being valuable.

6.1 Flow Diagram of Procedures Used

Fitting equations into graph is a step-by-step procedure. Figure 28 is a flow diagram of the procedure used in this work: It indicates the work to be done and the decisions to be made at each stage.

The box, in figure 28, marked with the asterisk shows that the iteration method, suggested in appendix 3, for those whose constants appear in the non-linear form and are non-reducable was never applied here. This is

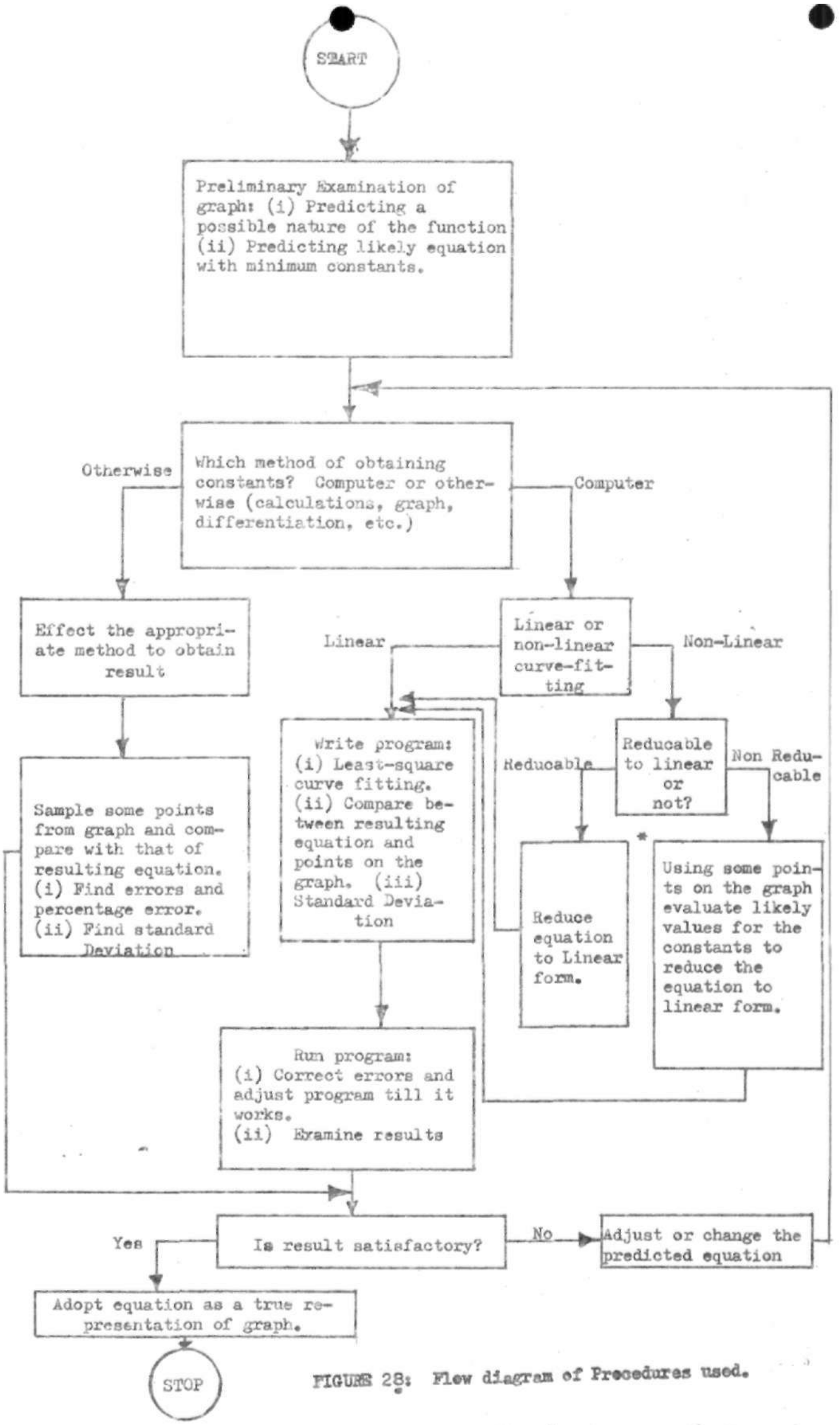


FIGURE 28: Flow diagram of Procedures used.

because, usually, the first estimates are accurate enough for our purpose. Also the result is not supposed to be extremely very accurate because design results are normally guidians: usually, it is not always the actual results obtained in a design that are used in the physical construction. However, it is easier to carry out linear least-square estimation than to carry out the non-linear.

6.2 Method of Fitting Equations

The major task in fitting equations to a graph, after predicting a suitable form of equation for the graph, is evaluating the constants which will appear in the equation. There are two methods of doing this: Using computer or the other method which involves either or more than one of the followings: Calculations, plotting graph, differentiation, etc., The latter does not require any explanation, however a better understanding will be achieved later in the Chapter.

The use of computer involves the least-squares method. This method finds the values of the constants in the chosen equation that minimize the sum of the squared deviations of the observed values from those predicted by the equation. The 'observed values' are values on the graph. This method is justified by the fact that the estimates obtained are the most precise, unbiased estimates that are linear functions of the observations. The application of this method falls under two categories: that in which the equation to be fitted is linear in the coefficients, and that in which it is non-linear in some of its coefficients. The former is thus referred to

as linear least-squares estimation, while the latter is non-linear least-squares estimation. The theory of the two are presented in appendixes 3 and 4 respectively.

Since in this work only the linear least-squares estimation theory is applied, all the programs used follow the same flow-diagram of figure 29. Shirpley's method was adopted for matrix inversion, and its explanation is presented in appendix 5.

6.3 The Graphs (Fitted)

The followings are the graphs fitted:

(1) Output constant for polyphase induction machines.

(2) Ampere conductor for polyphase induction machines.

(3) Approximate output constant for split-phase and capacitor start induction motors for continuous duty.

(4) Core-path shortening factor for 2-poles machines.

(5) Core-path shortening factor for 4-poles machines.

(6) Core-path shortening factor for 6-poles and over machines.

(7) B-H, magnetization curve for Lohys Ordinary material.

(8) Slot constants for flat - bottom trapezoidal slots.

(9) Slot constants for round-bottom slots.

(10) Belt-leakage constants

(11) Speed at maximum torque, single-phase induction motors.

(12) Fundamental-frequency iron losses in induction motors.

6.3.1 Output Constant for Polyphase Induction Machines

6.3.1.1 Derivation of Output Constant for Poly-and single-Phase Induction Machines

The r.m.s. value of the induced e.m.f. in induction machines is given by,

$$E_{rms} = 4Nf_b fK_{w1}\phi \quad \text{---------} \quad (6.1)$$

The flux (ϕ) in the air-gap is given in terms of the air-gap flux density, B_g, as,

$$\phi = \frac{2}{\pi} yLB_g \quad \text{-----} \quad (6.2)$$

$$y = \text{pole-pitch} = \pi D_1/(2p) \quad \text{--------} (6.3)$$

D_1 is the bore diameter while p is the number of pole-pairs.

The frequency f can be proved to be,

$$f = pN_s/60 \quad \text{------} \quad (6.4)$$

where N_s is the Synchronous speed of the machine. Combining (6.2), (6.3), and (6.4) we have:

$$\phi f = D_1 LB_g N_s/60 \quad \text{------} \quad (6.5)$$

The ampere-conductor, Q, can be written in the form

$$Q = \frac{2mNI}{D_1 a} \quad \text{------} \quad (6.6)$$

a = 1 for most a.c. machines.

From (6.6), $I = \frac{D_1 Q}{2mN}$ ----- (6.7)

Substituting (6.5) in (6.1), we have,

$$E_{rms} = 4Nf_b K_{w1} D_1 LB_g N_s/60 \quad \text{----} \quad (6.8)$$

the VA power is thus given by multiplying (6.7) with (6.8) and η, hence,

$$VA = \frac{\text{watts}}{\eta x pf} = \frac{\pi^2 f_b K_{w1}}{30} B_g Q D_1^2 L N_s \quad \text{------} \quad (6.9)$$

Equation (6.9) is the output equation of the induction machines.

η = efficiency, while pf is the power factor of the machine.

For 3 - phase machines the output equation is usually written in KVA, hence,

$$KVA = \frac{KW}{\eta x pf} = \left(\frac{\pi^2 f_b K_{w1} x 10^{-3}}{30}\right) B_g Q D_1^2 L N_s \quad \text{----} \quad (6.10)$$

Generally, equations (6.9) and (6.10) are written thus

$$\text{Output} = C_o D_1^2 L N_s \quad \text{------} \quad (6.11)$$

where C_o, $\frac{C_o}{\eta x pf} = \frac{\pi^2 f_b K_{w1}}{30} B_g Q$ or $\left(\frac{\pi^2 f_b K_{w1} x\ 10^{-3}}{30}\right) B_g Q$, is a constant referred to as the output constant of a machine. It is constant for a particular machine. Equation (6.11) may be written as

$$D_1^2 L = \text{Output}/(C_o N_s).$$

6.3.1.2 Fitting Equation to Curve of Output Constant for Polyphase Induction Machines

In the previous section an expression for C_o was found in terms of f_b, K_{w1}, B_g and Q. Actually it is difficult to calculate the output Constant C_o from this expression. Hence, equation (6.11) is normally used thus,

$$C_o = \frac{\text{Output}}{D_1^2 L N_s} \quad \text{-----} \quad (6.12)$$

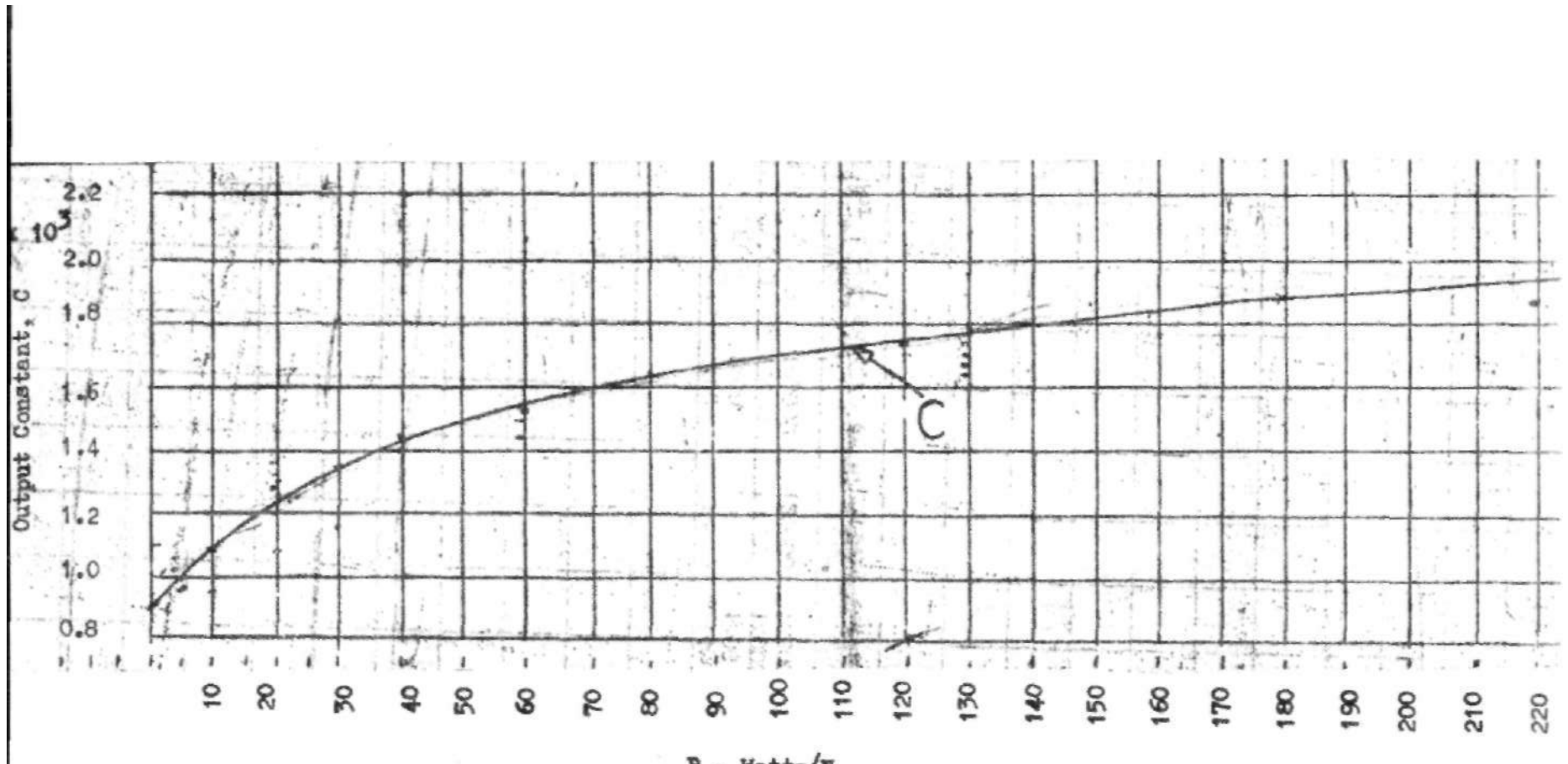


FIGURE 30: Output Constant for Polyphase Induction Machines.

The necessary measurements of the dimensions in equation (6.12) can be done on a wide range of existing polyphase induction machines and using equation (6.12) the graph of figure 30 which whows the variation of the output constant C_o with the output power, can be obtained.

In figure 30, the output constant C_o appears on the ordinate while the output, $P = \frac{Watt}{N_s}$, appears on the abscissa. In design the usual thing is to evaluate P and then use it to obtain C_o, from which D_1^2L is then calculated. However, our interest here is to fit an equation into this curve to obtain a suitable expression that links C_o and P and hence eliminate the need for reading the graph always.

Follcwing the procedure of figure 28, the first step was to predict a suitable functional relationship for the curve. Using the knowledge from past dealings with curves it was easy to come to the conclusion that the curve resembles that of a rising exponential function. Hence, an equation of the form.

$$C_o = K_1 - K_2 e^{-K_3 P} \qquad \text{------ (6.13)}$$

was then predicted. However, before finally arriving at this equation an equation of the form $C_o = 1 - K_1 e^{-K_2 P}$ was first predicted and was found to fail for it fitted only a small portion of the curve.

In fitting this equation (6.13) it was decided that the use of computer will give a more accurate fitting, though it is easier to carry out the fitting by mere differentiation and calculations. A close observation of (6.13) showed that K_1, K_2 and K_3 appear in the non-linear form.

Further observation showed that it is not reducable to the linear form. Hence, a means of evaluating the constants through the linear least square formula was devised.

Two means were devised thus: (i) Finding an approximate value for K_3 in order that the remaining constants appear in the linear form, or (ii) finding an approximate value for K_1 in order that K_2 and K_3 appear in the non-linear form that is reducable to linear form. The former is preferred because it is less complicated.

To find an approximate value for K_3, three equations for the three unknowns K_1, K_2, and K_3 were generated. For these equations to be simultaneously solved the three points (P_1, C_1), (P_2, C_2), and (P_3, C_3) were chosen in such a way that the ratio $P_1 : P_2 : P_3$ is $P_1 : P_1+a : P_1+2a$; where a is any suitable constant. The ratio of the form $P_1 : 2P_1 : 4P_1$ is more suitable because, unlike the former, it reasonaly covers the whole portion of the curve, though it is slightly more involving. The chosen points were $(\frac{50}{1.34}, 1.5)$, $(\frac{100}{1.34}, 1.7)$, $(\frac{200}{1.34}, 1.9)$

Thus the equations are:

$$\left.\begin{aligned} 1.5 &= K_1 - K_2 e^{-\frac{50}{1.34}K_3} \\ 1.7 &= K_1 - K_2 e^{-\frac{100}{1.34}K_3} \\ 1.9 &= K_1 - K_2 e^{-\frac{200}{1.34}K_3} \end{aligned}\right\} \quad \text{-----} \quad (6.14)$$

Then solving,

$$\left.\begin{aligned} K_1 - 1.5 &= K_2 e^{-\frac{50}{1.34}K_3} \\ K_1 - 1.7 &= K_2 e^{-\frac{100}{1.34}K_3} \\ K_1 - 1.9 &= K_2 e^{-\frac{200}{1.34}K_3} \end{aligned}\right\} \quad \text{--------} \quad (6.15)$$

Taking natural logarithm of both sides,

$$\left.\begin{aligned} \log_e (K_1 - 1.5) &= \log_e K_2 - \frac{50}{1.34}K_3 \\ \log_e (K_1 - 1.7) &= \log_e K_2 - \frac{100}{1.34}K_3 \\ \log_e (K_1 - 1.9) &= \log_e K_2 - \frac{200}{1.34}K_3 \end{aligned}\right\} \quad \text{--------} \quad (6.16)$$

Then subtracting 2nd from 1st and 3rd from 2nd,

$$\left.\begin{aligned} \log_e \frac{(K_1 - 1.5)}{(K_1 - 1.7)} &= \frac{50}{1.34} K_3 \\ \log_e \frac{(K_1 - 1.7)}{(K_1 - 1.9)} &= \frac{100}{1.34} K_3 \end{aligned}\right\} \quad \text{------} \quad (6.17)$$

Dividing 1st of (6.17) by its 2nd,

$$2 \log_e \frac{(K_1 - 1.5)}{(K_1 - 1.7)} = \log_e \frac{(K_1 - 1.7)}{(K_1 - 1.9)} \quad \text{------} \quad (6.18)$$

That is,

$$\frac{(K_1 - 1.5)^2}{(K_1 - 1.7)^2} = \frac{K_1 - 1.7}{K_1 - 1.9} \quad \text{--------} \quad (6.19)$$

$$(K_1-1.5)^2(K_1-1.9) = (K_1-1.7)^3 \quad \text{-----} \quad (6.20)$$

$$K_1^3 - 4.9K_1^2 + 7.95K_1 - 4.275 = K_1^3 - 5.1K_1^2 + 8.67K_1 - 4.913$$

$$0.2K_1^2 - 0.72K_1 + 0.638 = 0$$

$$K_1 = 2.023606798 \text{ or } 1.576393202$$

Judging from figure 30 the choice of $K_1 = 2.023606798$ is preferable.

Hence, using one of (6.17),

$$K_3 = \frac{1.34}{50} \log_e \frac{(K_1 - 1.5)}{(K_1 - 1.7)} \quad \text{-----} \quad (6.21)$$

$$= 0.0128964 76.$$

An approximate value of $K_3 = 0.013$ was therefore chosen.

Equation (6.13) therefore becomes

$$C_o = K_1 - K_2 e^{-0.013P} \quad \text{-----} \quad (6.22)$$

The unknown constants K_1 and K_2 now appear in the linear form. Using the flow diagram of figure 29, which employs the linear least-square estimation theory and the Shirpley's method of appendixes 3 and 5 respectively, the program on appendix 6 was written. This program was run on the University's computer, cyber 72 employing a University of Minnesota Fortran compiler version (5.0-77/03/24), many times, each, after a series of corrections and adjustments, until the results in table 8 were obtained.

Table 8: Fitting of Output Constant for polyphase induction machines.

$P = \frac{\text{Watts}}{N_s}$	C_o (from graph)	C_o (from equation)	Deviation	% Deviation
7.463	1100.0	1179.7	79.7	7.25
14.925	1240.0	1261.1	21.1	1.70
18.657	1300.0	1298.9	1.1	0.08
22.388	1360.0	1334.9	25.1	1.85
29.851	1440.0	1402.0	38.0	2.64
37.313	1500.0	1462.8	37.2	2.48
52.239	1600.0	1568.1	31.9	1.99
59.702	1639.0	1613.6	25.4	1.55
67.164	1666.7	1654.9	11.8	0.71
74.627	1700.0	1692.3	7.7	0.45
82.090	1733.4	1726.3	7.1	0.41
97.015	1766.7	1785.2	18.5	1.05
104.478	1800.0	1810.6	10.6	0.59
111.940	1833.3	1833.7	0.4	0.02
119.403	1840.0	1854.6	14.6	0.79
126.866	1866.7	1873.6	6.9	0.37
149.254	1900.0	1920.7	20.7	1.09
164.179	1933.4	1945.2	11.9	0.61

Mean deviation = 20.54

Standard deviation = 18.57

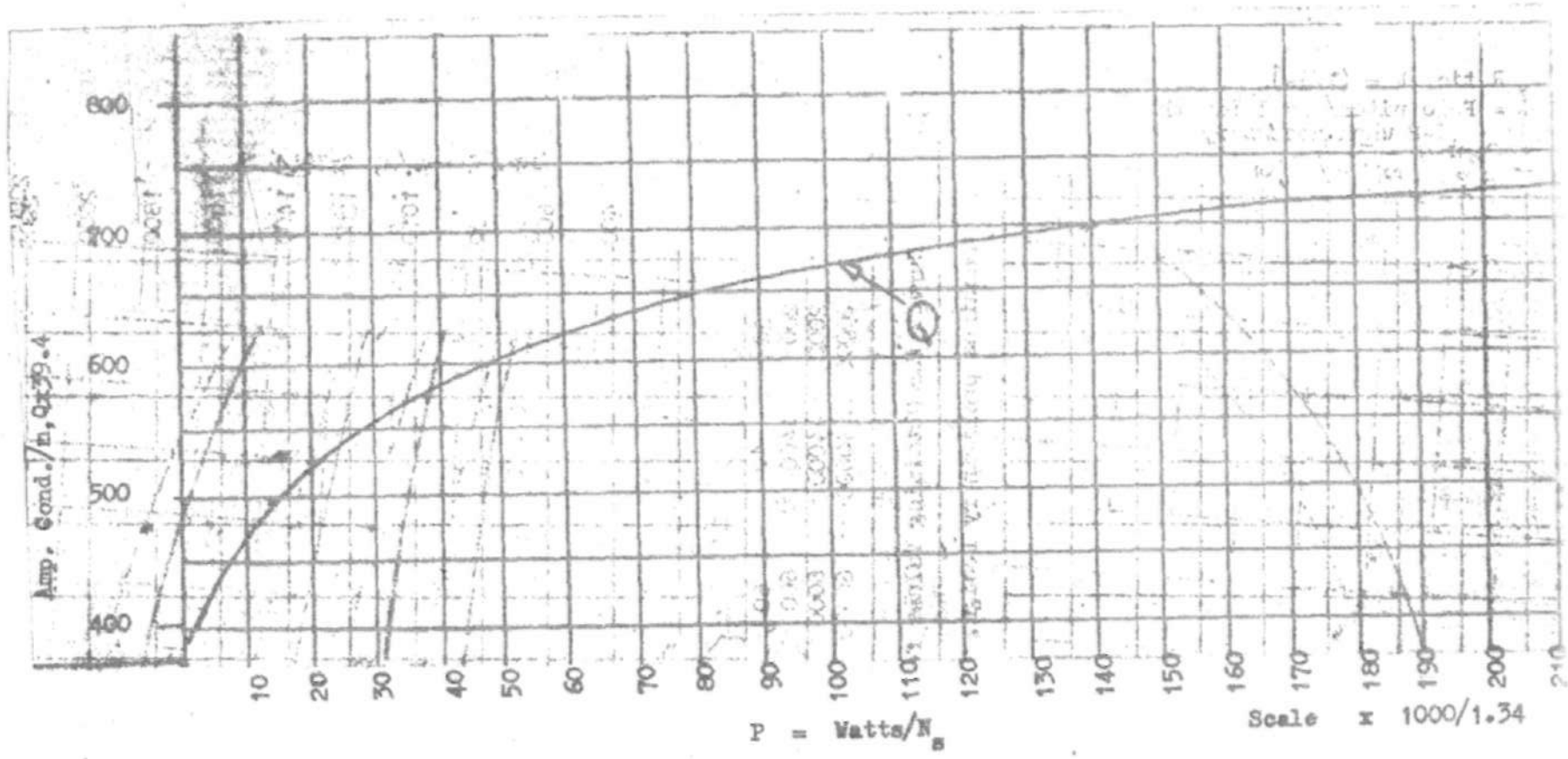


FIGURE 31: Ampere Conductors for Polyphase Induction Machines.

Figure 30 can then be expressed to a reasonable degree of accuracy by the following equation:

$$C_o = 2060 - 970EXP\ (-0.013P) \quad \text{------} \quad (6.23)$$

where P = Watt/Synchronous Speed.

6.3.2 Ampere-Conductors for Polyphase Induction Machines

The ampere-conductors per metre of stator gap circumference Q was introduced in 6.3.1.1. Its value, depends upon the size of the motor, the voltage of the stator winding, the type of ventilation, and the permissible leakage reactance. The variation of its approximate value with P is as shown on figure 31. In design its value is obtained from this figure. Hence our interest here is to establish a suitable relationship between Q and P in order to avoid the use of graph.

The procedure followed is similar to that followed in 6.3.1.2. Hence, to avoid repetition a summary will be presented thus:

(i) The predicted functional relation is that of a rising exponential function.

(ii) The predicted form of equation is,

$$Q = K_1 - K_2 e^{-K_3 P} \quad \text{------} \quad (6.24)$$

(iii) The three chosen points used in establishing an approximate value for K_3 are: $(\frac{50}{1.34}, 603.75x39.4)$,

Table 9: Fitting of ampere-conductor.

P = $\frac{\text{Watts}}{N_s}$	Q (from Curve)	Q (from equation)	Deviation	%Deviation
7.463	18518.0	19292.74	774.74	4.18
11.194	19700.0	19956.97	256.97	1.30
14.925	20586.5	20577.13	9.37	0.05
22.388	21965.5	21696.73	268.77	1.22
26.119	22556.5	22201.45	355.05	1.57
29.851	23049.0	22672.68	376.32	1.63
37.313	23787.75	23523.42	264.33	1.11
44.776	24428.0	24265.00	163.0	0.67
52.239	25117.5	24911.44	206.06	0.82
59.702	25560.75	25474.93	85.82	0.34
67.164	26004.0	25966.13	37.87	0.15
74.627	26441.34	26394.31	47.03	0.18
82.090	26750.63	26767.54	16.91	0.06
89.552	27061.5	27092.90	31.40	0.12
97.015	27320.75	27376.50	55.76	0.20
104.478	27580.0	27623.72	43.72	0.16
111.940	27777.0	27839.23	62.23	0.22
119.403	27974.0	28027.08	53.08	0.19
126.866	28171.0	28190.83	19.83	0.07
134.328	28269.5	28333.57	64.07	0.23
141.791	28368.0	28457.99	89.99	0.32
149.254	28466.5	28566.46	99.96	0.35
156.716	28565.0	28661.0	96.00	0.34
164.179	28594.55	28743.42	148.87	0.52

Mean deviation = 151.13

Standard deviation = 171.50

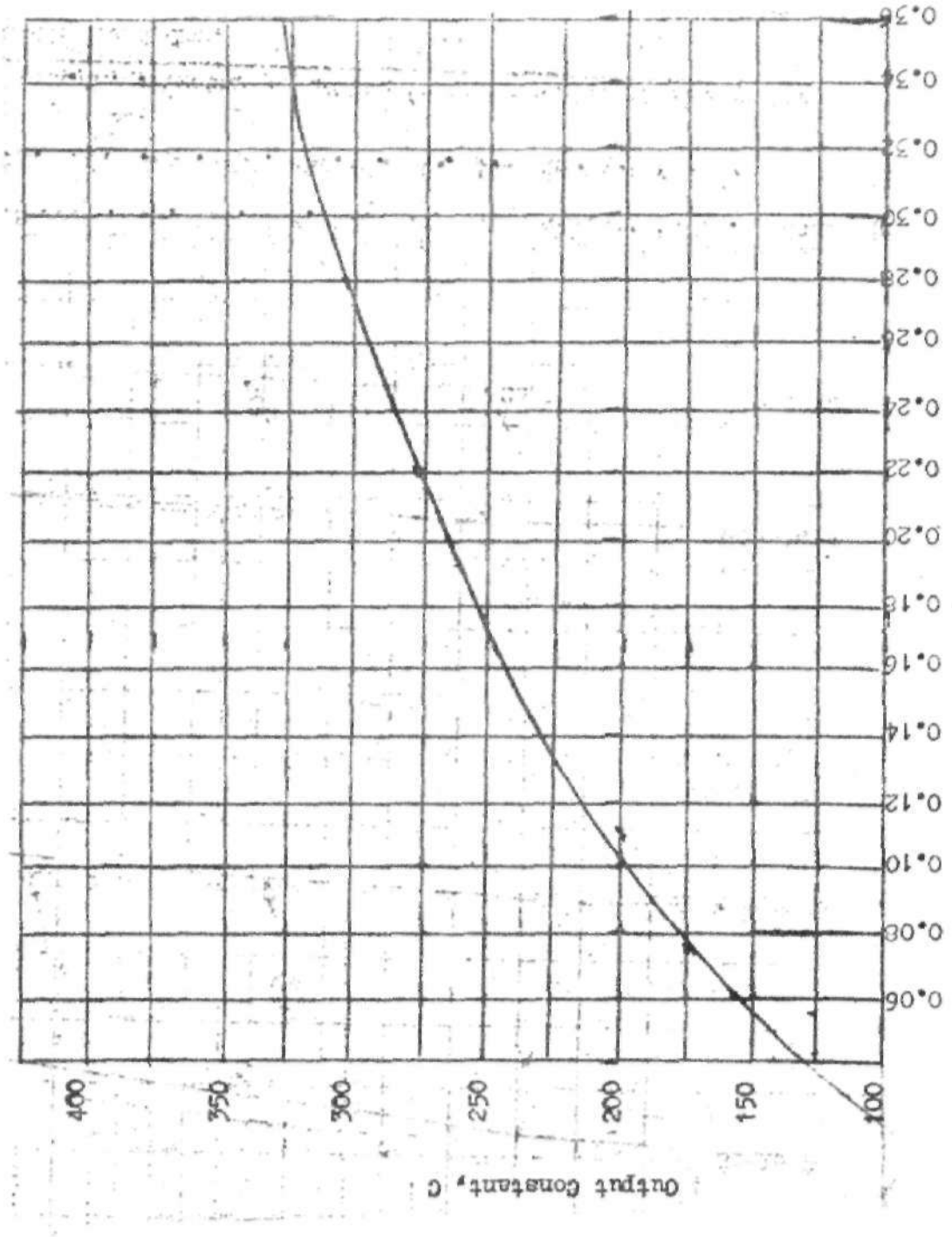


FIGURE 32: Approximate Output Constant for Split-phase & Capacitor Start Induction Motors for Continuous Duty.

$\left(\frac{100}{1.34}, \quad 671.1 \times 39.4\right)$, and $\left(\frac{150}{1.34}, \quad 705.0 \times 39.4\right)$

(iv) The approximate value for K_3 is 0.0184

(v) The computer program used is basically the same as that used for the output constant, and it is as in appendix 7.

(vi) The results obtained after running this program is as shown on table 9.

(vii) The resulting equation for Q in terms of $P = \frac{\text{Watts}}{N_s}$ is

$$Q = 29303.35 - 11484.05EXP(-0.0184P) \quad \text{-----} \quad (6.25).$$

6.3.3 Approximate Output Constant for Split-Phase and Copacitor Start Induction Motors for Constinuous Duty

The output constant for single-phase induction machine is as shown on figure 32. The procedure used in fitting an equation to this curve is as before. Hence, the summary:

(i) The predicted functional relation is that of a rising exponential function.

(ii) The predicted form of equation is,

$$C_o = K_1 - K_2 e^{-K_3 P} \quad \text{-----} \quad (6.26)$$

(iii) The three points used in establishing an approximate value for K_3 were chosen thus: (0.10, 197.5),(10.20, 265.0), and (0.30, 312.5).

(iv) The approximate value for K_3 was found to be 3.514.

(v) The computer program used is the same as before and it is as shown in appendix 8.

Table 10: Fitting of Output constant for split-phase Induction motors

$P = \frac{Watts}{N_s}$	C_o (from graph)	C_o (from equation)	Deviation	%Deviation
0.06	155.0	160.53	5.53	3.57
0.08	177.5	178.80	1.3	0.73
0.10	197.5	195.82	1.68	0.85
0.12	215.0	211.70	3.30	1.53
0.14	230.0	226.49	3.50	1.53
0.16	242.5	240.28	2.22	0.92
0.18	255.0	253.14	1.86	0.73
0.20	265.0	265.12	0.12	0.05
0.22	275.0	276.29	1.29	0.47
0.24	286.4	286.70	0.30	0.11
0.26	295.5	296.41	0.91	0.31
0.28	303.75	305.45	1.70	0.56
0.30	312.5	313.89	1.39	0.45

Mean deviation = 1.93

Standard deviation = 1.46

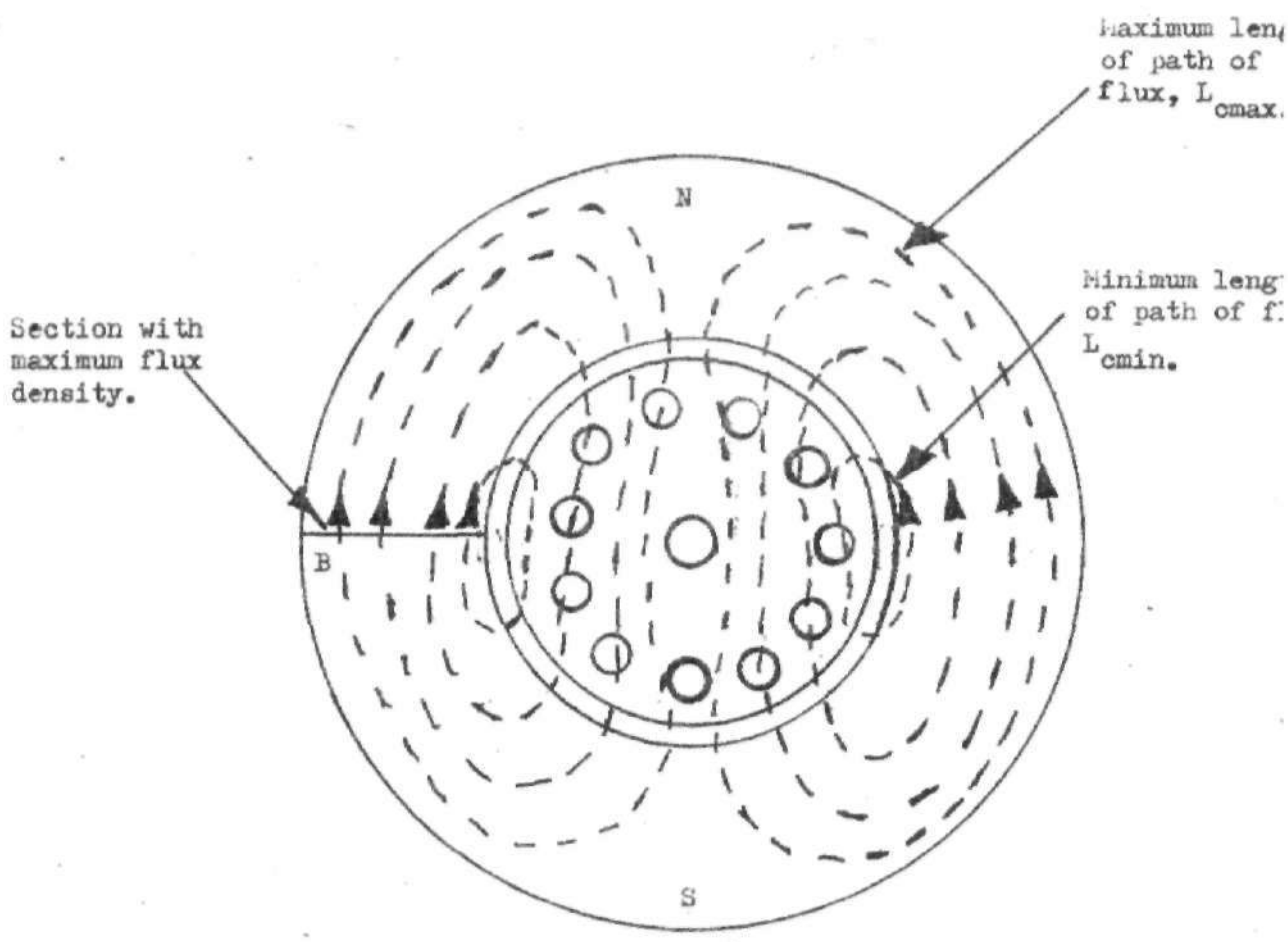


FIGURE 33: Flux distribution pattern in concentric winding design, 2-pole case.

(vi) The results obtained after running this program is as shown on table 10.

(vii) The resulting equation for C_o, approximate output constant for split-phase and capacitor start induction motors for continuous duty is:

$$C_o = 429.7 - 332.35EXP(-3.5P) \quad \text{---------} \quad (6.27)$$

6.3.4 Core-Path Shortening Factors Curves for 2-, 4-, and 6 and Over Poles

Concentric winding is generally used in single-phase motors, and the flux distribution pattern is shown in figure 33 for a two-pole case. It is evident that; (a) the flux density varies over the core section, and (b) the length of paths taken by flux through the cores also vary. The values of flux density and length of paths given in table 7, the magnetic circuit calculations, are the maximum values respectively. The effects of these variations on the cores' mmfs are taken care of by K_{c1} and K_{c2} for the stator and rotor respectively

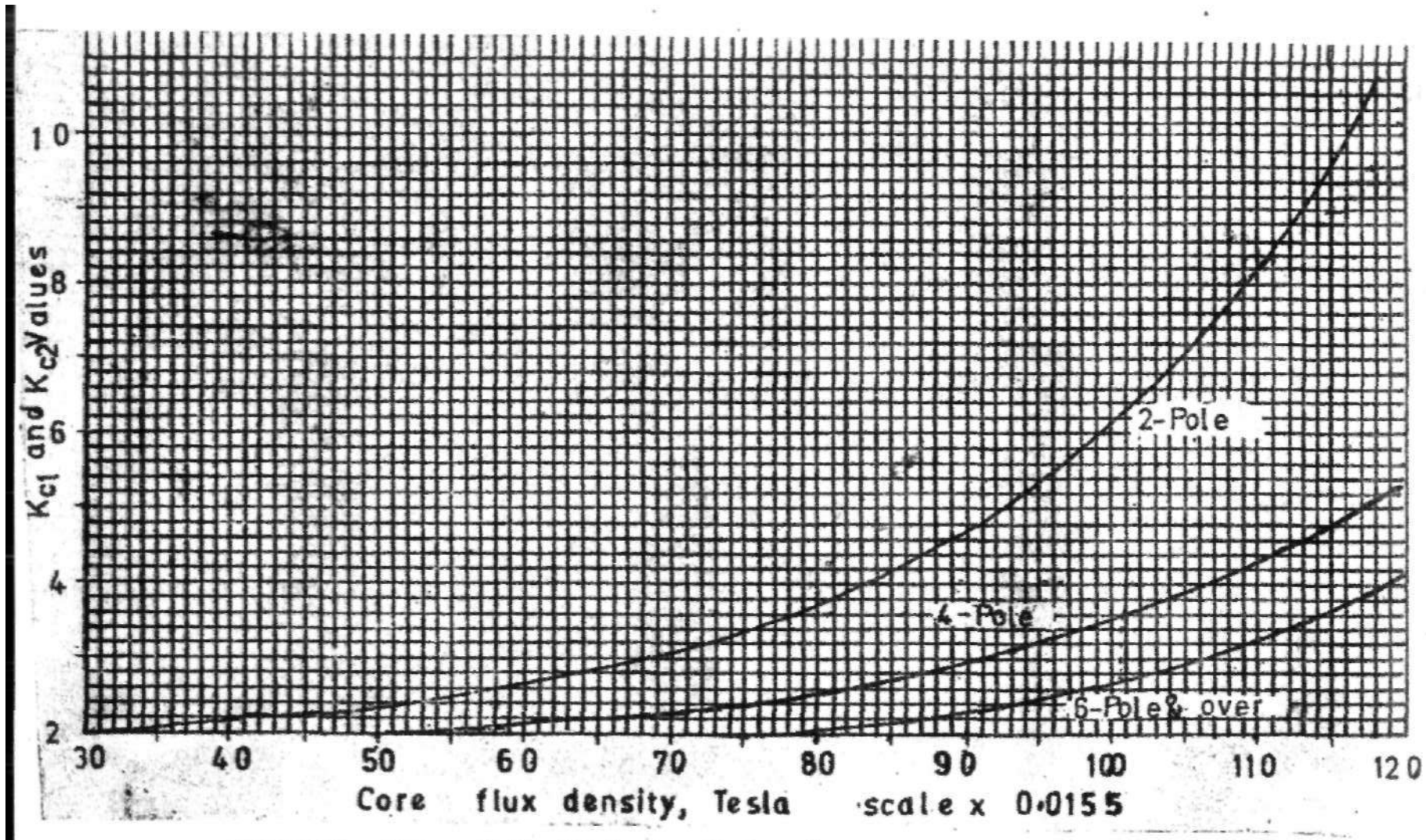


FIGURE 34: Core Path Shortening Factor Curves.

Its variation with the core flux density for various number of poles are as shown on figure 34. In design its values is obtained from this graph. Our interest is to fit the equations for these curves to avoid having to read the graphs. The procedure followed are basically the same as before, hence a summary will be presented.

(i) The predicted functional relation and equation is an exponential of the form,

$$K_c = K_1 + K_2 e^{K_3 B} \qquad \text{-------} \qquad (6.28)$$

where B is the core flux density in Tesla. K_1, K_2 and K_3 are the unknown constants as in previous cases.

(ii) The three points used in obtaining an approximate value for K in each case were chosen thus:

For 2-poles: (30x0.0155, 2.0), (60x0.0155,2.6) and (120x0.0155, 11.8)

For 4-poles: (65x0.155,2.2), 90x0.0155,2.95), and (115 x 0.0155, 4.8).

For 6-poles and over: (87.5x0.0155,2.2), (102.5x0.0155,2.78), and (117.5x0.0155,3.9).

(iii) The approximate values for K_3 were found to be 2.69, 2.33, and 2.83 for 2, 4, and 6 and over poles machines respectively.

(iv) The computer programs used are basically the same as before and are as shown in appendixes 9, 10, and 11 for 2, 4 and 6 and over

Table 11: Fitting of Core-path shortening factor (2-pole Machines)

B	K_c (from graph)	K_c (from equation)	Deviation	%Deviation
0.465	2.0	2.10	0.10	5.0
0.667	2.2	2.26	0.06	2.73
0.814	2.4	2.45	0.05	2.08
0.930	2.6	2.66	0.06	2.31
0.992	2.8	2.80	0.00	0.00
1.054	3.0	2.97	0.03	1.0
1.124	3.2	3.20	0.00	0.00
1.170	3.4	3.38	0.02	0.59
1.217	3.6	3.58	0.02	0.56
1.256	3.8	3.77	0.03	0.79
1.287	4.0	3.93	0.07	1.75
1.322	4.2	4.14	0.06	1.43
1.349	4.4	4.30	0.10	2.27
1.380	4.6	4.52	0.08	1.74
1.460	5.2	5.13	0.07	1.35
1.519	5.8	5.72	0.08	1.38
1.589	6.6	6.51	0.09	1.36
1.635	7.2	7.13	0.07	0.97
1.705	8.2	8.22	0.02	0.24
1.751	9.0	9.07	0.07	0.78
1.783	9.6	9.70	0.01	1.04
1.814	10.4	10.37	0.03	0.29
1.830	10.8	10.73	0.07	0.65
1.860	11.6	11.51	0.09	0.78

Mean deviation = 0.057

standard deviation = 0.031

Table 12: Fitting of Core path shortening factor (4-pole Machines)

B	K_c (from graph)	K_c (from equation)	Deviation	%Deviation
0.775	2.0	1.98	0.02	1.0
1.008	2.2	2.20	0.00	0.0
1.163	2.4	2.42	0.02	0.83
1.271	2.6	2.63	0.03	1.15
1.349	2.8	2.82	0.02	0.71
1.411	3.0	2.99	0.01	0.33
1.473	3.2	3.20	0.00	0.00
1.519	3.4	3.37	0.03	0.88
1.566	3.6	3.56	0.04	1.11
1.612	3.8	3.78	0.02	0.53
1.690	4.2	4.19	0.01	0.24
1.721	4.4	4.38	0.02	0.45
1.752	4.6	4.58	0.02	0.43
1.783	4.8	4.80	0.00	0.00
1.814	5.0	5.03	0.03	0.6

Mean deviation = 0.018

Standard deviation = 0.012

Table 13: Fitting of Core path shortening factor (K_c vs δ)

B	K_c (from graph)	K_c (from equation)	Deviation	% Deviation
1.163	2.0	1.97	0.03	1.5
1.356	2.2	2.23	0.03	1.36
1.442	2.4	2.40	0.00	0.00
1.519	2.6	2.59	0.01	0.38
1.597	2.8	2.82	0.02	0.71
1.643	3.0	2.99	0.01	0.33
1.697	3.2	3.22	0.02	0.63
1.736	3.4	3.40	0.00	0.00
1.767	3.6	3.57	0.03	0.83
1.806	3.8	3.79	0.01	0.26
1.837	4.0	3 99	0.01	0.25

Mean deviation = 0.015

Standard deviation = 0.011

poles machines respectively.

(v) The results obtained after running these programs are as shown on tables 11, 12, and 13 for 2, 4, and 6 and over poles machines respectively.

(vi) The resulting equations are:

For 2-poles: $K_c = 1.87\ (1+0.0346EXP(2.69B))$ ---- (6.29)

For 4-poles: $K_c = 1.686\ (1+0.029EXP(2.33B))$ ---- (6.30)

and

For 6-poles and over: $K_c = 1.62\ (1+0.0081EXP(2.83B))$ -- (6.31)

6.3.5 Magnetization Curve for Lohy's Ordinary Material

A magnetization curve is a graphical representation of the magnetic property of a magnetic material, usually used in the construction of electrical machines. As already indicated in table 7 the magnetic properties of a material is necessary in order to succesfully carry out a design of an electric machine, most especially in the magnetic circuit calculations. However, a magnetization curve shows the variation of flux-density B, with the ampere-turns per metre H; for example figure 35 shows the B-H relationship for a material called Lohy's Ordinary. All materials do not have the same magnetic properties, hence different magnetization curves for different materials.

In routine design, the usual thing is to obtain the value of one of the variables, by reading the graph, from the knowledge of the value of the other. It is here necessary to find a suitable

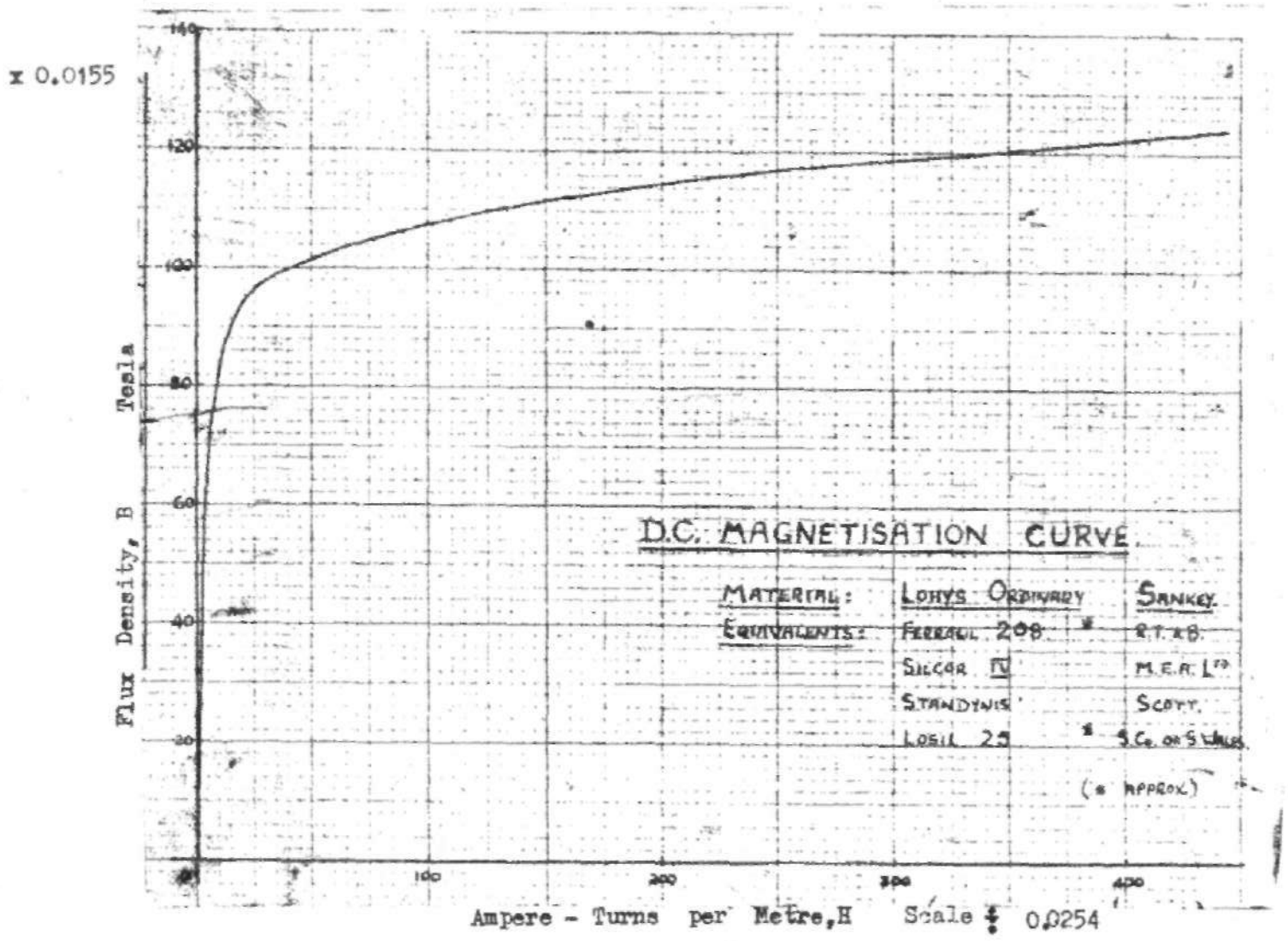


FIGURE 35: Magnetization Curve for Lohys Ordinary.

equation for this curve in order to avoid the reading of graphs. It is impossible to fit equations into the magnetization curves of all the materials used in the construction of electrical machines, but the method used here is believed to be suitable for all others.

It is worth mentioning that due to some other reasons, apart from that of design alone, tremendous work, have been done in this area[21,22] Hence, unlike the case in all others, use were made of the previous achievements in fitting this curve. The procedure followed was basically the same as the preceeding ones, hence the summary will be presented.

(i) A more study of figure 35 and with experiences from past dealings with curves a functional relation of that of a rectangular hyperbola was predicted.

(ii) An equation of the form $B = \frac{1 + bH}{1 + CH}$ was first predicted but a series of trials and errors and adjustments proved that it is suitable only if as much as 30% deviation can be condoned. Then, with the aid of a previously published work[22] an equation of the form

$$B = \frac{H}{a + bH} \quad \text{-----} \quad (6.32)$$

was finally used.

TABLE 14: Fitting of Magnetisation Curve for Iohys Ordinary Material

H (Amp. turns/m)	B, From graph (Tesla)	B, From equation (Tesla)	Deviation	% Deviation
39.378	.310	.316	.006	1.883
78.740	.465	.541	.076	16.318
98.425	.682	.631	.051	7.522
118.110	.775	.709	.066	8.482
137.795	.930	.779	.151	16.286
157.480	.961	.840	.121	12.583
196.850	1.039	.945	.094	9.042
236.220	1.116	1.030	.086	7.703
354.331	1.240	1.213	.027	2.187
393.701	1.271	1.258	.013	1.068
511.811	1.364	1.362	.002	.174
590.551	1.395	1.414	.019	1.338
787.402	1.457	1.507	.050	3.444
984.252	1.488	1.569	.081	5.477
1220.472	1.519	1.621	.102	6.741
1614.173	1.550	1.678	.128	8.244
2086.614	1.581	1.728	.139	8.796
2755.906	1.612	1.756	.144	8.956
3346.457	1.643	1.777	.134	8.152
4133.858	1.674	1.796	.122	7.275
5039.370	1.705	1.818	.185	6.104
6102.362	1.736	1.822	.086	4.969
7448.945	1.767	1.832	.065	3.708
8976.378	1.798	1.841	.043	2.765
11023.622	1.829	1.848	.019	1.025
13484.252	1.860	1.854	.006	.319
15551.181	1.891	1.857	.034	1.797
MEAN DEVIATION=	.072			
STANDARD DEVIATIO=	.048			

(iii) Though the unknown constants in (6.32) can easily be obtained by either simple calculation or from the graph of 1/B against 1/H, but the use of computer is believed to be better for accuracy.

The unknown constants a and b appear in a linear form in (6.32), hence the straight use of the linear least-square estimation theory. Using the flow diagram of figure 29 a program, which is similar to all others, was drawn and ran many times, for corre tion of errors and necessary adjustments, until the results of table 14 was obtained. The program is as shown in appendix 12.

(iv) The resulting equation for the magnetization curve of figure 35 is

$$B = \frac{H}{103.72 + 0.532H} \quad \text{-----} \quad (6.33)$$

6.3.6 Slot Constants for Flat-Bottom Trapezoidal Slots

Mention was made of this in Chapter 5, article 5.3.1. Figure 36 shows how to obtain the slot constant of a flat-bottom trapezoidal slot whose dimensions are known. ϕ is shown to vary, as shown in the figure, with the ratio of a_1 to a_2. To fit an equation into this curve the following procedure was followed:

(i) By mere observation the functional relation was predicted to be that of an inverse proportion.

(ii) Hence, equation of the following nature was assumed

$$\phi = K\frac{a_2}{a_1} \quad \text{-------} \quad (6.34)$$

Table 15: Fitting of Slot constant for flat-bottom Trapezoidal slots

a_1/a_2	a_2/a_2	ϕ (from graph)	ϕ (from equation)	Deviation	% Deviation
0.65	1.538	0.5	0.506	0.006	1.2
1.1	0.909	0.3	0.299	0.001	0.33
1.6	0.625	0.2	0.206	0.006	3.0
2.1	0.476	0.15	0.157	0.007	4.67
3.1	0.323	0.1	0.106	0.006	6.0

Mean deviation = 0.0052

Standard deviation = 0.0024

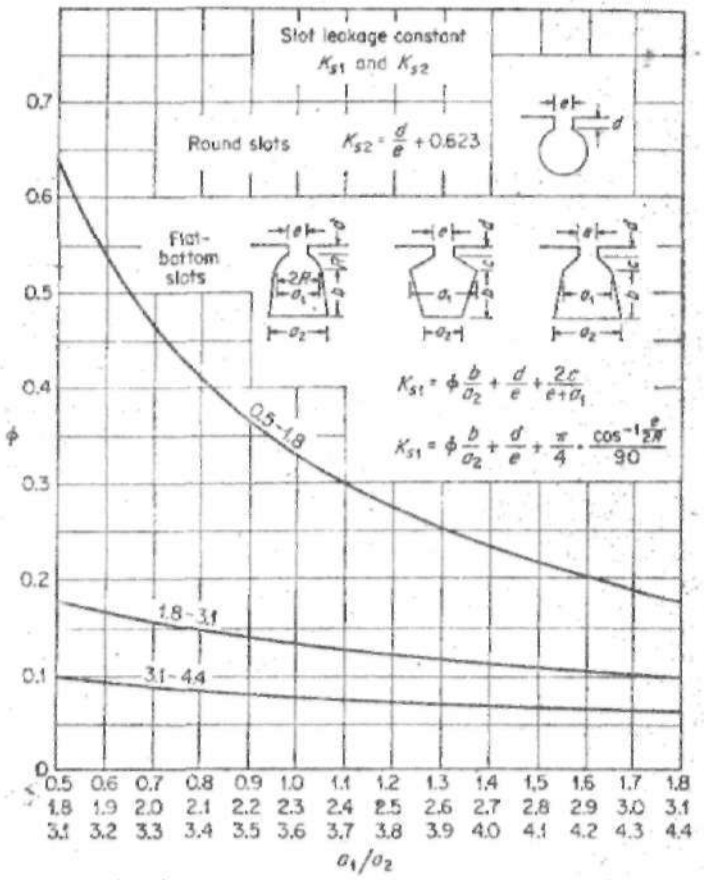


FIGURE 36:Slot Constants for Flat-Bottom Trapezoidal Slots.

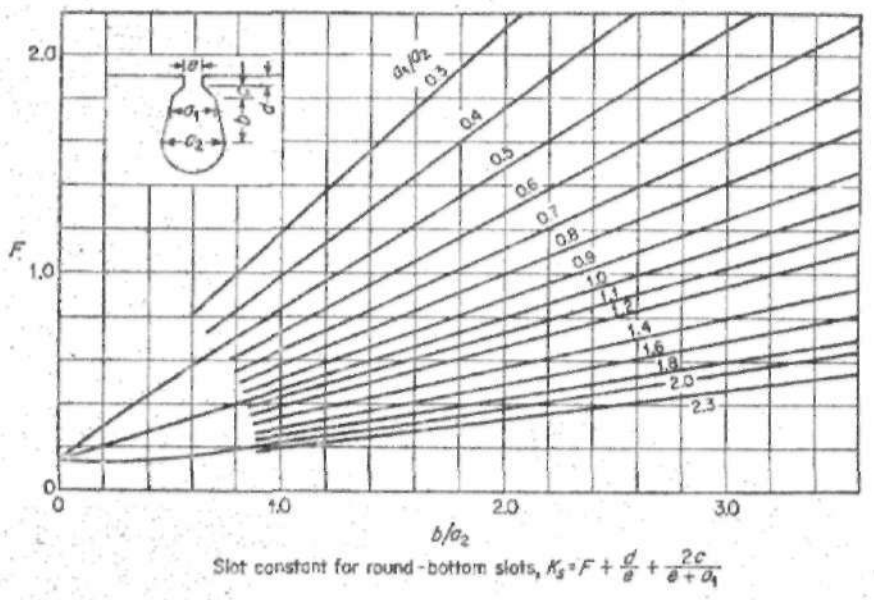


FIGURE 38: Slot Constants for Round-Bottom Slots.

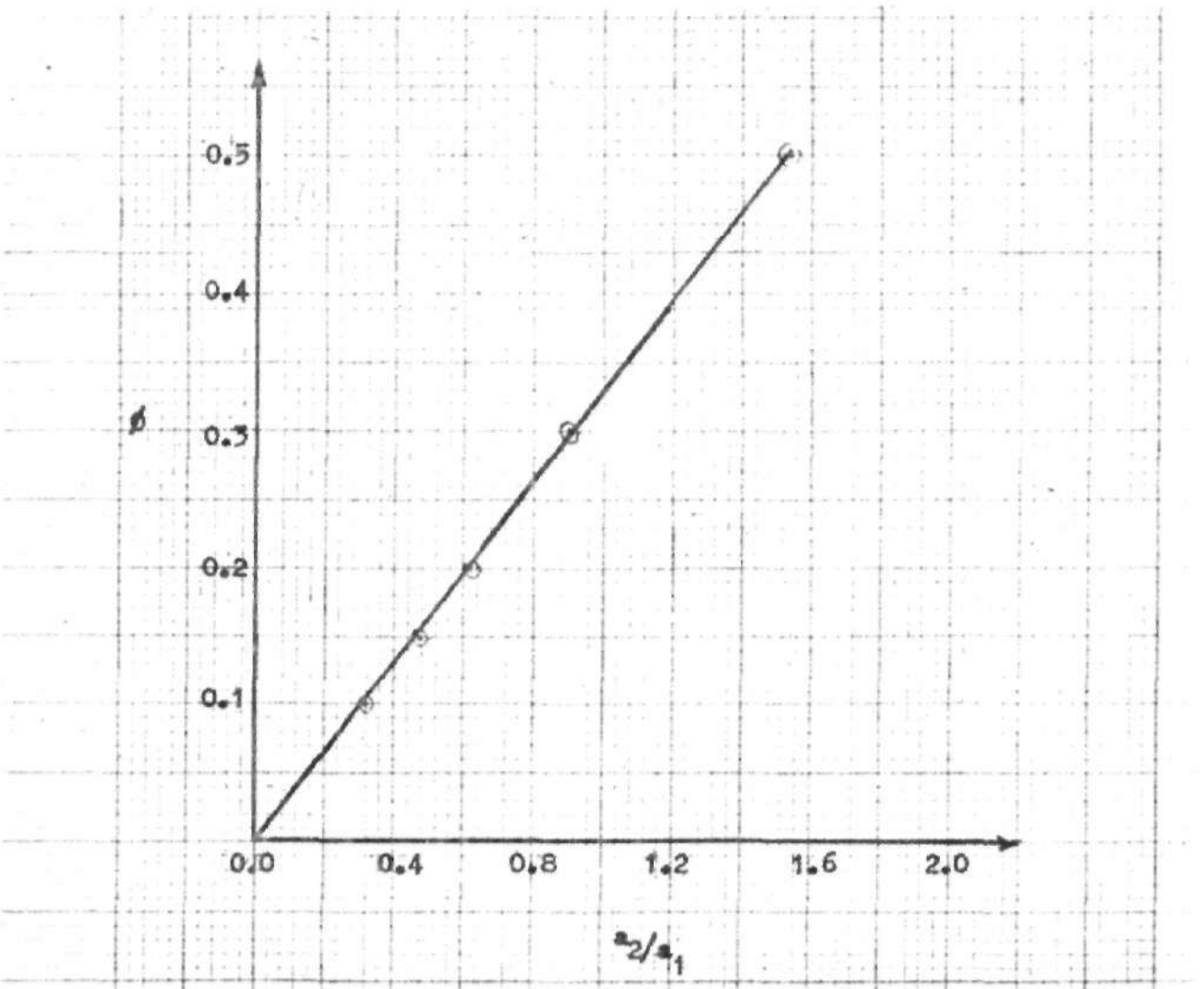


FIGURE 37: Fitting of slot constants for flat-bottom Trapezoidal slots.

where K is the constant of proportionality.

(iii) The constant was easily obtained by a graphical method. ϕ was plotted against a_2/a_1, with the aid of some evenly sampled points, as shown on figure 37. Figure 37 gives a straight line graph passing through the origin. Hence, the predicted equation is correct. K was then obtained from the slope of this straight line.

(iv) Table 15 shows the analysis of the result.

(v) The resulting equation is,

$$\phi = 0.329 \frac{a_2}{a_1} \quad \text{----} \quad (6.35)$$

and hence ϕ can be substituted, where applicable, in any of the equations in figure 36.

6.3.7 Slot Constants for Round-Bottom Slots

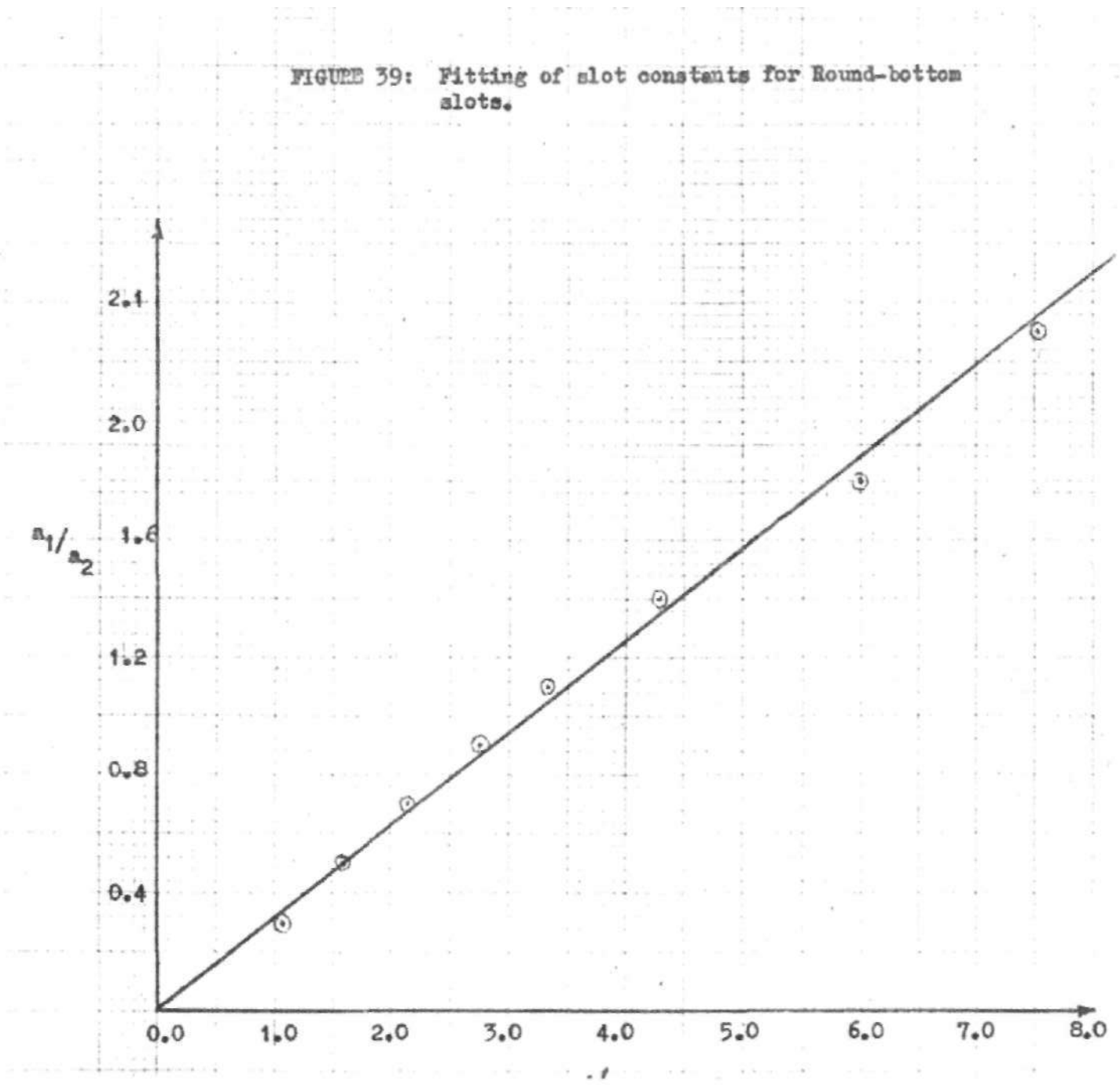
Figure 38 shows how to obtain the slot constant of a round bottom slot whose dimensions are known. The procedure followed in fitting equations into this is as follows:

(i) It was predicted that the curves on the figure are family of straight lines of the form:

$$F = m \frac{b}{a_2} + C \quad \text{------} \quad (6.36)$$

where m and c are unknown constants but vary with the ratio a_1/a_2. The constant m, is related to the slopes of the lines while C is related to the intercepts of the lines on the ordinate.

FIGURE 39: Fitting of slot constants for Round-bottom slots.



(ii) Expressions for m and c were easily obtained by graphical method. The expression for m was first established before using it to obtain that for c, both in terms of a_1/a_2. Evenly spaced samples of the lines, implying a_1/a_2, were chosen. For each, the slopes were calculated. The graph of a_1/a_2 was plotted against the inverse of the measured slopes 1/m. This gave a straight line as shown on figure 39. The line passed through the origin, hence its slope gave the constant of proportionality between a_1/a_2 and 1/m. Thus the expression for m in terms of a_1/a_2, was obtained as

$$m = 0.311\frac{a_2}{a_1} \quad \text{-----} \quad (6.37)$$

(iii) Substituting (6.37) into (6.36), C became the only unknown expression. Thus,

$$F = 0.311\,\frac{a_2}{a_1}\,\frac{b}{a_2} + C \quad \text{------} \quad (6.38)$$

On each of the sampled lines, a_1/a_2, a point was chosen, thus giving, F and $\frac{b}{a_2}$, and the corresponding value of C was evaluated for each as shown on table 16. For each value of C obtained the corresponding value of the inverse was calculated and put in the table. With a_1/a_2 on the ordinate and 1/C on the abscissa the straight line graph of figure 40 was drawn. From this the following expression between C and a_1/a_2 was then obtained:

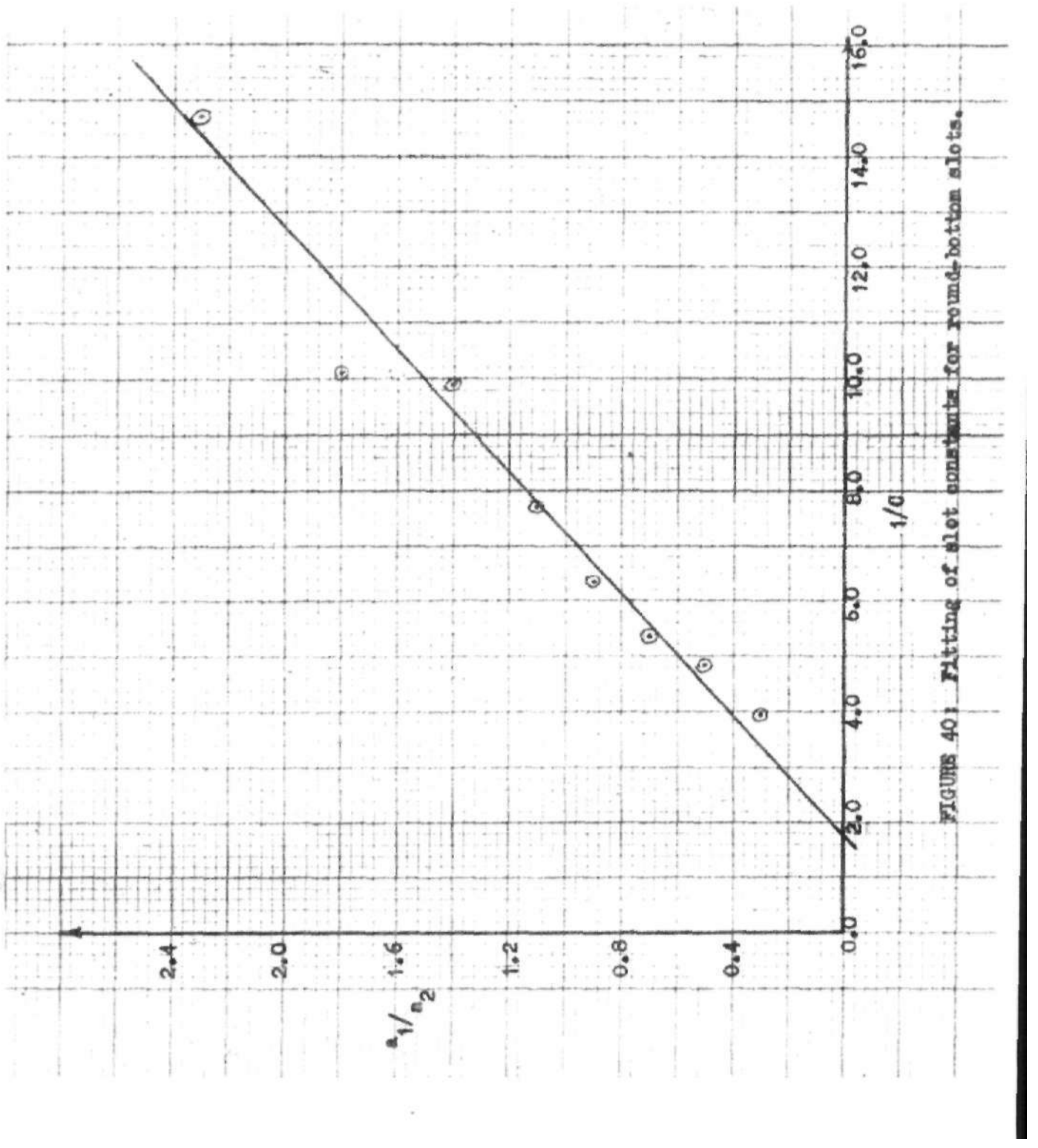


FIGURE 40: Fitting of slot constants for round-bottom slots.

Table 16: Fitting of Slot constantsffor round-bottom slots.

a_1/a_2	m	1/m	C	1/C	b/a_2	F (from graph)	F (from equation)	Deviation	%Deviation
0.3	0.933	1.072	0.254	3.937	0.8	1.0	1.119	0.119	11.9
0.5	0.634	1.577	0.208	4.808	1.25	1.0	0.997	0.003	0.3
0.7	0.467	2.141	0.186	5.376	2.6	1.4	1.332	0.068	4.86
0.9	0.364	2.747	0.157	6.369	2.317	1.0	0.949	0.051	5.1
1.1	0.3	3.333	0.13	7.692	2.9	1.0	0.947	0.053	5.3
1.4	0.233	4.292	0.101	9.901	3.0	0.8	0.772	0.028	3.50
1.8	0.167	5.988	0.099	10.101	3.0	0.6	0.604	0.004	0.67
2.3	0.133	7.519	0.068	14.706	3.0	0.467	0.475	0.008	1.71

Mean deviation = 0.042
Standard deviation = 0.0399

$$C = \frac{0.182}{a_1/a_2 - 0.328} \quad \text{-----} \quad (6.39)$$

(iv) The resulting expression fitted was,

$$F = 0.311\frac{b}{a_1} + \frac{0.182}{\frac{a_1}{a_2} - 0.328} \quad \text{-----} \quad (6.40)$$

F can then be substitued in the equation on figure 38 to obtain an expression for the slot constant of a round-bottom slot.

6.3.8 Belt-Leakage Constants

Mention was made of this in Chapter 5, article 5.3.4. Figure 41 shows a graph from which the value of the belt-leakage constant K_B can be obtained from that of the average number of slots per pole, $N_{sp} = (S_1 + S_2)/2p$. The following procedure was followed in fitting this curve:

(i) A functional relation of an inverse proportional type was predicted.

(ii) Hence, an equation of the form,

$$K_B = K\frac{1}{N_{sp}} \quad \text{-----} \quad (6.41)$$

was predicted.

(iii) K was obtained by drawing the graph of K_B against the inverse of N_{sp} for some sampled points shown on table 17. This graph is as shown on figure 42. It is a straight line graph having an intercept on the K_B axis.

(iv) By measuring the slope of the straight line in figure 42 and its intercept on the ordinate the following expression was obtained:

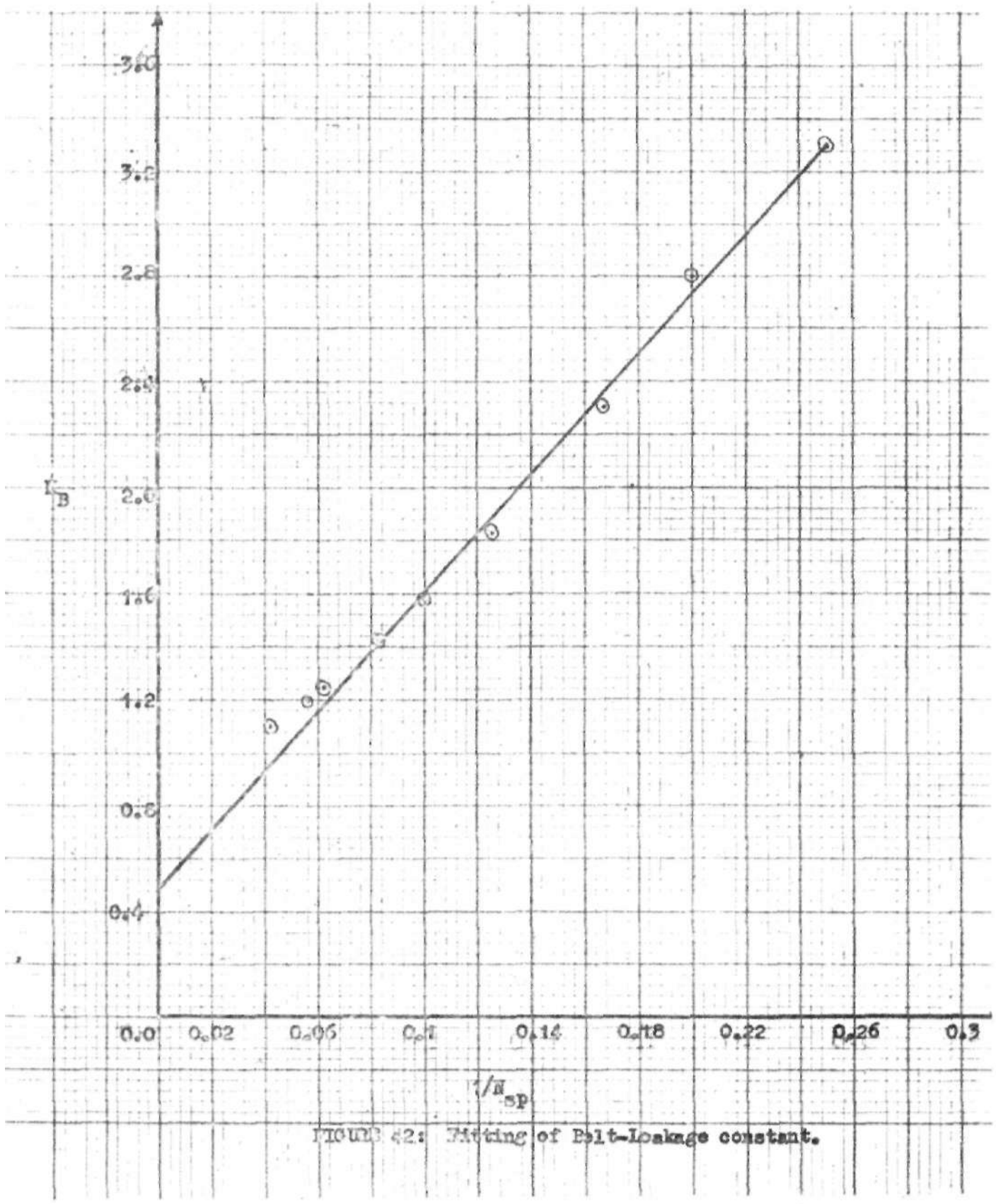


FIGURE 42: Fitting of Belt-Leakage constant.

Table 17: Fitting of Bolt-Leakage Constant

N_{sp}	$1/N_{sp}$	K_B (from graph)	K_B (from equation)	Deviation	%Deviation
4.0	0.25	3.3	3.293	0.007	0.21
5.0	0.2	2.8	2.730	0.07	3.46
6.0	0.167	2.3	2.359	0.059	2.57
8.0	0.125	1.83	1.886	0.056	3.06
10.0	0.1	1.58	1.605	0.025	1.58
12.0	0.083	1.43	1.414	0.016	1.12
16.0	0.0525	1.25	1.183	0.067	5.36
18.0	0.056	1.2	1.110	0.09	7.50
24.0	0.0425	1.1	0.957	0.143	13.0

Mean deviation = 0.0592

Standard deviation = 0.0417

$$K_B = \frac{11.25}{N_{sp}} + 0.48 \quad \text{------} \quad (6.42)$$

(v) Table 17 shows the analysis of the result.

6.3.9 Speed at Maximum Torque, Single-Phase Induction Motor

The speed at maximum torque can be determined from the curve of figure 43. The speed is usually required in the performance calculations. S_{po} is the ratio of the speed at the maximum torque to the synchronous speed, and it is a function of the ratio of the secondary resistance to the total leakage reactance; r_2/x. The following procedure was followed in fitting this curve:

(i) The functional relation of a decaying exponential was predicted.

(ii) Hence, judging by the datas on the graph the equation of the form,

$$S_{po} = a - be^{-cr_2/x} \quad \text{-------} \quad (6.43)$$

was adopted.

(iii) The unknown constant a, b, and c were obtained by the following simple calculations:

when $\frac{r_2}{x} = 0$, $S_{po} = 1.0$, hence,

$$1 = a - b \quad \text{--------} \quad (6.44)$$

As r_2/x tends to ∞, S_{po} tends to 0.7, hence

$$a = S_{po} = 0.7 \quad \text{-------} \quad (6.45)$$

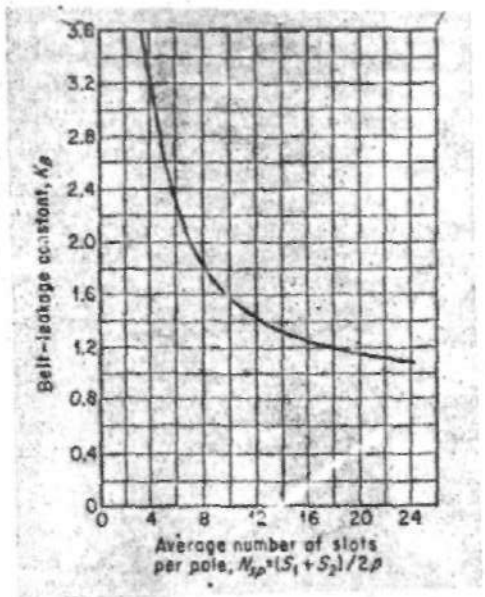


FIGURE 41: Belt Leakage Constant.

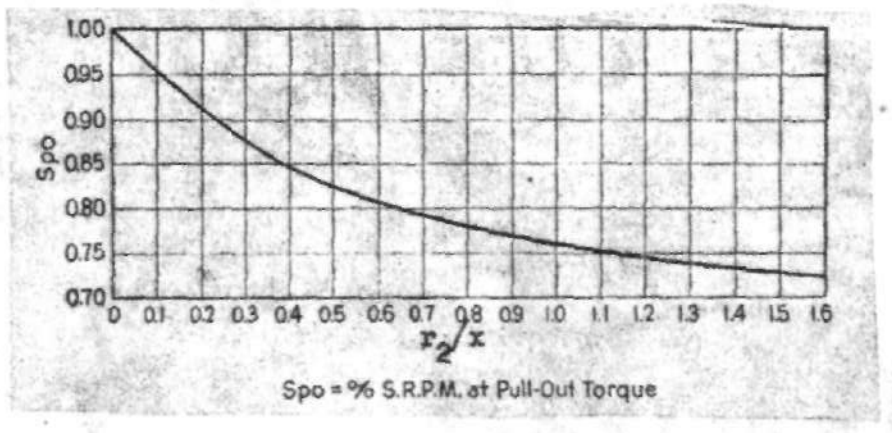


FIGURE 43: Speed at Maximum Torque, Single Phase Induction Motor.

x 1/(0.0254)

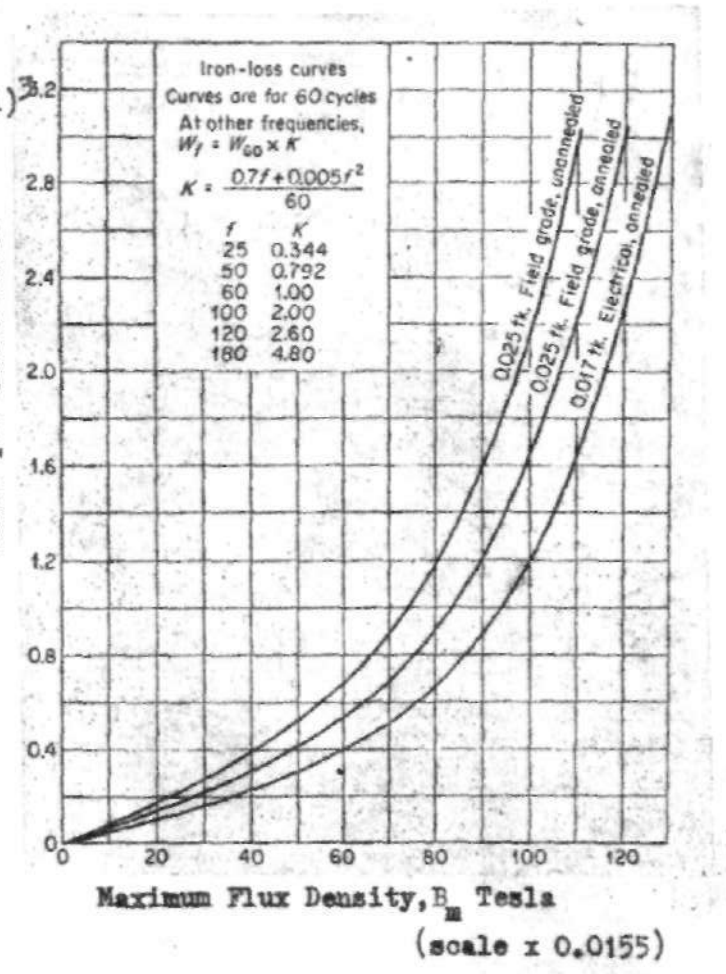


FIGURE 44: Fundamental-frequency Losses in Induction Motors.

Table 18: Fitting of speed at Maximum torque, single-phase induction motors

$\frac{r_2}{x}$	S_{po} (from graph)	S_{po} (from equation)	Deviation	%Deviation
0	1.0	1.0	0	0
0.1	0.954	0.953	0.001	0.10
0.233	0.90	0.902	0.002	0.22
0.3	0.875	0.881	0.006	0.69
0.4	0.846	0.853	0.007	0.83
0.5	0.825	0.829	0.004	0.48
0.6	0.808	0.809	0.001	0.12
0.65	0.80	0.800	0.0	0
0.8	0.779	0.778	0.001	0.13
0.9	0.769	0.766	0.003	0.39
1.15	0.75	0.743	0.007	0.93
1.3	0.738	0.733	0.005	0.68
1.4	0.733	0.728	0.005	0.68
1.6	0.725	0.720	0.005	0.69

Mean deviation = 0.0034

Standard deviation = 0.0025

Substituting (6.45) in (6.44),

$$b = -0.3.$$

Hence, (43) becomes

$$S_{po} = 0.7 + 0.3e^{-c^{r_2/x}} \text{ ------} \quad (6.46)$$

To obtain c the point (0.65, 0.80) was used. Hence, substituting $S_{po} = 0.80$ and $^{r_2}/_x = 0.65$ in (6.46) C = 1.69.

Hence the resulting equation is,

$$S_{pc} = 0.7 + 0.3e^{-1.69^{r_2/x}} \text{ -----} \quad (6.47)$$

(vi) Table 18 shows the analysis of the result.

6.3.10 Fundamental-Frequency Iron Losses in Induction Motors

Mention was made of this in Chapter 5, article 5.5. The per unit volume value of the fundamental-frequency iron losses in induction machines can be obtained from the curves on figure 44 for a known value of the maximum flux density. These three curves, were fitted as follow:-

(i) Prediction of the functional relation was quite tedious. However, after several trials a functional relation of the Hoerl's special functions[23] gave a satisfactory result.

(ii) This function has the equation of the form.

$$P_{CL} = aB_m^b e^{cB_m} \text{ -------} \quad (6.48)$$

Where P_{CL} is the fundamental-frequency iron losses in Watts per cubic metre and B_m is the maximum flux density in tesla.

(iii) The unknown constants a, b, and c appear in non-linear form but (6.48) is linearized to,

$$\ln P_{CL} = \ln a + b(\ln B_m) + CB_m \quad \text{----} \qquad (6.49)$$

Hence, linear least-square curve fitting technique was then applied to obtain the constants. A program similar to the preceeding ones, and based on the flow-diagram of figure 29, was written to evaluate the constants for all the three curves. This program and related details are shown in appendix 13.

(iv) The program was run many times due to errors and adjustments, before the result in table 19 was obtained.

(v) The resulting equations for the three curves were:

0.017tk. Electrical, Annealed:

$$P_{CL} = 7355.534\ B_m^{0.604}\ e^{1.357\ B_m} \quad \text{------} \qquad (6.50)$$

0.025tk. Field grade, Annealed:

$$P_{CL} = 10568.036 B_m^{0.615}\ e^{1.292\ B_m} \quad \text{--------} \qquad (6.51)$$

0.025tk. Field grade, Unannealed:

$$P_{CL} = 14595.578 B_m^{0.711}\ e^{1.217\ B_m} \quad \text{--------} \qquad (6.52)$$

TABLE 19: Fitting of Fundamental-Frequency Iron Losses in Induction Motors

(0.017tk Electrical, Annealed)

B_m (Tesla)	P_{CL}, from graph (Watts/Cubic Metre)	P_{CL}, from equation (Watts/Cubic Metre)	Deviation	% Deviation
.155	2562.997	2942.836	379.839	14.820
.310	6102.374	5520.219	582.155	9.540
.465	10268.918	8702.893	1366.025	13.567
.620	14218.532	12778.112	1440.420	10.131
.775	18795.313	18044.131	751.182	3.997
.930	24409.498	24859.687	450.189	1.844
1.085	31549.276	33671.385	2122.109	6.726
1.188	36614.246	40931.006	4316.759	11.790
1.343	48818.995	54392.632	5573.636	11.417
1.468	61023.744	66958.607	5934.862	9.725
1.550	73228.493	78488.685	5260.192	7.184
1.635	85433.242	90935.356	5502.114	6.440
1.692	97637.991	100361.733	2723.742	2.790
1.754	109842.739	111967.587	1724.847	1.570
1.795	122047.488	119653.395	2394.093	1.961
1.847	134252.237	138582.463	3669.774	2.733
1.886	146456.986	139367.770	7089.216	4.839
1.925	158661.735	148706.198	9955.544	6.275
1.963	170866.483	158631.475	12235.009	7.161
2.002	183071.232	169179.389	13891.844	7.588
MEAN DEVIATION=	4368.174			
STANDARD DEVIATION=	3924.168			

Table 19 (Continued)

(0.025tk. Field grade, Annealed)

.155	3661.425	4102.852	441.427	12.056
.310	8360.253	7675.886	684.367	8.186
.465	13730.342	12032.290	1698.052	12.367
.620	19344.527	17543.458	1801.069	9.310
.775	25446.901	24583.723	863.178	3.392
.930	32525.656	33595.336	1069.680	3.289
1.085	42716.621	45121.917	2405.296	5.631
1.008	36614.246	39005.484	2391.238	6.531
1.175	48818.995	53264.620	4445.625	9.106
1.298	61023.744	66347.860	5324.116	8.725
1.392	73228.493	78235.499	5007.006	6.838
1.472	85433.242	89804.264	4371.022	5.116
1.537	97637.991	100236.139	2598.148	2.661
1.599	109842.739	111265.728	1422.989	1.295
1.653	122047.488	121815.007	232.481	.190
1.705	134252.237	132697.303	1554.934	1.158
1.737	146456.986	139942.234	6514.751	4.448
1.782	158661.735	150731.688	7930.855	4.998
1.821	170866.483	160577.088	10289.395	6.022
1.860	183071.232	171017.952	12053.288	6.584

MEAN DEVIATION= 3654.906
STANDARD DEVIATION= 3348.451

Table 19 (Continued)

(0.025tk. Field grade, Unannealed)

.155	4576.781	4685.015	108.234	2.365
.310	8543.324	9259.113	715.789	8.378
.465	17269.728	14915.382	2354.338	13.633
.620	24226.426	22097.618	2128.808	8.787
.775	32525.656	31270.632	1255.024	3.859
.930	42716.621	42986.104	269.483	.631
1.085	54921.378	57919.464	2998.094	5.459
.854	36614.246	36853.530	239.283	.654
1.020	48818.995	51251.625	2432.630	4.983
1.150	61023.744	65289.620	4265.876	6.991
1.247	73228.493	77806.079	4577.586	6.251
1.325	85433.242	89367.495	3934.253	4.605
1.395	97637.991	100978.365	3340.375	3.421
1.453	109842.739	111569.943	1727.204	1.572
1.511	122047.408	123132.260	1084.772	.889
1.563	134252.137	134281.453	29.216	.022
1.602	146456.906	143236.887	3220.099	2.199
1.640	158661.705	152726.084	5935.738	3.741
1.679	170866.403	162779.166	8087.318	4.733
1.712	183071.202	171856.906	11214.326	6.126

MEAN DEVIATION= 2995.922

STANDARD DEVIATION= 2050.010

CHAPTER 7

D^2L SEPARATION CHART

To obtain the main dimensions, the stator bore diameter (D_1) and the axial length (L), of a machine its D_1^2L product is first established and then split into its components, D_1 and L. This product, which is actually a measure of the physical volume of a machine, is a function of two variables, D_1 and L. Hence, their evaluation requires one more independent equation, which must also be a function of D_1 and L, in order to set up two equations which are to be solved simultaneously for these two unknowns. This requirement is not necessary if one of the unknowns can be known aprior or determined independently.

However, several literatures[1,6,7,9,19,20] show that there is no simple or fixed method for either setting up the independent equation or having the knowledge of one of the variables aprior so that the separation will give the best machine. This is because the best machine at minimum cost must have its main dimensions satisfy all necessary constraints. Though various methods were suggested by various designers, the most satisfactory is the trial and error method which involves the assumption of different sets of values, working out the design roughly for each case, and picking out that which will give good operation at a reasonable cost. For a successful execution of this method with ease and within a relatively short time, the use of computer is obvious. In computer-aided design this is easily done by the process of iteration.

However, it is believed that all the existing methods can be unified into one simple and easy to use method. This method, which is one of the author's innovations in this work, is fully presented in this Chapter.

7.1 Existing Methods

All these methods try to establish the extra independent equation, referred to above, by finding the most favourable proportion of D_1 and L for any specific case. Various factors involved in establishing this proportion are power factor, economical considerations in terms of labour cost, cost of materials, ventilation, peripheral velocity, existence of frame sizes with accessories, and other performance factors.

(i) Vickers[19] made an analytical study and concluded that, for best power factor,

$$\frac{L}{y} = \frac{Y}{7.1} \qquad \text{---} \quad (7.1)$$

where y is the pole-pitch in cm. and $= \frac{\pi D_1}{2p}$ ----- (7.2)

since, the D_1^2L product equation is

$$V = D_1^2 L \quad \text{-----} \quad (7.3)$$

with V known, then putting (7.2) in (7.1) and solving (7.1) and (7.3) simultaneously will result in the respective values of D_1 and L. The problem with this method is that it does not take into consideration other factors mentioned above.

(ii) The shape of the pole face is often considered as the basis for establishing a significant relationship between D_1 and L. This is done in terms of the ratio of axial length (L) to pole pitch (y). For a square pole face, L/y = 1.0. Kuhlman[6] suggests that L/y = 2.0 for minimum cost integral - kilowatt motors and 0.6 for small motors. However, with the knowledge of the most suitable ratio and equation (7.3) the respective values of the main dimensions can be found. The problem here is that the ratio that satisfies one factor may not satisfy the other, hence it is difficult to find the ratio that satisfies all the factors, for a particular case.

The pole pitch y will evidently depend somewhat upon the kilowatt per pole and will be considerably larger in a machine of large output and few poles than in a machine of small output and many poles. On the basis of equal output per pole, the area of the air gap (y x L) must be large for a low-frequency than for a high-frequency machine, because of the slower rate of cutting of the flux by the conductors in the slots.

However, this method is best used for obtaining dimensions for a minimum cost machine.

(iii) Where the peripheral velocity plays a leading role,

$$U = N_s \pi D_1, \quad \text{--------} \quad (7.4)$$

is used. U is the velocity in metre/second and N_s is the syndronous speed in revolution per second. With U and N_s known, D_1 obtained from equation (7.4) is used in equation (7.3) to obtain L. This method

satisfies only the peripheral velocity but not the other factors.

(iv) Various designers suggested various ratios between D_1 and L based on their experiences. For example Trickey suggested making $L = 0.3D_1$.

7.2 Chart for Separating D_1 and L from $D_1^2 L$

This chart is developed from the fact that for a D_1^2L product there exists infinite different sets of values of D_1 and L. Out of these, only one set will be used in the final construction of the machine, usually that which will give the best machine with minimum cost. Hence, the problem is to choose this set. This chart does not totally solve this problem but it simplifies it by presenting a diagrammatic view of the infinite sets. Hence, by mere observation of the chart the best set or a range of possible best sets may be established. From a range of possible best sets, the best can be obtained by using, with the aid of a computer, the trial and error method, as mentioned in the introduction of this Chapter.

In establishing this chart the following two equations were used:

$$V = D_1^2 L \qquad \text{-----} \quad (7.5)$$

$$K = L/y = 2pL/\pi D_1 \qquad \text{----} \quad (7.6)$$

where K is the ratio of the axial length to the pole pitch.

Equation (7.6) which is from method (ii) in 7.1 above, is preferred for use to the others because it has a similar problem as that of separating D_1 and L from D_1^2 L. Also, since these two equations are

independent, there will always be solution for D_1 and L for any positive values of V and K aside from zero, which is not of any practical importance, anyway. However, a major reason for the preference of (7.6) to others is that the pole face of any machine is a function of both the performance and cost factors, as listed in 7.1 above. Hence, there must always exist a pole face, thus K, that satisfies all these factors and thus gives the best machine at the minimum cost as well.

Detailed observations of these two equations show that for given V and K equation (7.5) gives an inverse square curve while (7.6) gives a straight line curve. Hence, if both equations are plotted on the same axis they will always intersect at only one point. It is this point of intersection that we are interested in. Thus, the charts of figures 45, 46, and 47 were formed by taking the diameter D_1 and axial length L as the ordinate and abscissa respectively and then drawing families of curves for equations (7.5) and (7.6). The limits of all the variables are chosen to include all the dimensions of the existing machines for a particular number of pole 2p. A different chart is established for different number of pole because in equation (7.6) the ratio K is proportional to the number of pole-pair.

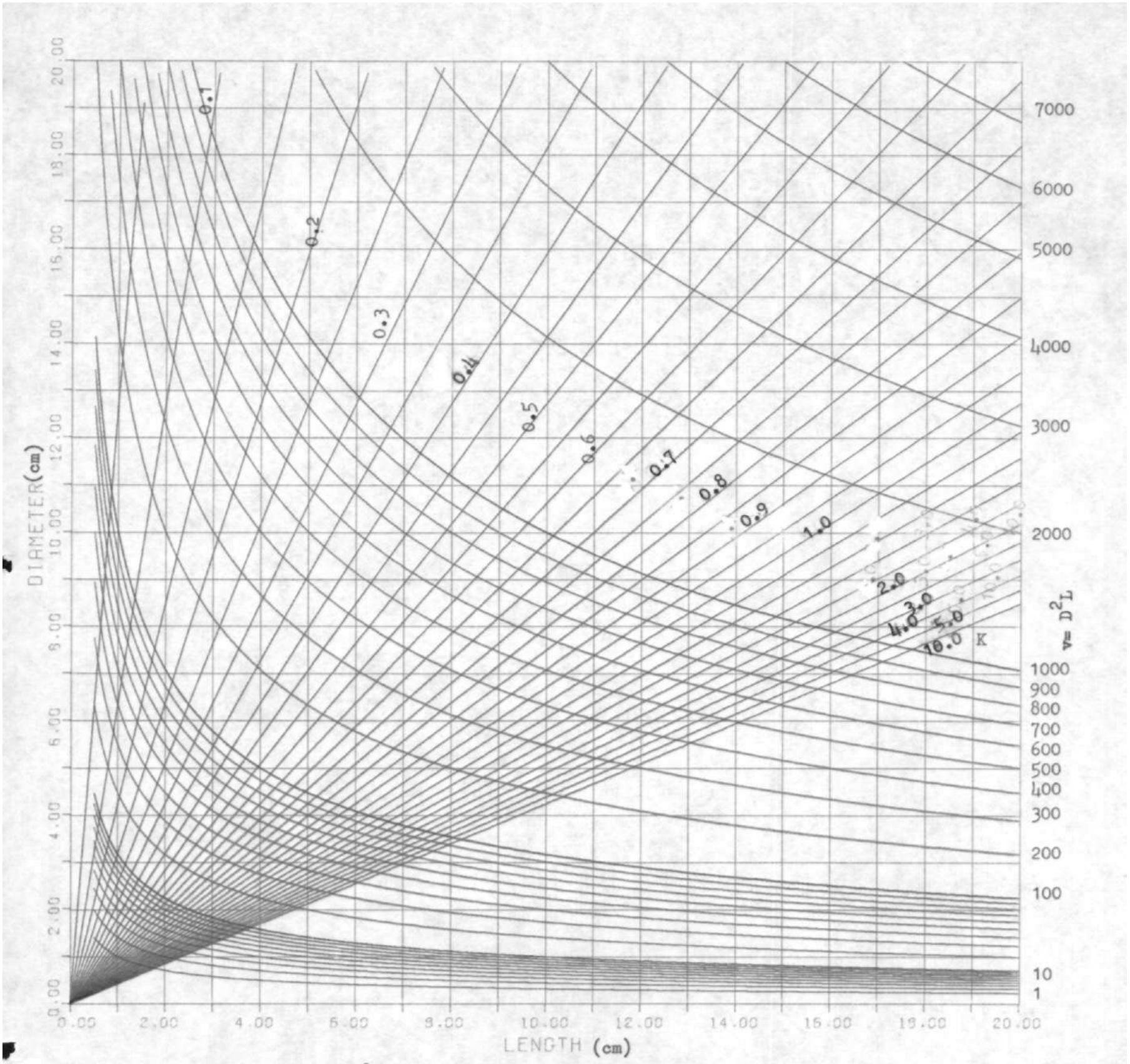


FIGURE 45: D^2L Seperation Chart; 2-Pole Machine.

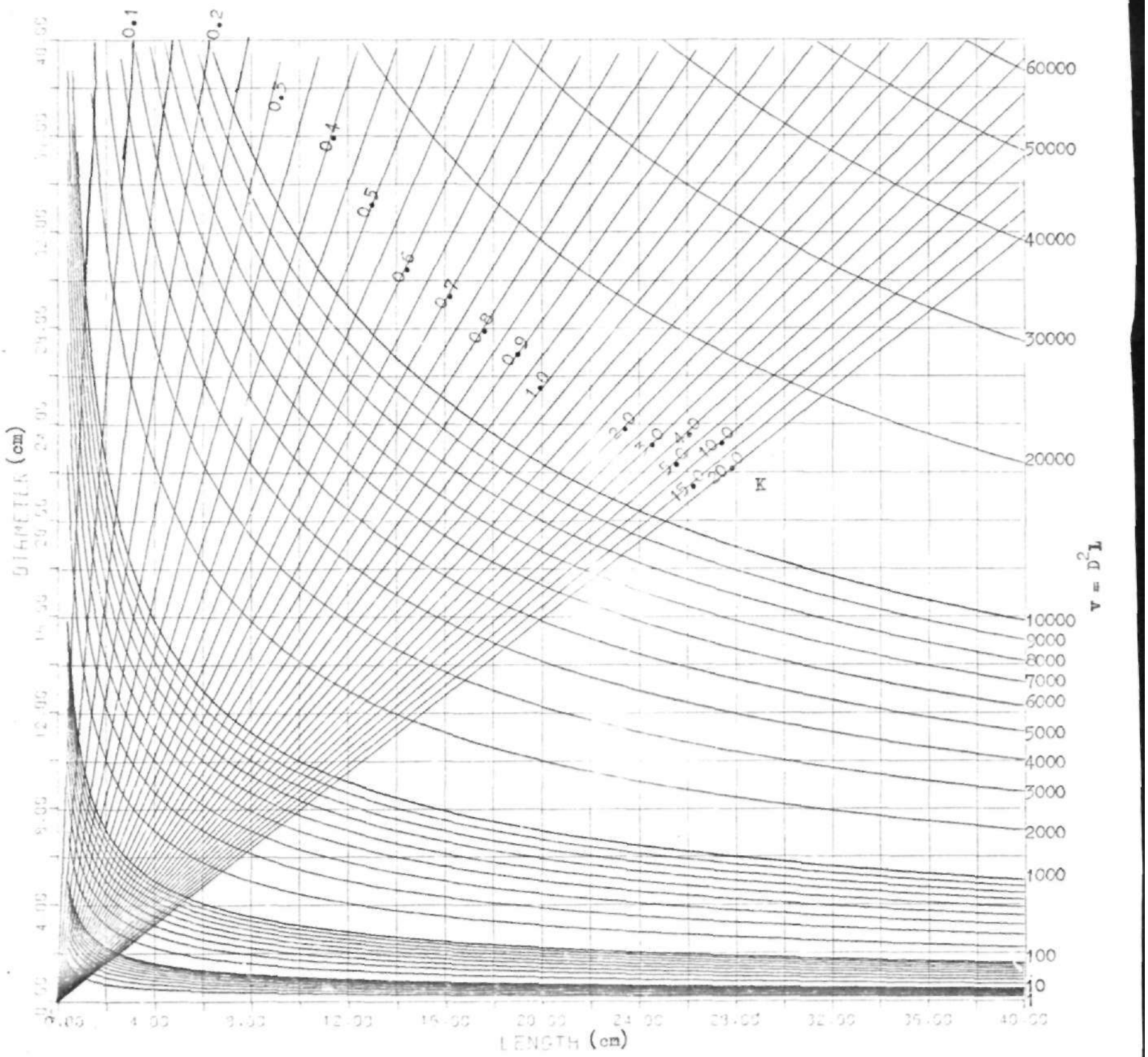


FIGURE 46: D^2L Separation Chart ; 4-Pole Machine.

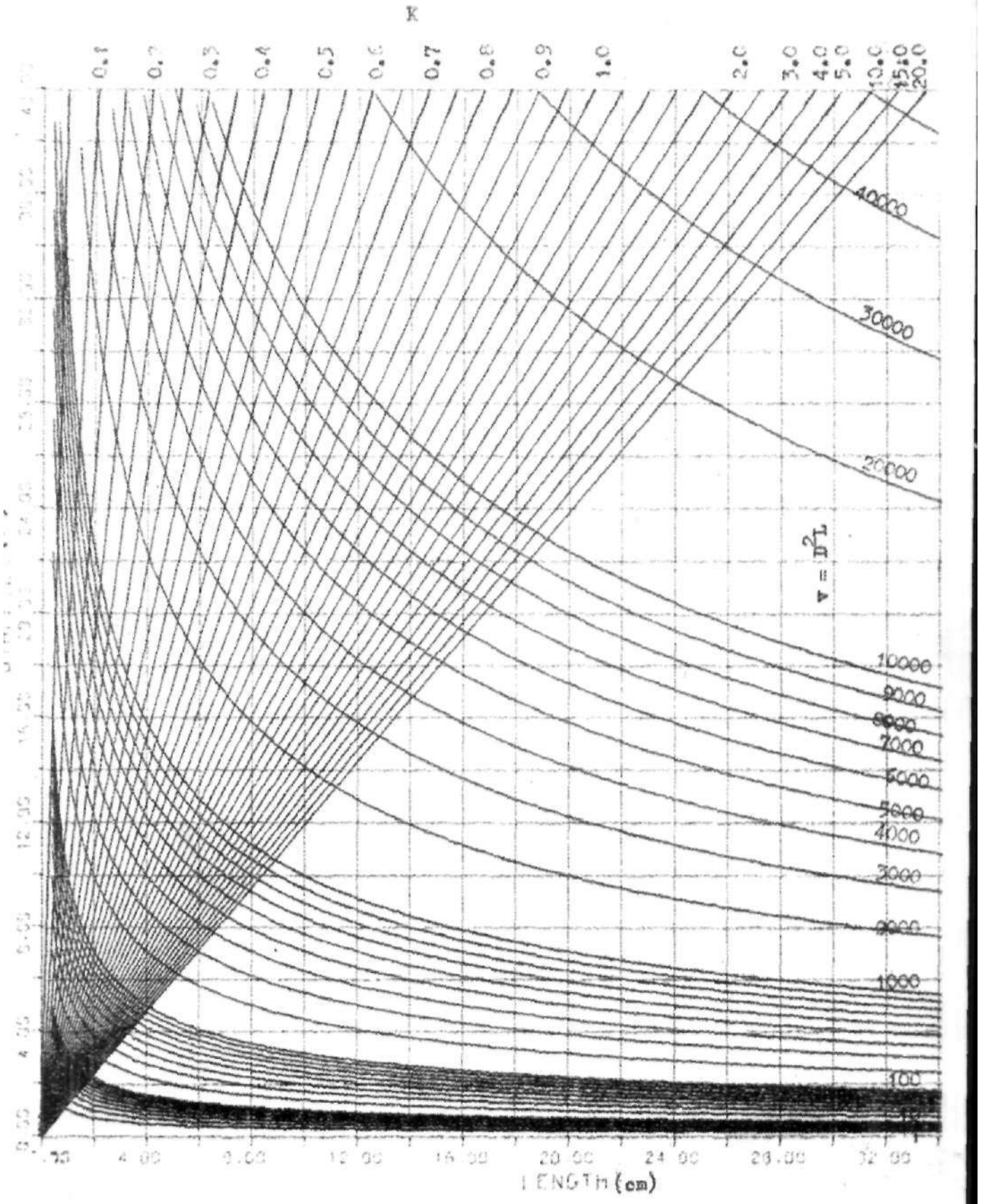


FIGURE 47: D^2L Separation Chart ; 6-Pole Machine.

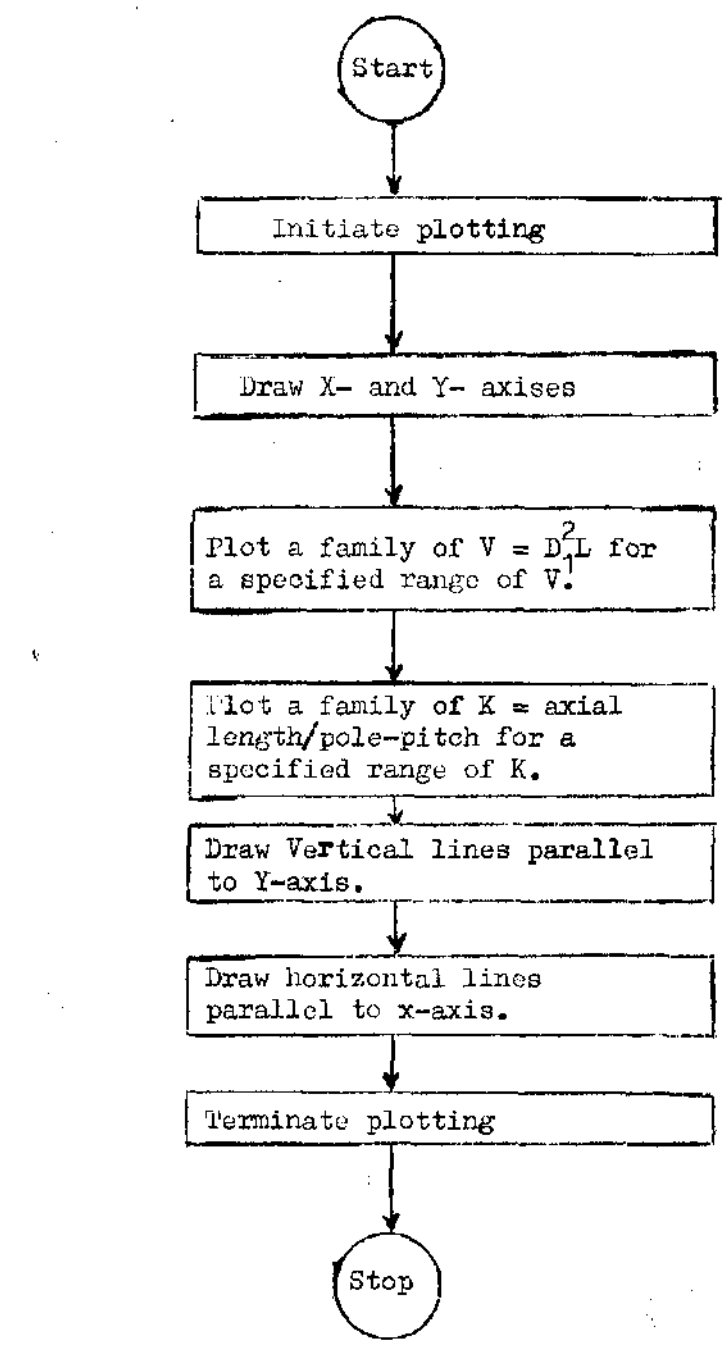


FIGURE 48: Flow diagram for the plotting of the D_1^2L separation charts.

These charts were drawn with the aid of the computer. The programs used are as shown on appendixes 16, 17, and 18, for 2, 4, and 6 poles machines respectively, and the flowchart for their easy understanding is as shown in figure 48.

A point on any of the chart is a function of four varibales, V, K, D_1 and L. Hence, the chart can also be used to establish the values of two of these variables if the remaining two are known.

CHAPTER 8

COMPUTER AIDED DESIGN ANALYSIS OF A SINGLE-PHASE INDUCTION MACHINE

In this chapter the way to accomplish the flow diagrams of the subroutines that are combined to form a library of programs for the design of a single-phase induction machine will be discussed.

8.1 Aspects of Machine Design

There are nine aspects of the design of a single-phase induction machine, excluding the mechanical design. These are as follow, in order:

1. The volume of active materials
2. The stator punching
3. The rotor punching
4. Magnetic Circuit Calculations
5. Main winding
6. Rotor Cage
7. Running performance calculations
8. Auxiliary winding
9. Combined-winding performance calculation

8.2 Volume of Active Materials

This involves the evaluation of the main dimensions of the machine and its maximum air-gap flux density. Articles 6.3.1.1 to 6.3.3, in Chapter 6, and the whole of Chapter 7 are very useful here. Figure 49 shows the flow diagram of the procedure to be followed.

8.3 The Stator Punching

This involves the calculation of all the dimensions of the stator slot. Figure 50 and table 20 give complete details. Figure 51 gives the flow diagram of the procedure to be followed.

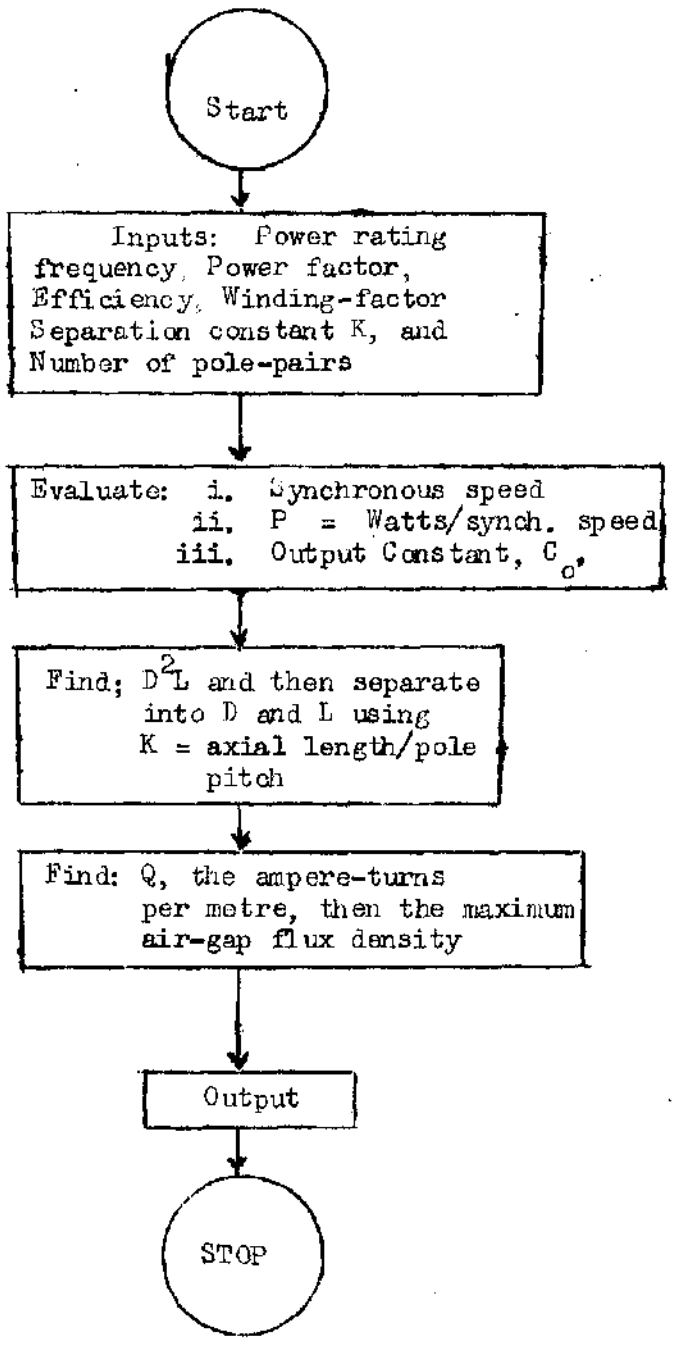


Figure 49: Flow diagram for Volume of active materials

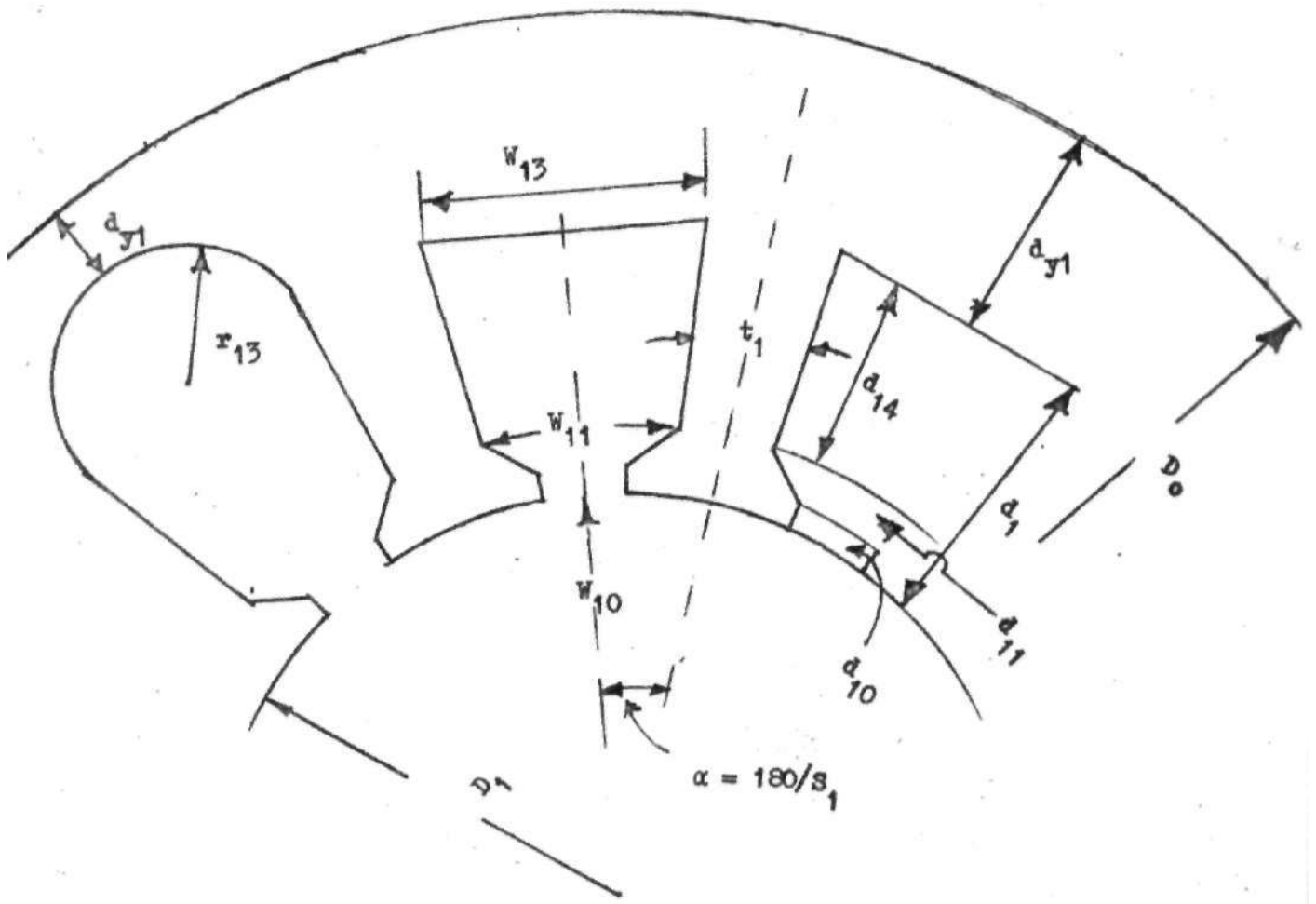


FIGURE 50: Stator Punching Design

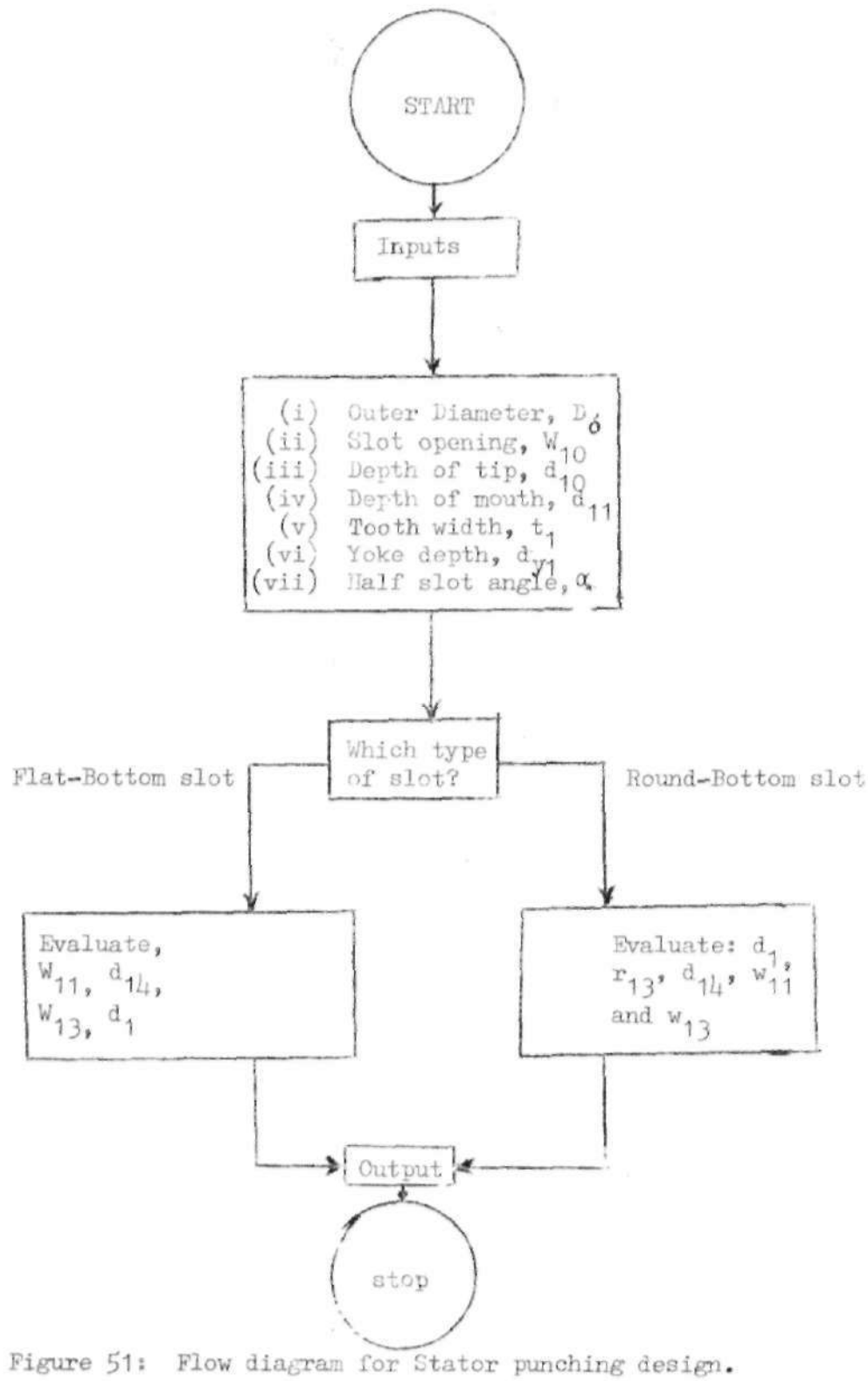
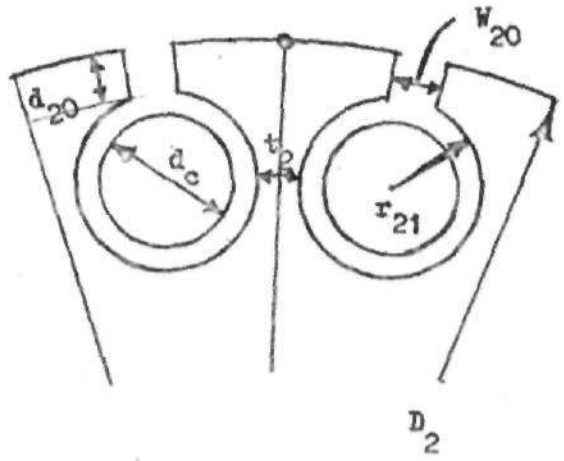
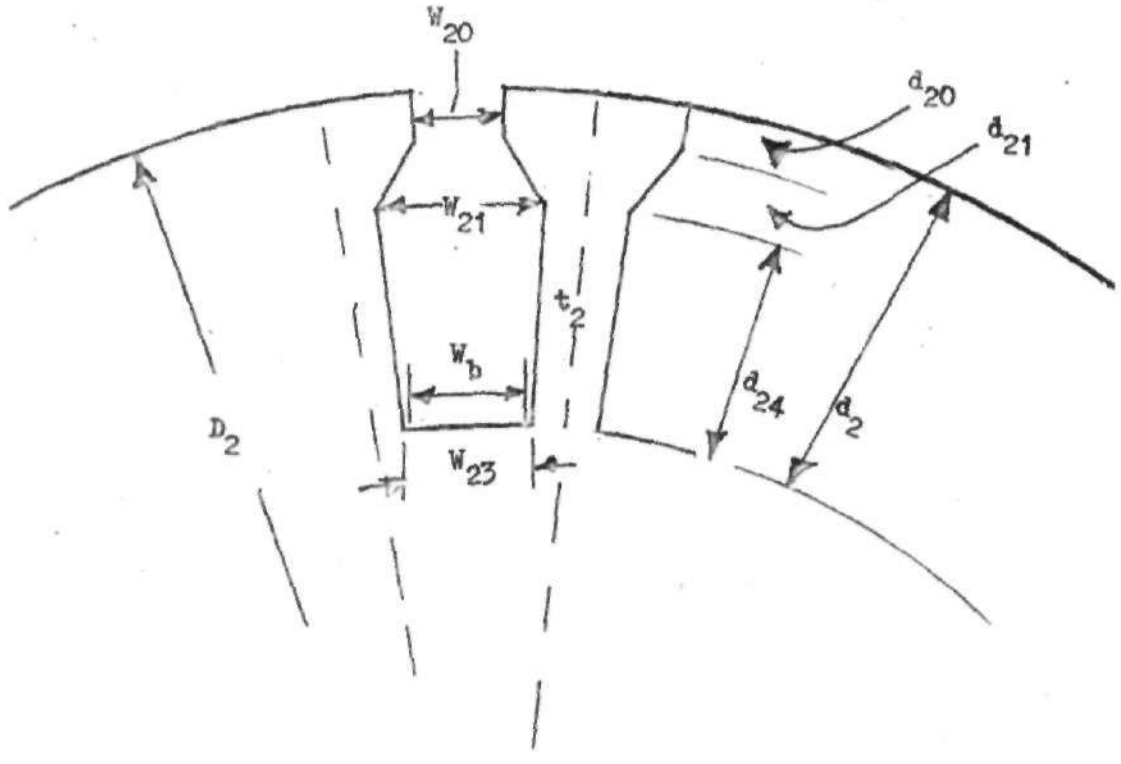


Figure 51: Flow diagram for Stator punching design.



(a) ROTOR ROUND SLOTS DESIGN



(b) ROTOR TRAPEZOIDAL SLOTS DESIGN

FIGURE 52: Rotor Punching Design.

8.4 The Rotor Punching

This is the evaluation of all the dimensions of the lamination. Figure 52 and table 21 give complete details. Figure 53 gives the flow diagram of the procedure to be followed.

8.5 Magnetic Circuit Calculations

This is summarized in table 7. A flow diagram of procedure to be followed is as shown in figure 54.

Table 20: Stator Punching[1] (All dimensions are in cm)

Outer Diameter	$Do = (D_1 (1.175 + 1.03/(2p))) + 1.5h3$
Bore Diameter	D_1
Number of slots	S_1
Slot open	If $S_1 = 24$, $W_{10} = 0.068 + 0.0175D_1$ If $S_1 = 36$, $W_{10} = 0.038 + 0.0175D_1$ If $S_1 = 48$ and above, $W_{10} = 0.0175D_1$
Depth of tip	$d_{10} = 0.08$
Depth of mouth	$d_{11} = (1.0 \text{ to } 1.5)\ d_{10}$

Table 20 (Contd.)

Tooth width	For 2-poles, $t_1 = D_1\ (1.10+0.0315D_1)/S_1$ For 4 poles and over, $t_1 = D_1\ (1.27 + 0.0354D_1)/S_1$
Yoke depth	$d_{y1} = (B_t/B_y)\ (S_1 t_1/2P)$ where B_t and B_y are tooth and yoke density respectively and P = number of pole-pairs. Take $(B_t/B_y) = 1.15$ initially.
Half - Slot angle	$\alpha = \alpha_s/2 = 180/S_1$
Flat - Bottom Slots	Round - Bottom Slots
$W_{11} \quad \frac{(D_1 + 2(d_{10}+d_{11})}{S_1} t_1$ $d_{14} = 0.5(D_o - D_1) - (d_{10} + d_{11} + d_{y1})$ $W_{13} = W_{11} + 2d_{14} \tan \alpha$ $d_1 = d_{10} + d_{11} + d_{14}$	$A = (D_1 \text{ Sin } \alpha - t_1)/2$ $B = 0.5\ (D_o - D_1) - d_{y1}$ $d_1 = \frac{B(1 + \text{Sin } \alpha) + 0.2A}{1 + 0.8 \sin \alpha}$ $r_{13} = \frac{A + B \text{ Sin } \alpha}{1 + 0.8 \text{ Sin } \alpha}$ $d_{14} = d_1 - (r_{13}+d_{10}+d_{11})$ $W_{11} = \frac{2(r_{13} - d_{14} \text{ Sin } \alpha}{\text{Cos } \alpha}$ $W_{13} = 2r_{13}$ approximately.

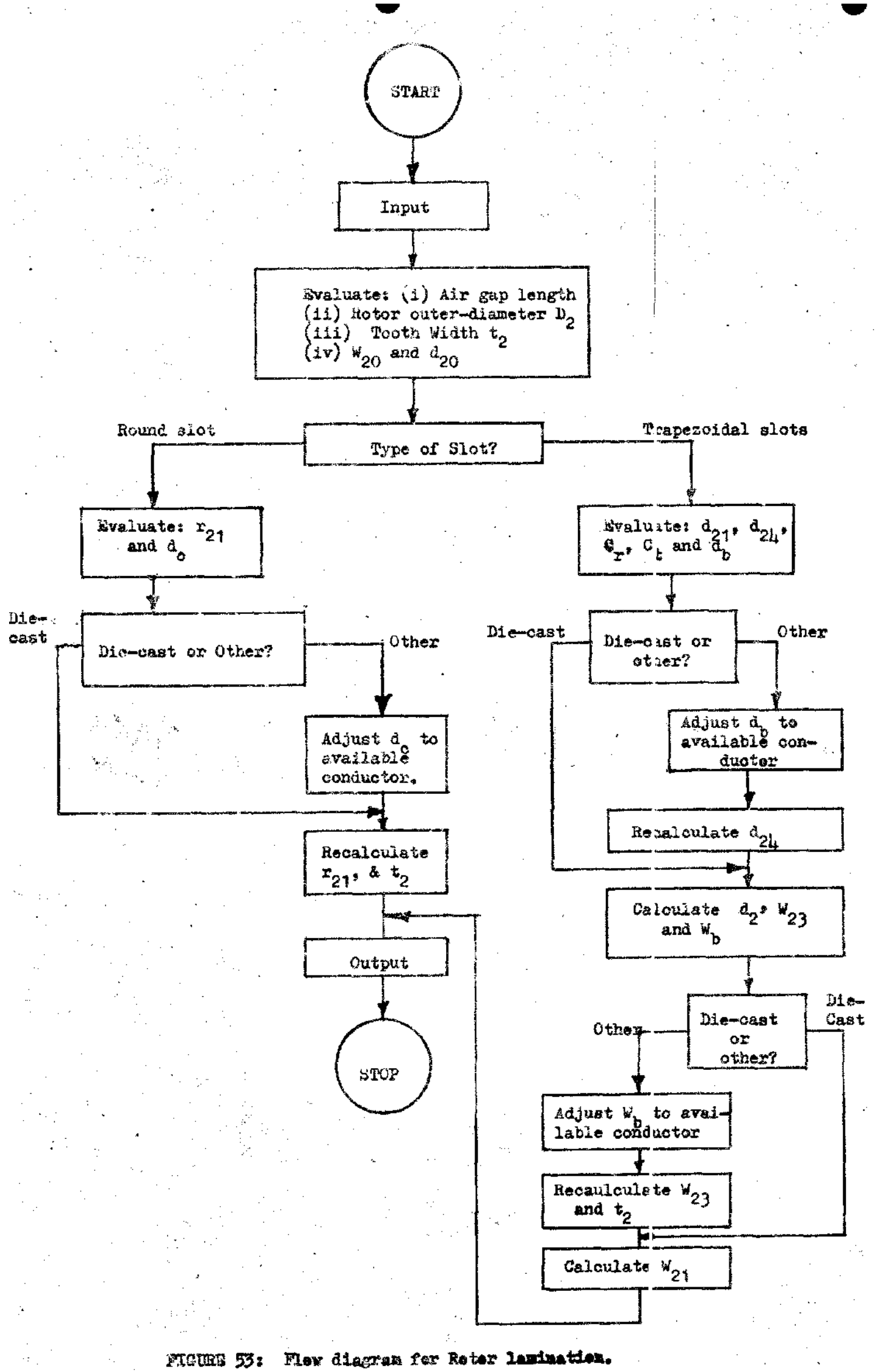


FIGURE 53: Flow diagram for Rotor lamination.

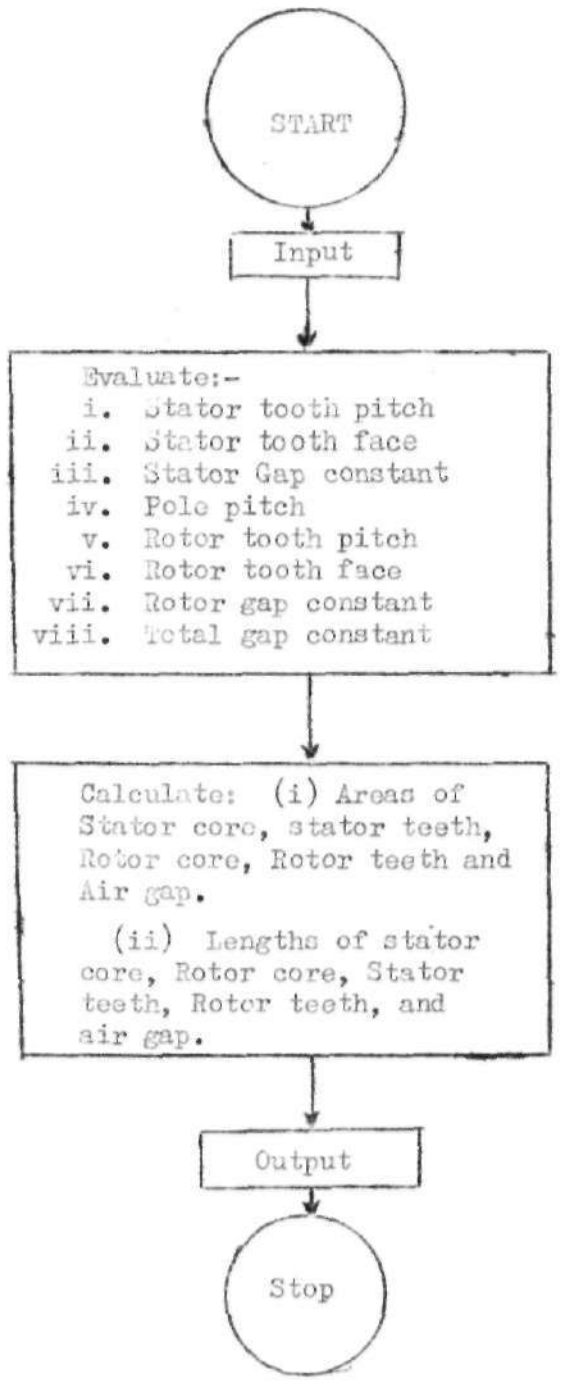


Figure 54: Flow diagram of magnetic circuit calculations

Table 21: Rotor Punching[1] (All dimensions are in Cm)

Air - gap	$l_g = 0.013 + 0.0042D_1//(2p)$
Rotor Outer Diameter	$D_2 = D_1 - 2l_g$
Tooth width	$t_2 = 0.95\ S_1 t_1/S_2$
Number of rotor slots	S_2
Slot open	$W_{20} \geq$ lamination thickness, to 0.08
Depth of tip	$d_{20} \geq W_{20}$
Round Slots	Trapezoidal slots
$r_{21} = \frac{\pi (D_2 - 2d_{20}) - S_2 t_2}{2(S_2 + \pi)}$ $d_c = 2r_{21} \geq 0.038$ Adjust d_c to the nearest Size of available conductor. In die-cast rotors this is not necessary and d_c may even be put = $2r_{21}$. $r_{21} = d_c/2$. $t_2 = \frac{\pi (D_2 - 2d_{20} - 2r_{21})}{S_2} - 2r_{21}$	$d_{21} = (1 \text{ to } 1.5)\ d_{20}$ $d_{24} = 0.254 + 0.03D_1$ Radial Clearance = $C_r = d_{24} - d_b$ $= 0.03$ to 0.04 Tangential clearance = $C_t = W_{23} - W_b$ $= 0.03$ $d_b = d_{24} - C_r$ *d_b and W_b are applicable to shaped conductor sizes. They do not apply in wound and die-cast rotor cases. However d_b and w_b values will have to be adjusted to the available conductor sizes.

Table 21 (Contd).

	$d_{24} = d_b + C_r$ (after adjustment) $d_2 = d_{24} + d_{21} + d_{20}$ $W_{23} = \frac{\pi (D_2 - 2d_2)}{S_2} - t_2$ $W_b = W_{23} - C_t$ (See *) $W_{23} = W_b + C_t$ (after adjustment) $W_{21} = W_{23} + 2d_{24} \tan (180/S_2)$ $t_2 = (\pi(D_2 - 2d_2)/S_2) - W_{23}$

8.6 Main Winding

The main winding is designdwith the aid ofthe whole of Chapter 5. The table in appendix 14, showing the distribution factor and harmonic content of concentric winding[1], is useful as well. The flow diagram of a procedure is as shown in figure 55.

Slot area (gross) $= (d_{11}(W_{10}+W_{11}) + d_{14}(W_{11}+W_{13}) + \pi r_{13}^2)/2$ —— (8.1)

(Note, for flat-bottom slots $r_{13} = 0$

Slot fullness $= \frac{nd^2}{A} \times 100$ (per cent) —— (8.2)

Fullest slot has $.55 \leqslant$ slot fullness $\leqslant .70$.

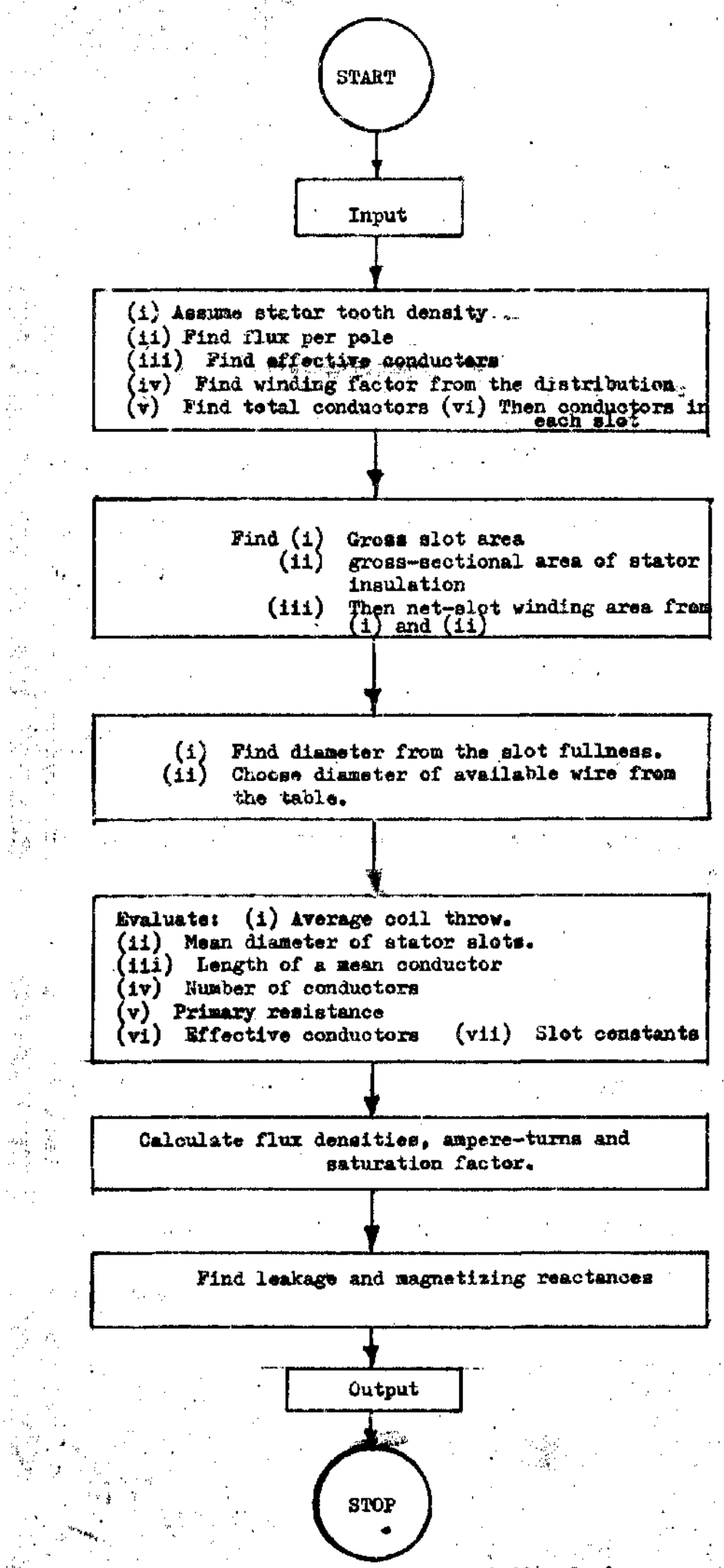


FIGURE 55: Flow diagram for main winding design.

8.7 Rotor Cage

Choice of the proper value of rotor resistance is a very important factor in the design of a small induction motor. It should be as low as possible to keep down secondary copper losses and to maintain high efficiency, high full-load speed, and minimum temperature rise.

Normal commercial fractional-kilowatt motors have the value of the ratio rotor resistance to short-circuit reactance (r_2/x) runs approximately as follows[1]:

Split-phase motors - - -	0.45 - 0.65
Capacitor-start motors - - -	0.45 - 0.80
Polyphase motors - - -	0.45 - 0.60
Permanent-split capacitor motors -	0.80 - 1.30

The flow diagram of figure 56 together with Chapter 5, article 5.4.2, will help in successfully carrying out the design of a rotor cage.

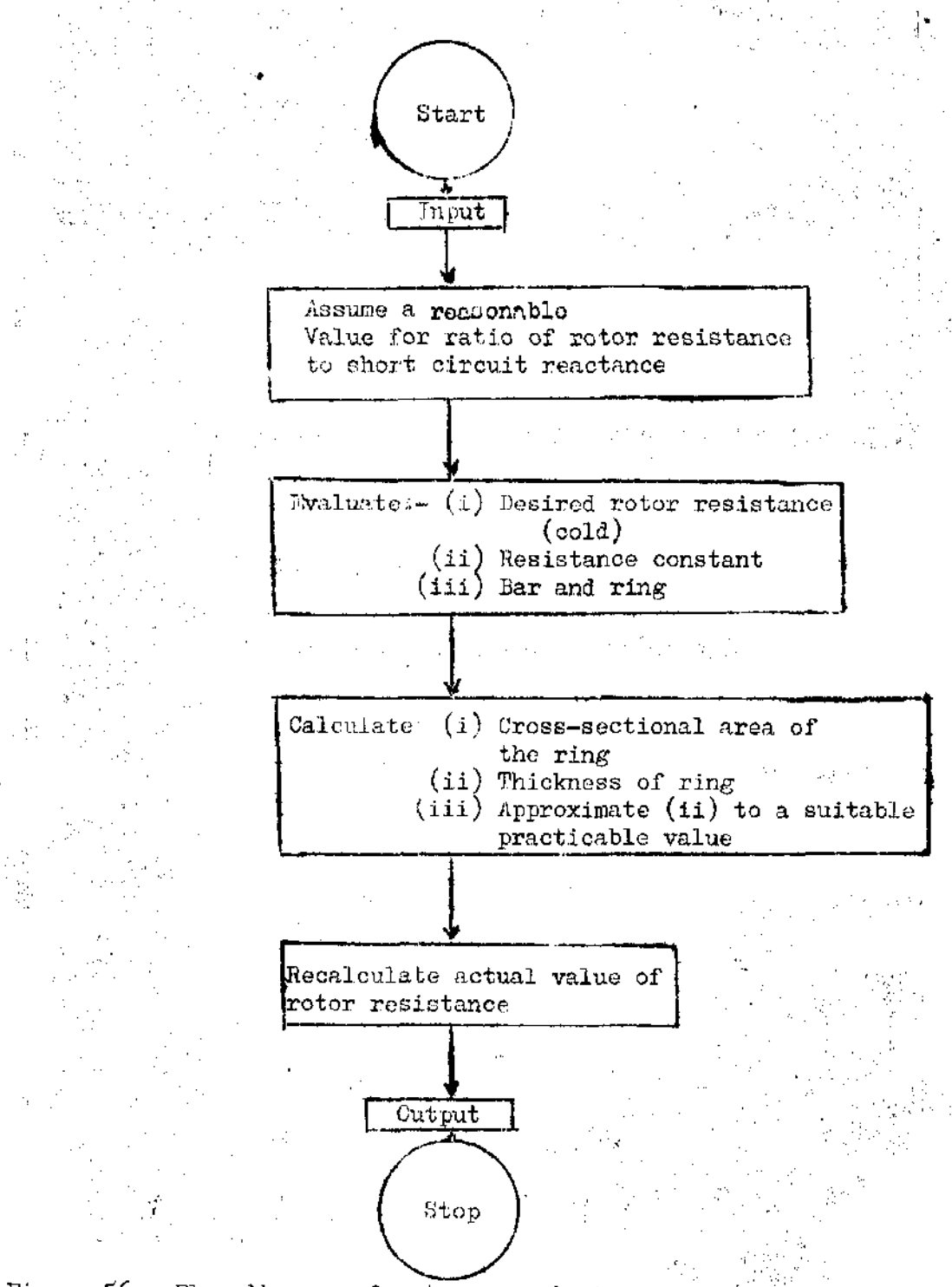


Figure 56: Flow diagram of rotor cage design.

8.8 Running Performance Calculations

The following empirical formula for the breakdown torque of a single-phase induction motor was developed by Veinott[1].

$$T_b = 0.08474\left(\frac{V}{115}\right)^2 \frac{p}{2} \times \frac{60}{f} \times \frac{345-9.2(R/x)^2}{R+X} \times K_r \quad - (8.3)$$

Core-loss and friction calculation procedures are summarized in Chapter 5, article 5.5. Fundamental-frequency losses are calculated from the innovated equations of article 6.3.10 in Chapter 6. The maximum flux density used are those calculated for Stator core and stator teeth in the main winding design.

The running performance calculations, consisting of no-load and full-load inputs and breakdown torque, are done using the revolving field theory presented in Chapter 4. The procedures for this are summarized in the Veinott's table of appendix 1.

8.9 Auxiliary Windings

The locked-rotor impedance of an induction motor, when magnetizing reactance is taken into account, is

$$Z_L = r_1 + r_2 C_r + j X C_R \qquad (8.4)$$

$$\text{Where } C_r = \frac{K_r}{1 + (r_2/X_o)^2} \quad - \quad (8.5)$$

$$C_R = \frac{1+(r_2/X)\ (r_2/X_o)}{1+(r_2/X_o)^2} \quad - \quad (8.6)$$

Note that C_r is the ratio of the apparent rotor resistance to actual rotor resistance, and C_R is the ratio of apparent short-circiut reactance to "ideal" short-circuit reactance.

X_o = open circuit reactance = $X_1 + X_m$

However, a complete system for defining the locked-rotor impedances and currents for single-phase motors is outlined in table 22.

Equation 4.43 gives the torque for any single-phase motor with windings in space quadrature, when both windings are energized at any slip s. At standstill, s = 1.0, and $R_f = R_b$, so that this equation then reduces to

$$T = 2a\ I_m I_a\ (\sin\phi)\ (R_f + R_b) \text{ syn. watts} \quad - \quad (8.7)$$

By putting s = 1.0 in equations we obtain

$$R_f + R_b = \frac{r_2 K_r}{1+(r_2/X_o)^2} = r_2 C_r = r_2^1 \quad - \quad (8.8)$$

ϕ represents the time phase angle between the respective currents in the main and auxiliary windings; hence, $\phi = \varrho_m - \varrho_a$.

Hence, (8.7) becomes

$$T = \frac{0.08474 \times 1.88 \times (2p)}{f}\ a r_2^1\ I_m I_a \sin(\varrho_m - \varrho_a) \quad - \quad (8.9)$$

Table 22: Motor constants for Locked-Rotor Conditions

	Windings Only		Windings with external impedance in series		
	Main Winding	Aux. Winding	Aux. Winding with resistor	Aux. Winding with capacitor	Main Winding with reactor
Applied Volts	V	V_a	V_{ar}	V_{ac}	V_{mR}
External Impedance	None	None	Z_r	Z_c	Z_R
Real component of external Impedance	0	0	R_r	R_c	R_R
Imaginary component of external impedance	0	0	X_r	X_c	X_R
Rotor resistance, referred to primary winding concerned	r_2	r_{2a}	r_{2a}	r_{2a}	r_2
Apparent rotor resistance	$r_2^1=r_cC_r$	$r_{2a}^1=r_{2a}C_r$	$r_{2a}^1=r_{2a}C_r$	$r_{2a}^1=r_{2a}C_r$	$r_2^1=r_2C_r$
Resistance of primary Winding	r_1	r_{1a}	r_{1a}	r_{1a}	r_1
Real component of total impedance	$R_m=r_1+r_2^1$	$R_a=r_{1a}+r_{2a}^1$	$R_{ar}=R_a+R_r$	$R_{ac}=R_a+R_c$	$R_{mR}=R_m+R_R$
"Ideal" Short-Circuit reactance	X_m	X_a			

...../(Cont.)

Table 22 (cont.)

"Apparent" reactance of imaginary component of impedance	$X^1_m = X_m C_R$	$X^1_a = X_a C_R$	$X^1_{ar} = X^1_a + X_r$	$X^1_{ac} = X^1_a + X_c$	$X^1_{mR} = X^1_m + X_R$
Total impedance (scalar)	$Z_m = \sqrt{R^2_m + X^{12}_m}$	$Z_a = \sqrt{R^2_a + X^{12}_a}$	$Z_{ar} = \sqrt{R^2_{ar} + X^{12}_{ar}}$	$Z_{ac} = \sqrt{R^2_{ac} + X^{12}_{ac}}$	$Z_{mR} = \sqrt{R^2_{mR} + X^{12}_{mR}}$
Current in one phase	$I_m = V/Z_m$	$I_a = V_a/Z_a$	$I_{ar} = V_{ar}/Z_{ar}$	$I_{ac} = V_{ac}/Z_{ac}$	$I_{mR} = V_{mR}/Z_{mR}$
Phase angle between current and voltage	θ_m	θ_a	θ_{ar}	θ_{ac}	θ_{mR}
Equations for angles	$\theta_m = \tan^{-1} \frac{X^1_m}{R_m}$	$\theta_a = \tan^{-1} \frac{X^1_a}{R_a}$	$\theta_{ar} = \tan^{-1} \frac{X^1_{ar}}{R_{ar}}$	$\theta_{ac} = \tan^{-1} \frac{X^1_{ac}}{R_{ac}}$	$\theta_{mR} = \tan^{-1} \frac{X^1_{mR}}{R_{mR}}$

which is the locked-rotor torque, or the starting torque equation, in N.m.

Veinott[1] shows that the following are the three criteria for fixing the starting winding:

(a) The total value of resistance in the auxiliary winding that must be used to obtain a maximum-torque winding is

$$R_a = \frac{X'_a}{X'_m}(R_m + Z_m) \quad \text{-------} \quad (8.10)$$

whichimplies that the total resistance in the primary of the starting winding, to satisfy (8.10), should be

$$r_{1a} = R_a - r'_{2a} \quad \text{------} \quad (8.11)$$

(b) A starting winding that gives maximum starting torque per ampere of line current for a fixed value of main winding and a specified line current is specified by the following:

$$R_a = \frac{R_m + Z_m (I_L/I_m)}{(I_L/I_m)^2 - 1} \quad \text{-------} \quad (8.12)$$

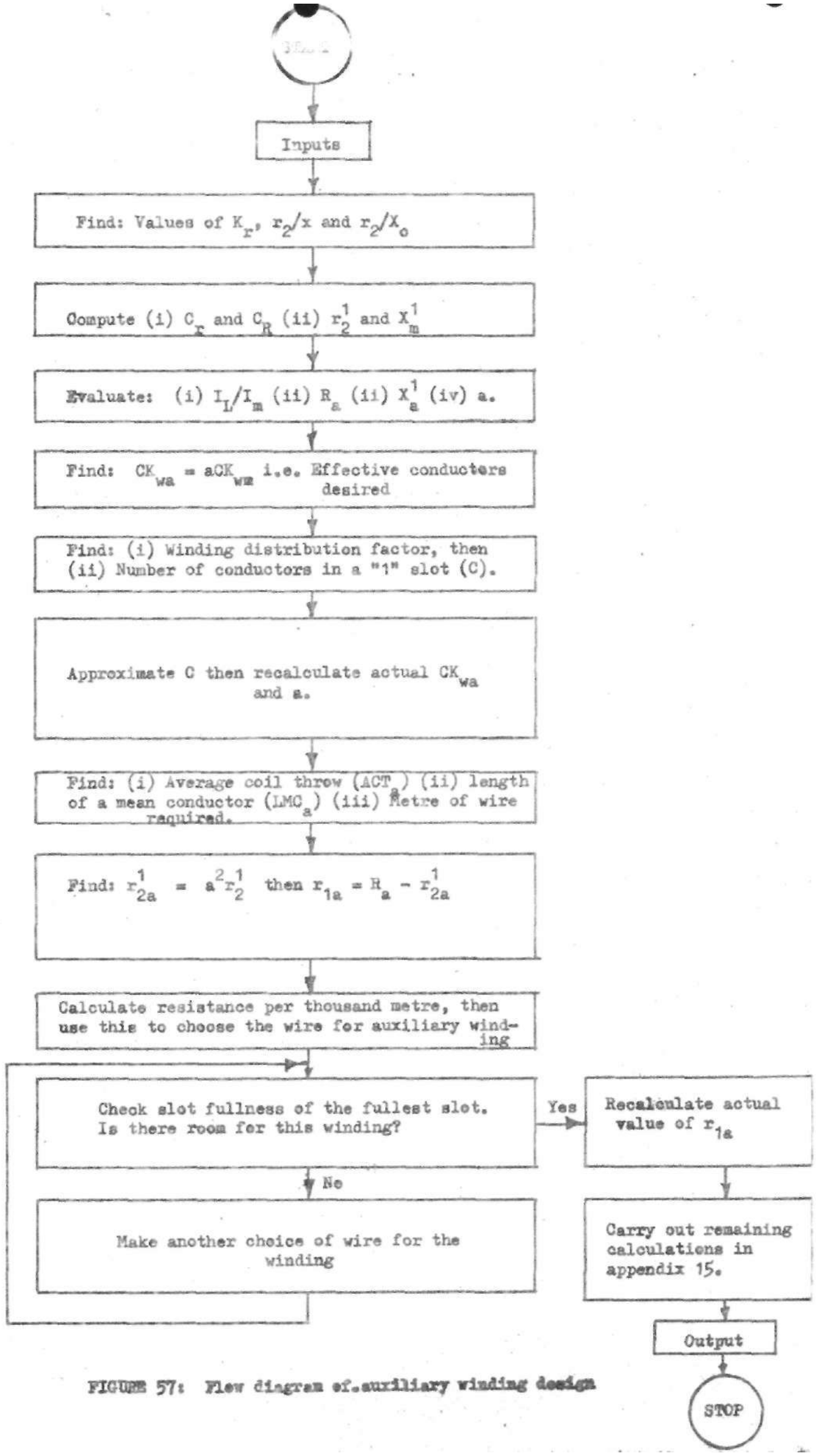


FIGURE 57: Flow diagram of auxiliary winding design

and

$$X_a^1 = \frac{X_n^1}{(I_L/I_n)^2 - 1} \qquad \text{(8.13)}$$

Note that in all the above equations the subscripts a, L and n denotes auxiliary or starting winding, line, and main winding quantities respectively. L in (8.4) specifies a locked rotor quantity.

(c) This is similar to (b) above except that

$$X_a^1 = \frac{R_a}{R_n}\left(X_m^1 - 2Z_m \operatorname{Sin}\frac{\theta_m}{3}\right) \qquad \text{(8.14)}$$

is used in place of (8.13) and a becomes a variable of the form

$$a = \sqrt{(X_a^1/X_n^1)} \qquad \text{(8.15)}$$

The major difference between (b) and (c) is that the latter takes into consideration the effect of changing the turns ratio a incident to the changing of X_a^1.

With the aid of the calculting form, used by Veinott[1], shown in appendix 15 and based on the theory summarized above, and the flow diagram of the procedure to be followed, which is as shown on figure 57, the auxiliary winding can be designed.

8.10 Combined Winding Performance Calculations

This is carried out as on Veinott's table, in appendix 2 which is based on the combined winding theory presented in Chapter 4.

8.11 Design Analysis Program

On the basis of all the procedures presented in the preceding sections, 8.2 to 8.10, a fortran IV computer program was written as shown in appendix 19 for the design of a split-phase induction machine. Each of the aspects mentioned in section 8.1 were written as a subroutine, except for the main winding design which was written in two subroutines. This program is easily understood with the aid of the list of abbreviations and notations used in the computer program (appendix 19). Table 23 shows the list of inputs, for the whole program, in order.

The whole program is partitioned into three: the first partition comprises of subroutines D2L, SPUNCH, RPUNCH, MAGCIR, and MW1, which take care of the volume of active materials, the stator punching, the rotor punching, magnetic circuit calculations, and part of main winding aspects respectively; the second partition consists of subroutines MW2, MW3, PERFCAL, and AUX1, which take care of the remaining part of the main winding, rotor cage, running performance calculations, and part of the auxiliary winding aspects respectively; the last partition comprises of subroutines AUX2 and COWNDPC, which take care of the remaining part of the auxiliary winding and the combined winding performance calculations aspects respectively.

In running the program for a design, there are three stages involved:

Stage 1: The program which is made of the first partition only is ran and the results obtained are used to chose the best main winding wire from the table of wires[1].

Stage 2: With the choice of the most suitable main winding wire made, a program which is made up of a merger of the first and the second partitions is ran. The results obtained, like in stage 1, are used in choosing the best auxiliary winding wire from the same table of wires.

Stage 3: The three partitions are merged to make a complete program, which is ran many times until satisfactory results are obtained.

Table 23: List of Inputs for the Program

Inputs	Units	Symbol/Abbreviation
Power	Watts	PJ
Frequency	Hz	FREQ
Number of polepairs	-	NPP
Power factor	-	PF
Efficiency	-	EFF
Winding factor	-	WF1
D^2L separation Constant	-	SCON
Number of Stator slots	-	NoS
Number of rotor slots	-	NRS
Stacking factor	-	F
Impressed voltage	volts	VMIN, VMAX
Stator teeth density	Tesla	BT
Main Winding Distribution	-	MD()
Number of slots containing conductors	-	LD

Table 23 (contd.)

Inputs	Units	Symbol/Abbreviations
Insulator thicknesses:		
Top Wedge	cm	TWI
Slot cell	cm	ISC
Fullerboard separator	cm	TFS
Estimated slot fullness	per cent	SLFULL
Number of coil sides per slot	-	NCSPS
Actual Wire Diameters	cm	DIACT
No. of type of wires	-	NDIN
Number of parallel paths	-	NPP
Resistance/1000 metres	ohms	RES
Resistance of commercially pure copper at ambient temperature	ohms	RCPC
Grade of steel factor	-	GSF
Journal outer diameter for sleeve bearings	cm	DJOUR
Indication for weather motor is totally enclosed fan-cooled	-	ITE
Specified Locked-rotor current	Amps	CL
Auxiliary Winding distribution	-	NAA()
Number of slots containing conductors	-	LDA
Slip at which running performance is calculated	-	SLIP
Number of sides in the fullest slot	-	NH
Diameter of chosen wire for auxiliary winding	cm	DIAA
Resistance/1000 metre	ohms	RWIRELA
Slip at which combined winding performance calculation	-	SLIP
Auxiliary winding voltage	volts	VA
Area of auxiliary Wire	Circular mils	AGA

8.11.1 Case Study

The program of appendix 19 was tested by using it to carry out the initial design of a 187 Watts, 115/120 Volts, 50 Hz, single-phase split-phase induction motor. The input specifications are as shown on table 24. By following the above procedures the program was ran on the university's computer, Cyber 72, employing the university of Minnisota Fortran Compiler (version 5.0 - 77/03/24), to give the results as shown on pages 163-168. The table of wire used is as shown in appendix 20.

Critical analysis of these results is impossible since there is no standard ones to compare them with. However, a closer study of some of the resulting values, like the dimensions, slip at which fulload running performance calculations is carried out, slip at which the maximum torque is achieved for combined-winding operation, efficiency, power factor, and starting to fulload torque ratio, it could be concluded that the whole exercise is successful and the results are good, at least for an initial design. Further, adjustments of some of the parameters, like those from the choice of the most suitable wire and the winding distribution, could be made to obtain better results.

The thickness of ring (0.002027 cm) obtained in this result is definately too low to be realistic. However, since this value is suppose to be the minimum possible, it can be increased as long as the cross-sectional area of the ring is kept constant. Hence, an increase of the thickness should be followed by a reduction of the width of the ring.

TABLE 24: Input Parameters to the Program in Appendix 19 for the Case Study.

Definition	Symbol/Abb.	Value
Power	PW	187 Watts
Frequency	FREQ	50 Hz
Number of Pole-pairs	NPP	2
Power factor	PF	0.75
Efficiency	EFF	0.75
Winding Factor	WF1	0.85
D^2L Separation Constant	SCON	0.80
Number of Stator slots	NSS	36
Number of rotor slots	NRS	48
Stacking Factor	F	0.97
Type of Stator Slot	IBS	0 (Note: 0 - Flat-bottom slot; 1 - Round-bottom slot)
Diameters of available	ROCBD( )	0.0453 x 2.54 cm
		0.0508 " "
		0.0570 " "
		0.0640 " "
		0.0720 " "
		0.0810 " "
		0.0910 " "

Table 24 (contd.)

		0.1020 x 2.54 cm
		0.1140 " "
		0.1290 " "
		0.1440 " "
		0.1620 " "
		0.1820 " "
		0.2040 " "
		0.2290 " "
		0.2580 " "
Widths of available Rectangular Copper Boss	RECCBW ( )	0.051 x 2.54 cm
		0.057 " "
		0.064 " "
		0.072 " "
		0.081 " "
		0.091 " "
		0.102 " "
		0.114 " "
		0.129 " "

Table 24 (contd.)

Depth of available Rectangular Copper Bar	RECCBD ( )	0.144 x 2.54 cm	
		0.162	" "
		0.182	" "
		0.204	" "
		0.229	" "
		0.258	" "
		0.289	" "
		0.325	" "
		0.365	" "
		0.375	" "
		0.500	" "
		0.625	" "
Type of rotor	IRT	0	
	(Note:	0-Bar	
		1-Wound	
		2-Die-cast)	
Type of rotor slot	IRS	0	
	(Note:	0-Round slot	
		1-Trapezoidal slot)	

Table 24 (contd.)

Impressed Voltage	VMIN	115 volts
	VMAX	120 volts
Stator tooth density	BT	1.32 Tesla
Main Winding Distribution	KD ( )	1, 1, 1
Number of slots containing conductors	LD	9
Insulator thicknesses:		
Top Wedge	TTW	0.079 cm
Slot Cell	TSC	0.043 cm
Fullerboard Separator	TFS	0.079 cm
Estimated slot fullness	SLFULL	65.0 %
Number of coil sides per slot	NCSPS	1
Number of elements in the distribution array(KD ( ))	NN	3
Diameter of Chosen Wires	DIACT( )	0.109728 cm
Number of elements in the DIACT ( ) array	NDW	1
Number of parallel paths	MPP	1
Resistance of chosen wire per 1000 metres	RES	21.358 ohms

Table 24 (contd.)

Resistance of commercially pure copper at ambient temperature	RCPC	0.423×10^{-7} ohms
Grade of steel factor	GSF	1.85
Journal outer diameter for sleeve bearings	DJOUR	1.905 cm
Indication for Weather motor is totally enclosed or not	ITE	0 (Note: 0-0.017tk, Electrical, Annealed 1-0.025tk, Field Grade, Annealed. 2-0.025tk, Field grade, Unannealed.
Specified locked - rotor current	CL	23.0 Amps
Auxiliary Winding distribution	KDA ( )	1, 1, 1
Number of slots containing conductor	LDA	10
Number of elements in array KDA ( )	NNA	3

Table 24 (contd.)

Number of sides in the fullest slot	NM	1
Diameter of Chosen wire for auxiliary winding	DIAA	0.049276 cm
Resistance of chosen wire per 1000 metre	RWIRNLA	136.54855 cm
Area of auxiliary wire	ACM	254.1 circular Mils
Auxiliary winding voltage	VA	115 volts

DESIGN RESULTS OF A 187 WATTS, 115/120 VOLTS, 50HZ,
SINGLE - PHASE SPLIT - PHASE INDUCTION MOTOR

SOME OF THE SPECIFICATIONS:

RATED POWER(WATTS)	=	187.000000
FREQUENCY	=	50.000000
POWER FACTOR	=	.750000
EFFICIENCY	=	.750000
FUNDAMENTAL WINDING FACTOR	=	.850000
DIAMETER AND LENGTH SEPARATION CONSTANT	=	.800000
STACKING FACTOR	=	.970000
NUMBER OF POLE PAIRS	=	2
NUMBER OF STATOR SLOTS	=	36
NUMBER OF ROTOR SLOTS	=	48

VOLUME OF ACTIVE MATERIALS

STATOR INSIDE DIAMETER(CM)	=	9.730053
STATOR AND ROTOR AXIAL LENGTH(CM)	=	6.117742
AMPERE-CONDUCTOR PER METRE	=	17845.612669
MAXIMUM AIR-GAP FLUX DENSITY(TESLA)	=	.217022

STATOR PUNCHING

STATOR OUTER DIAMETER,DO(CM)	=	15.581701
STATOR SLOT OPENING,W10(CM)	=	.200276
STATOR DEPTH OF TIP,D10(CM)	=	.000000
STATOR DEPTH OF MOUTH,D11(CM)	=	.104888
STATOR TOOTH WIDTH,T1(CM)	=	.436351
STATOR YOKE DEPTH,DY1(CM)	=	1.437562
STATOR HALF SLOT ANGLE(DEGREES)	=	5.000000

TYPE OF STATOR SLOT IS FLAT-BOTTOM

D1	1.480252
W11	.444879
D14	1.304262
W13	.673088

ROTOR PUNCHING

AIR-GAP LENGTH(CM)	=	.033483
ROTOR OUTER DIAMETER,D2(CM)	=	9.663107
ROTOR TOOTH WIDTH,T2(CM)	=	.305479
ROTOR SLOT OPENING,B2](CM)	=	.080000
ROTOR DEPTH OF TIP,[2](CM)	=	.080000
TYPE OF ROTOR SLOT IS ROUND		
R21	=	.148540
DC	=	.259780

MAGNETIC-CIRCUIT CALCULATIONS

STATOR TOOTH PITCH(CM)	=	.849107
STATOR TOOTH FACE(CM)	=	.640831
STATOR GAP CONSTANT	=	1.157506
POLE PITCH(CM)	=	7.615701
ROTOR TOOTH PITCH(CM)	=	.632454
ROTOR TOOTH FACE(CM)	=	.552494
ROTOR GAP CONSTANT	=	1.142680
TOTAL GAP CONSTANT	=	1.206919
STATOR CORE AREA(CM*CM)	=	17.061567
STATOR TEETH AREA(CM*CM)	=	23.304570
ROTOR CORE AREA(CM*CM)	=	16.208509
ROTOR TEETH AREA(CM*CM)	=	21.751898
AIR-GAP AREA(CM*CM)	=	46.590898
STATOR CORE LENGTH(CM)	=	5.554386
ROTOR CORE LENGTH(CM)	=	2.981520
AIR-GAP LENGTH(CM)	=	.049391
STATOR TEETH LENGTH(CM)	=	1.488280
ROTOR TEETH LENGTH(CM)	=	.099027

MAIN WINDING

ASSUMED STATOR TOOTH DENSITY(TESLA)	=	1.320000
SUPPLY VOLTAGE(VOLTS)	=115.000/120.000	
FLUX PER POLE(WEBERS)	=	.091252
NUMBER OF SLOTS PER POLE	=	9
EFFECTIVE CONDUCTORS	=	512.521484
WINDING FACTOR	=	.831287
TOTAL CONDUCTORS	=	616
NUMBER OF CONDUCTORS IN A "1" SLOT	=	25
GROSS SLOT AREA(CM*CM)	=	.763000
NET SLOT-WINDING AREA(CM*CM)	=	.559621
TOTAL NUMBER OF WIRES IN THE SLOT	=	26
DIAMETER OF WIRE WITH INSULATION(CM)	=	.116218

DIAMETERS OF WIRE(CM)	=	.1037[illegible]
ACTUAL SLOT FULLNESS	=	55.9[illegible]
AVERAGE COIL THROW	=	5.[illegible]
MEAN DIAMETER OF STATOR SLOTS(CM)	=	11.[illegible]
LENGTH MEAN CONDUCTOR(CM)	=	15.[illegible]
NUMBER OF CONDUCTORS	=	6[illegible]
STATOR WINDING RESISTANCE(OHMS)	=	1.[illegible]
STATOR RESISTANCE PER SECTION(OHMS)	=	1.[illegible]
EFFECTIVE CONDUCTORS	=	498
STATOR SLOT CONSTANT	=	1.[illegible]
ROTOR SLOT CONSTANT	=	1.[illegible]
FLUX PER POLE(WEBERS)	=	.[illegible]
FLUX DENSITIES(TESLA):		
STATOR CORE	=	1.[illegible]
STATOR TEETH	=	1.[illegible]
ROTOR CORE	=	1.[illegible]
ROTOR TEETH	=	1.[illegible]
AIR GAP	=	.[illegible]
AMPERE-TURNS PER METRE:		
STATOR CORE	=	810.[illegible]
STATOR TEETH	=	538.[illegible]
ROTOR CORE	=	689.[illegible]
ROTOR TEETH	=	457.[illegible]
AIR GAP	=	344450.[illegible]
TOTAL AMPERE-TURNS	=	195.[illegible]
SATURATION FACTOR	=	1.[illegible]
DISTRIBUTION FACTOR FOR SLOT LEAKAGE	=	1.[illegible]
TOTAL SLOT CONSTANT	=	2.[illegible]
ZIG-ZAG CONSTANT	=	.[illegible]
AVERAGE NUMBER OF SLOTS PER POLE	=	10
BELT LEAKAGE CONSTANT	=	1.[illegible]
SKEW ANGLE (DEGREES)	=	10.[illegible]
SKEW LEAKAGE FACTOR	=	.[illegible]
SKEW FACTOR	=	.[illegible]
DIFFERENTIAL LEAKAGE CONSTANT	=	204.[illegible]
REACTANCE CONSTANT	=	.[illegible]
LEAKAGE REACTANCES:		
SLOT	=	2.[illegible]
ZIG-ZAG	=	2.[illegible]
END	=	1.[illegible]
BELT	=	.[illegible]
SKEW	=	.[illegible]
TOTAL	=	7.[illegible]
MAGNETIZING REACTANCE	=	103.[illegible]
IDEAL SHORT-CIRCUIT REACTANCE	=	5.[illegible]
OPEN-CIRCUIT REACTANCE	=	105.[illegible]

RCTOR CAGE

RCTOR RE ISTANCE (OHM)	=	2.2
RESISTANCE CONSTANT	=	.02
CROSS-SECTIONAL ARE A CF A RCTCR BAR (CMXCM)	=	.05
INTERNAL CIAMETER CF RING(CM)	=	6.24
OUTER CIAMETER OF RING(CM)	=	9.66
THICKNESS OF RING(CM)	=	.00

PERFORMANCE CALCULATIONS

BREAKCCWN TORQUE(VEINCTT FCRMULA)(N.M)	=	3.08
LCSSES(WATTS):		
STATOR CORE	=	15.3
STATOR TEETH	=	7.75
SURFACE LCSS	=	4.15
TCTAL CORE LOSS	=	27.24
JCURNAL OUTER CIAMETER(CM)	=	1.90
GRADE CF STEEL FACTCR	=	1.85
FRICTICN AND WINDAGE LOSSES(WATTS)	=	7.91
SLIP	=	.02
BREAK CCWN SLIP	=	.15
RESISTANCES (CHMS):		
APPARENT TO FCRWARD FIELC	=	24.93
APPARENT TO FCRWARD FIELC(BREAKCCWN)	=	7.47
APPARENT TO BACKWARD FIELD	=	.61
APPARENT TO BACKWARD FIELD(BREAKCOWN)	=	.66
TCTAL	=	27.77
TCTAL(BREAKCOWN)	=	10.35
REACTANCES(OHMS):		
APPARENT TO FORWARD FIELC	=	23.91
APPARENT TO FCRWARD FIELC(BREAKCCWN)	=	2.55
APPARENT TO BACKWARD FIELD	=	1.42
APPARENT TO BACKWARD FIELD(BREAKCOWN)	=	1.48
TCTAL	=	28.24
TCTAL(BREAKCOWN)	=	6.8
TOTAL IMPECANCE(OHMS)	=	39.61
TCTAL IMPECANCE(BREAKCOWN)(CHMS)	=	12.43
CURRENT(AMP)	=	2.9
BREAKCCWN CURRENT	=	9.24
CCRRECTED CURRENT	=	3.34
NC-LOAC CURRENT	=	2.0
PRIMARY LCSS (WATTS)	=	25.5
NC-LCAC PRIMARY LOSS	=	9.41
SECCNCARY LOSS	=	15.9
NC-LCAC SECCNCARY LCSS	=	5.17
POWER INPUT	=	259.
NC-LCAC POWER INPUT	=	137.9
PCWER CUTPUT	=	187.2
BREAKCCWN POWER OUTPUT	=	554.2
SPEED (RPM)	=	1459.5
BREAKCCWN SPEEC (RPM)	=	1260.3

TORQUE (N.M)	=	1.225585
BREAKDOWN TORQUE(N.M)	=	4.199504
EFFICIENCY	=	.723104
POWER FACTOR	=	.739913
APPARENT EFFICIENCY	=	.535073
PERCENTAGE FULLOAD	=	100.159314

AUXILIARY WINDING

WINDING FACTOR	=	.901912
NUMBER OF CONDUCTORS IN A "1" SLOT	=	20
TOTAL CONDUCTORS	=	480
EFFECTIVE CONDUCTORS	=	432
AVERAGE COIL THROW	=	7.
LENGTH MEAN CONDUCTOR (CM)	=	16.565651
WIRE LENGTH (M)	=	79.515124
RESISTANCE PER 1000 METRES (OHMS)	=	121.455701

AUXILLIARY WINDING IS SATISFACTORY

DIAMETER OF CHOSEN WIRE (CM)	=	.049276
RESISTANCE PER 1000 METRES (OHM)	=	136.543866
PER CENT SLOT FULLNESS	=	64.696402

CONSTANTS FOR LOCKED-ROTOR CONDITIONS:

MAIN WINDING

REAL COMPONENT OF TOTAL IMPEDANCE	=	4.663876
APPARENT REACTANCE	=	5.802517
TOTAL IMPEDANCE	=	7.443866
CURRENT IN ONE PHASE	=	15.448902
PHASE ANGLE BETWEEN CURRENT AND VOLTAGE	=	.89387

AUXILLIARY WINDING

REAL COMPONENT OF TOTAL IMPEDANCE	=	14.333617
APPARENT REACTANCE	=	4.366488
TOTAL IMPEDANCE	=	14.974328
CURRENT IN ONE PHASE	=	7.673881
PHASE ANGLE BETWEEN CURRENT AND VOLTAGE	=	.299894

STARTING TORQUE (N.M.)	=	1.802956
ACTUAL LOCKED-ROTOR CURRENT	=	22.220780
CURRENT DENSITY	=	33.086753
PER CENT STARTING TO FULL-LOAD TORQUE	=	147.110187

COMBINED-WINDING PERFORMANCE CALCULATIONS

SLIP OF PERFORMANCE = .2685
AUXILLIARY WINDING VOLTAGE(VOLT) = 115.00000
IMPEDANCES(OHMS):
APPARENT TO FORWARD FIELD 4.657 1.93
APPARENT TO BACKWARD FIELD = .702 1.3
PRIMARY LEAKAGE OF MAIN WINDING = 2.221 2.5
PRIMARY LEAKAGE OF AUXILLIARY WINDING = 12.486 2.00
TOTAL OF MAIN WINDING = 7.550 6.1
TOTAL OF AUXILLIARY WINDING = 15.519 4.6
CURRENTS(AMP):
MAIN WINDING = 11.141 -6.7
AUXILLIARY WINDING = 4.736 -3.8
LINE = 15.877-10.6
INPUT POWERS(WATTS):
MAIN WINDING PHASE = 1281.219
AUXILLIARY WINDING PHASE = 544.623
TOTAL OR LINE = 1825.843
TORQUES(SYNCHRONOUS WATTS):
FORWARD FIELD = 836.936
BACKWARD FIELD = 151.242
NET INCLUDING FRICTION AND WINDAGE = 685.694
OUTPUT POWER(WATTS) = 481.397
EFFICIENCY(%) = .263
POWER FACTOR = .833
SPEED(RPM) = 111'.
TORQUE(N.M.) = .172
POWER LOSSES(WATTS):
FORWARD FIELD = 217.603
BACKWARD FIELD = 267.152
MAIN WINDING COPPER = 377.305
AUXILLIARY WINDING COPPER = 91.899
TOTAL = 365.985
OUTPUT POWER AND LOSSES(WATTS) = 1447.382
PULSATING TORQUE(SYNC. WATTS) = 782.855

CHAPTER 9

CONCLUSION

Computers usually plays four roles in the design of machines: analysis, synthesis, optimization, and problem study. Two of these roles were displayed in this work: analysis and problem study. Two design problems were studied; D_1^2L separation and reading of graphs into computer, and with the aid of the computer these were solved to give easier and more advantageous methods. The design analysis program developed, which completely takes care of all the machine design problems, except for the mechanical designs, make the computer serve as an aid to the designer in all possible ways except where taking of decision is concerned.

It is strongly believed that more and detailed investigations on the use of computer in electric machines design will later ensure complete design automation.

9.1 Suggestions for Further Works

The following are possible further works in this field:

(i) The analysis program in Chapter 8 should be run on any suitable computer for a machine whose design results are available for comparism. This program should be adequately corrected and adjusted on the basis of this comparism.

(ii) The type of studies conducted in this work should be extended to other families of the asynchronous machines like the series motor,

repulsion motor, and all forms of a-c commutator motors. They are useful machines in the industries to.

(iii) The same type of studies should be extended to the a-c synchronous machines and the a-c machine for completeness and since they are quite useful too.

(iv) Since a best machine, both in performance and cost, is the closest we can get to an ideal one, computer's role in all machines design synthesis and optimization should be given serious studies. Means should be devised for putting the wire table, mentioned in article 8.11, into computer and a suitable program should be devised to make the best choice of wire. This will enable the program to run once, instead of in stages, as mentioned in 8.11.

(v) It is the author's believe that computer can be employed in the winding diagram construction preparation for all forms of winding, but this requires an investigation.

The following suggestions, though general, are still within the range of the subject at hand:

(i) Most text books on electric machines design in print are just not detailed enough in making one to understand and appreciate the subject without having to go into their industry. Most delibrately leave out vital informations and hence leaving one almost not better than one was before taking the book. Some that are quite nice[1,6,7,8,9] are either out of print or re-revised in such a way as to make

them difficult to understand. All these, the author believes, are actions delibrately devised to achieve certain aims. However, to achieve our aims in this country, comprehensive literatures should be written on this subject.

(ii) As experience will prove, technology is only transferable in knowledge form only. Its physical realisation can only be achieved by the people themselves. For the people to sweat for technology development there is need for its appreciation. Various social, economic, and political problams are already generating this appreciation among the people. The society is getting more sophisticated each day. already there is a tremendous application of various types of electrical machines everywhere. Looking into the future and as standard of living rises, domestic appliances, like refrigerator, air-condition etc, specially applicable to the need of the ordinary people and adapted to the environmental conditions of the country may be developed. Also factories and industries necessary for their production in mass may spring up as well. Hence, the need for manufacturing electric motors in this country on a larger scale must arise.

APPENDIX 1

CALCULATION SHEET FOR MOTOR PERFORMANCE BY REVOLVING-FIELD THEORY

Single-phase Motor Performance by Revolving-field Theory

Given:	
r_1 hot	3.80
r_2 hot	4.65
X (s.c. react.)	8.3
X_0 (o.c. react.)	110
K_p	.964
K_f	.929
Fe loss (ff)	10.0
Fe loss (bf)	9.0
Fe loss (total)	19.0
Fr. & Wind.	10.0
Hp rating	¼
Volts	110
Cycles	60
Poles	4

Calculate:			
$x_1 = X/(1 + K_p)$	4.23	$M_2 = 0.5K_pX_0$	53.0
$M_1 = 0.5K_pr_2$	2.16	$M_4 = 0.5K_pr_1$	2.04
$M_2 = r_2/X_0$	.0423		

							No load	Breakdown torque
1	s	.044						.19
2	$2 - s$	1.956						1.81
3	M_1/s	49.1						11.37
4	$M_1/(2 - s)$	1.104						1.193
5	$(M_2/s)^2$	.924						.0496
6	$[M_2/(2 - s)]^2$	.000467						.00055
7	1.0 + (5)	1.924						1.0496
8	1.0 + (6)	1.0005						1.00055
9	$R_f = (3)/(7)$	25.5						10.83
10	$R_b = (4)/(8)$	1.103						1.192
11	r_1 =	3.8						3.80
12	$R = R_f + R_b + r_1$	30.40						15.82
13	$M_3 \times (5)$	49.0						2.62
14	$M_5 \times (6)$	.025						0.102
15	M_4	2.04						2.04
16	(13) + (15)	51.04						4.66
17	(14) + (15)	2.065						2.07
18	$X_f = (16)/(7)$	26.5						4.44
19	$X_b = (17)/(8)$	2.06						2.07
20	x_1	4.23						4.23
21	$X = X_f + X_b + x_1$	32.8						10.74
22	$Z = \sqrt{(12)^2 + (21)^2}$	44.7						19.12
23	$I = V/(22)$	2.46						5.75
24	I (corrected) *	2.52					1.860	
25	$R_f - R_b$	24.4						9.638
26	Fr. loss $= (24)^2 \times r_1$	24.1					13.1	
27	Sec. loss (f) $= (23)^2 sR_f$	6.8	19.0				0.0	
28	" " (b) $= (23)^2(2 - s)R_b$	13.1					7.5	
29	Fe loss (ff)	10.0					10.0	
30	$(23)^2 \times (25) \times (1 - s)$	141.2					19.0	273.1
31	Input = 26 to 30 inc.	195.2					49.6	
32	Fe loss (bf) + Fr & W	19.0						19.0
33	Output = (30) − (32)	122.1						239.1
34	Rpm = (1 − s) syn. rpm	1721						1458
35	Torq. = 112.7(33)/(34)	8.09						18.3
36	Eff. = (33)/(31)	62.6						
37	P.F. = (31)/(24)V	79.1						
38	App. Eff. = (36) × (37)	44.1						
39	% Full load	98.2						

* I (corrected) $= (23) + \dfrac{\text{Fe (ff)}}{V} \times \dfrac{(12)}{(22)}$

No-load Calcs.	
24	$I_0 = 2V/(X_0 + X)$
27	Sec. loss (f) = 0
28	Sec. loss (b) $= I_0^2 M_3$

APPENDIX 2[1]

CALCULATION SHEET FOR COMBINED WINDING PERFORMANCE

Performance Calculations on Capacitor Motors

V_m	115	V_a	115	Z_1	r_1 (hot) = .605	$x_1 = \frac{X_m}{1+K_p}$ = .375							
I_0	20.55	$K_a = V_a/V_m$	1.00	Z_{1a}	r_{1a} (hot) = 2.70	$x_{1a} = \frac{X_a}{1+K_p}$ = 1.31							
N_m	1.52	a	1.25	Z_c	R_c (hot) = 0.46	X_c = −5.52							
Hp	475	a^2	1.562	$Z_{1a}+Z_c$	$r_{1a}+R_c$ = 3.13	$x_{1a}+X_c$ = −4.01							
K_r	.926	Sym. rpm	1800	$M_1 = 0.5K_r r_2$ =	.395	$M_3 = 0.5K_p Y_0$ =	0.88						
K_p	.950	Fe loss	94.7	$M_2 = r_2/X_0$ =	.6415	$M_4 = 0.5K_{pa1}$ =	.377						
X_a	2.37	F & W	13.3		r-term	j-term	r-term	j-term	r-term	j-term	r-term	j-term	
r_2	.954	Fe + F & W	108.0	1	s = slip	M_4	.30	.372					
				2	$(M_3/s)^2$	$M_3(M_3/s)^2$	.04306	.4245					
				3	M_1/s	(1) + (2)	1.9750	7985					
				4	$(M_1/s)^2 + 1$		1.04306						
				5	$M_3 - s$	M_4	1.870	.3750					
				6	$(M_3/2 - s)^2$	$M_3(M_3/2 - s)^3$	.00653	.0065					
				7	$M_3/2 - s$	(5) + (6)	.2161	.3772					
				8	$(M_3/2 - s)^2 + 1$		1.00653						
				9	$K_r/(4)$	$K_p/(8)$	1.8975	.7856					
				10	$(6)/(8)$	$K_a/(8)$	.2102	.3779					
				11	(9) − (10)		1.6873	.4077					
				12	$a \times (11)$		2.1092	.5096					
				13	Z_c		.593	.775					
				14	(3) + (10)		2.1128	1.1408					
				15	$a^2 \times$ (14)		3.3023	1.7826					
				16	$R_a + Z_c$		3.193	−4.51					
				17	Z_T = (15) + (14)		.8056	1.9136					
				18	Z_{Ta} = (16) + (16)		5.1073	−2.8773					
				19	$E_T \times Z_{Ta}$ (Vector)		23.561	4.441					
				20	[Vector (12)]^2		1.147	7.028					
				21	(19) − (20)		13.414	2.417					
				22	$V_m/(21)$		8.573	−.2260					
				23	(18)		6.4633	−3.8272					
				24	$K_r \times$ (12) (Vector)		− 4353	2.693					
				25	(23) + (24)		8.9750	− 7382					
				26	$K_a \times$ (17)		2.9078	1.9150					
				27	− $j \times$ (12) (Vector)		.4832	−2.0930					
				28	(26) + (27)		3.3911	− 1774					
				29	I_m = (25)/(28) (Vector)	$A = 34.242$	$B = -8.935$	$A =$	$B =$	$A =$	$B =$	$A =$	$B =$
				30	I_a = (28)/(25) (Vector)	$a = 10.068$	$b = -3.423$	$a =$	$b =$	$a =$	$b =$	$a =$	$b =$
				31	$I_L = I_m + I_a$	53.410	−11.060						
						382.745							

Performance Calculations on Capacitor Motors

32	Ah	−117.02							
33	Bg	−164.46							
34	$Ah - Bg$	+46.94							
35	$I_m = \sqrt{A^2 + B^2}$	35.41							
36	$I_a = \sqrt{g^2 + h^2}$	19.37							
37	Line Amps	54.75							
38	Watts, Mn. Ph. $= V_m A$	3946.8							
39	Watts, Aux. Ph. $= V_{a\theta}$	2192.8							
40	Line Watts = (38) + (39)	6139.6							
41	I_m^2	1253.76							
42	$(bI_a)^2$	586.63							
43	(41) + (42)	1840.39							
44	2a × (34)	117.10							
45	(43) + (44)	1957.49							
46	(43) − (44)	1723.29							
47	(45) × R_f	3706.5							
48	(46) × R_b	377.9							
49	(47) − (48)	3328.6							
50	$1 - s$	.800							
51	(49) × (50)	2662.9							
52	(Fe + F & W)(1 − s)	86.4							
53	Output Watts = (51) − (52)	2576.5							
54	Efficiency = (53)/(40)	.4197							
55	P.F. = (40)/(37) × V_m	.9755							
56	Rpm = (50) × syn. rpm	1440.0							
57	Torque, oz-ft	201.6							
58	Sec. $I^2R(f)$ = (47) s	741.3							
59	Sec. $I^2R(b)$ = (48)(2 − s)	980.3							
60	Mn. Wdg. Cu. loss = $r_{1m} I_m^2$	871.4							
61	Aux. Wdg. Cu. loss = $r_{1a} I_a^2$	1013.4							
62	Capacitor loss = $R_c I_c^2$	172.6							
63	(Fe + F & W)(1 − s)	86.4							
64	Total losses	3563.3							
65	Output + losses	6141.8							
66	Cap. Volts = $I_a\sqrt{R_c^2 + X_c^2}$	113.02							
67	Aux. wdg. volts = $V - (30)Z_1$	169.07							
68	$T_p = \sqrt{[(11r)^2 + (11j)^2]}$ (45)(46)	3158							
69									
70									
71									

APPENDIX 3[11]

LINEAR LEAST-SQUARE CURVE FITTING

Linear least-square curve fitting problems are those where the undetermined constants which appear only in the linear form are determined by the least-squares method. The functional relation between x and y is of the form

$$y = C_1f_1(x) + C_2f_2(x) + \ldots\ldots + C_mf_m(x) \quad \text{---- (1)}$$

where the functions $f_1(x)$, $f_2(x)$, $f_3(x)$, etc, are completely known functions of x.

A3.1 Least-square Theory

If we have n sets of measured values, (x_1,y_1), (x_2,y_2)...., (x_n,y_n), and we substitute these into the given equation (1), we would like to satisfy the equations

$$C_1f_1(x_1) + C_2f_2(x_1) + \ldots\ldots + C_mf_m(x_1) = y_1$$

$$C_1f_1(x_2) + C_2f_2(x_2) + \ldots\ldots + C_mf_m(x_2) = y_2$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$C_1f_1(x_n) + C_2f_2(x_n) + \ldots\ldots + C_mf_m(x_n) = y_n$$

since the quantities x_1, x_2, etc; are known numbers, the quantities $f_1(x_1)$, $f_2(x_1)$, etc., are known numbers, so the above equations are just a set of n linear equations for the m unknowns, C_1, C_2,....C_m. If n is equal to m, there is exactly one solution (provided that the determinant of coefficients is not zero), that is, there is one set of values for C_1, C_2, ..., C_m that will cause the above equations to

be satisfied. If n is less than m, there are fewer equations than unknowns and there are an infinite number of solutions, each of which represents a curve passing through the given points. The problem in this case is not completely determined, and we cannot find a single "best" fit without further information of some sort. If n is greater than m, there are more equations than unknowns, and there is no solution. In this case we look for a solution in the "least-squares" sense. We write the equations in the form

$$C_1f_1(x_1) + C_2f_2(x_1) + \ldots\ldots + C_mf_m(x_1) - y_1 = d_1$$

$$C_1f_1(x_2) + C_2f_2(x_2) + \ldots\ldots + C_mf_m(x_2) - y_2 = d_2$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$C_1f_1(x_n) + C_2f_2(x_n) + \ldots\ldots + C_mf_m(x_n) - y_n = d_n$$

The quantities d_1, d_2, etc., are the "residuals". For a perfect fit these residuals would all be zero. Since we cannot make them be zero, we try instead to make them all small by looking for the values of C_1, C_2, ..., C_m which will minimize the expression $d_1^2+d_2^2+ \ldots.d_n^2$. In curve fitting, this last situation, in which there are more equations than unknowns, is the common one.

A3.2 Method of Performing Linear Least-Squares Fit

$$\sum_{i=1}^{m} C_if_i(x_j) - y_j = d_j, \quad j = 1, 2, \ldots..n \quad \text{------} \quad (3)$$

and we desire to choose the C_i's so that

$$\sum_{j=1}^{n} d_j^2 = \text{minimum} \quad \text{----} \quad (4)$$

This last quantity is to be regarded as a function of the C_i's. A necessary condition for it to be a minimum is that its partial derivatives by each of the C_i's must vanish,

$$\frac{\delta}{\delta C_k} \sum_{j=1}^{n} d_j^2 = 0 \quad \text{for } k = 1, 2, \ldots m$$

or

$$\sum_{j=1}^{n} d_j \frac{\delta d_j}{\delta C_k} = 0 \quad \text{for } k = 1, 2, \ldots m \quad \text{----} \quad (5)$$

Substituting this, and the value for d_j from (3) into (5), we have

$$\sum_{j=1}^{n} \left[\sum_{i=1}^{m} C_i f_i(x_j) - y_j \right] f_k(x_j) = 0 \quad \text{for } k = 1,2,\ldots, m$$

or

$$\sum_{i=1}^{n} C_i \sum_{j=1}^{n} f_i(x_j)\, f_k(x_j) = \sum_{j=1}^{n} y_j f_k(x_j) \quad \text{for } K=1,2,\ldots,m \quad \ldots\ldots \quad (6)$$

This is a system of m linear equations for the m unknowns, $C_1, C_2, \ldots, C_m$, and the solution is of course done through computer. Hence, in order to proceed with the construction of a flow chart, we

note that the problem is to solve the set of linear equations

$$\sum_{i=1}^{m} a_{ki} C_i = b_k \quad \text{for } k = 1, 2, \ldots m \qquad \text{---------- (7)}$$

where

$$a_{ki} = \sum_{j=1}^{n} f_i(x_j)\, f_k(x_j) \qquad \text{---------- (8)}$$

$$b_k = \sum_{j=1}^{n} y_j f_k(x_j) \qquad \text{---------- (9)}$$

The process can be written in a particularly nice form in matrix notation

let

$$F = \begin{bmatrix} f_1(x_1) & f_2(x_1) & \cdots & f_m(x_1) \\ f_1(x_2) & f_2(x_2) & \cdots & f_m(x_2) \\ \cdot & \cdot & \cdot & \cdot \\ f_1(x_n) & f_2(x_n) & \cdots & f_m(x_n) \end{bmatrix} \qquad \text{---------- (10)}$$

and

$$b = \begin{bmatrix} b_1 \\ b_2 \\ \\ \cdot \\ b_m \end{bmatrix}, \quad y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix}, \quad C = \begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_m \end{bmatrix}$$

Further let F^T stand for the matrix obtained by interchanging rows and columns in F. (F^T is read "F - Transpose") then

$$F^T = \begin{bmatrix} f_1(x_1) & f_1(x_2) & \cdots & f_1(x_n) \\ f_2(x_1) & f_2(x_2) & \cdots & f_2(x_n) \\ \cdots & \cdots & \cdots & \cdots \\ f_n(x_1) & f_n(x_2) & \cdots & f_n(x_n) \end{bmatrix}$$

Let

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix}$$

With this notation, equations (7), (8), and (9) become

$$AC = b$$

$$A = F^T F$$

$$b = F^T y$$

These equations really say the following,

If we wish the least-squares solution to the system of equations

$$FC = y \quad \text{--------} \quad (11)$$

where there are more equations than unknowns, we multiply both sides by F^T, and then solve the resulting system, which now has the same number of equations and unknowns:

$$(F^T F)\, C = F^T y$$

APPENDIX 4[11]

ITERATION SCHEME FOR FORMULAE NOT REDUCIBLE TO LINEAR

Let us suppose that we are attempting to fit a set of n points with the function

$$u = f(x, C_1, C_2, \ldots, C_m)$$

and that we already have rough estimates for the constants $C_1, C_2, \ldots, C_m$, for example

$$C_1 \approx K_1$$

$$C_2 \approx K_2$$

$$\ldots\ldots\ldots$$

$$C_m \approx K_m$$

where the K_i are known. More precisely, we can say that

$$C_1 = K_1 = E_1$$

$$C_2 = K_2 + E_2$$

$$\ldots\ldots\ldots\ldots$$

$$C_m = K_m + E_m$$

where $E_1, E_2, \ldots, E_m$ are unknown but small. Then

$$y = f(x, K_1+E_1, K_2+E_2, \ldots, K_m + E_m)$$

or, by Taylor's formula,

$$y = f(x,K_1,k_2, \ldots, K_m) + \frac{E_1 \partial f(x,K_1,K_2, \ldots, K_m)}{\partial C_1} \ldots$$

$$+ E_m \frac{\partial f(x,K_1,K_2, \ldots, K_m)}{\partial C_m}$$

This is a different formula for y, one in which everything is known but the coefficients E_1, E_2, ..., E_m. Since these appear linearly, they can be determined by the method of linear formulae. Once these are determined, we have a new estimate for the C_j's. If we desire, we can then use these new C values as K_1, K_2, ... , K_m and repeat the process. If the initial guess was sufficiently good, the process may converge to the desired values C_1, C_2, ... , C_m.

APPENDIX 5

SHIRPLEY'S METHOD FOR INVERTING A MATRIX

The process can be described as pivoting along the major diagonal elements of the matrix to be inverted. The pivoting operation is performed for each of the diagonal elements as follows:-

1. All elements not in the same row or column as the pivot element a_{kk} are modified by the use of equation (1)

$$a_{ij} = a^{\dagger}_{ij} - a_{ik}a_{kj}/a_{kk} \quad i \neq k \;; j \neq k \quad \text{---} \quad (1)$$

2. Elements in the pivot row k are replaced by the application of equation (2)

$$a^{1}_{kj} = - a_{kj}/a_{kk} \quad j \neq k \quad \text{.....} \quad (2)$$

3. Elements in the pivot column k are replaced by the application of equation (3)

$$a^{1}_{ik} = - a_{ik}/a_{kk} \quad i \neq k \quad \text{-----} \quad (3)$$

4. The pivot elements, a_{kk} is replaced by

$$a^{1}_{kk} = - 1/a_{kk} \quad \text{----} \quad (4)$$

The process is repeated for each diagonal element taken in any sequence. When the process is completed, the negative inverse has replaced the original matrix.

APPENDIX 6

PROGRAM FOR FITTING CURVE OF OUTPUT CONSTANT FOR

POLYPHASE INDUCTION MACHINES

```
MINNESOTA FORTRAN COMPILER (VERSION 5.0 - 77/03/24) ON THE CY72 M

     MNF,I=PCXF2C,B=0,J,T.

 018          PROGRAM CURFIT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
 218          DIMENSION FUN(18,2),FUNT(2,18),A(2,2),B(2),C(2),Y(18)
 218          DO 2,N=1,18
 658          READ 1,P,CO
 768  1       FORMAT(F5.1,F7.4)
 763          P=P/1.34
 778          FUN(N,1)=FUNT(1,N)=1.0
 108          FUN(N,2)=FUNT(2,N)=-EXP(-P*3.013)
 308          Y(N)=CO
 348  2       CONTINUE
 408          DO 3,M=1,2
 438          DO 3,N=1,2
 468          A(M,N)=0.0
 538          DO 3,K=1,18
 628          A(M,N)=A(M,N)+FUNT(M,K)*FUN(K,N)
 658  3       CONTINUE
 218          DO 4,M=1,2
 238          B(M)=0.0
 278          DO 4,K=1,18
 738          B(M)=B(M)+FUNT(M,K)*Y(K)
 338  4       CONTINUE
 718          DO 8,N=1,2
 738          IF(A(N,N).EQ.0.0)STOP
 148          DO 6,NN=1,2
 568          IF(NN.EQ.N)GO TO 6
 108          DO 5,JN=1,2
 138          IF(JN.EQ.N)GO TO 5
 158          A(NN,JN)=A(NN,JN)-A(NN,N)*A(N,JN)/A(N,N)
```

```
5408   5      CONTINUE
5448   6      CONTINUE
5508          DO 7,KN=1,2
5528          IF(KN.EQ.N)GO TO 7
5548          A(N,KN)=A(N,KN)/A(N,N)
5648          A(KN,N)=A(KN,N)/A(N,N)
5728   7      CONTINUE
5768          A(N,N)=-1.0/A(N,N)
6008   8      CONTINUE
6048          DO 81,I=1,2
6068          DO 81,K=1,2
6118          A(I,K)=-A(I,K)
6118   81     CONTINUE
6348          DO 11,M=1,2
6368          C(M)=0.0
6428          DO 9,K=1,2
6458          C(M)=C(M)+A(M,K)*B(K)
6458   9      CONTINUE
7018          PRINT 10,C(M)
7148   10     FORMAT(2X,F20.6)
7148   11     CONTINUE
7178          REWIND 5
7218          DO 13,N=1,18
7238          READ 1,P,CO
7348          P=R/1.34
7358          CON=2.06-0.97*EXP(-0.013*P)
7458          ERROR=CO-CON
7468          PRINT 12,P,CO,CON,ERROR
7618   12     FORMAT(2X,4F20.6)
7618   13     CONTINUE
7648          STOP
7658          END
```

Table A6.1: Input to Computer program of appendix 6.

FX1.34	C_o
10	1100.0
20	1240.0
25	1300.0
30	1360.0
40	1440.0
50	1500.0
70	1600.0
80	1639.0
90	1666.7
100	1700.0
110	1733.4
130	1766.7
140	1800.0
150	1833.3
160	1840.0
170	1866.7
200	1900.0
220	1933.4

APPENDIX 2

PROGRAM FOR FITTING CURVE OF AMPERE CONDUCTOR FOR

POLYPHASE INDUCTION MACHINES

```
OF MINNESOTA FORTRAN COMPILER (VERSION 5.0 - 77/03/24) ON TPS
      MNF,I=PEXP2Q,B=E,J,T.
0000008           PROGRAM CURFIT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OU
0021218           DIMENSION FUN(24,2),FUNT(2,24),A(2,2),B(2),C(2)
0021218           DO 2,N=1,24
0023238           READ 1,P,CO
0023348     1     FORMAT(F5.1,F7.2)
0023348           P=P/1.34
0023358           CO=CO*39.4
0023378           FUN(N,1)=FUNT(1,N)=1.0
0023508           FUN(N,2)=FUNT(2,N)=-EXP(-P*0.01884)
0023708           Y(N)=CO
0023748     2     CONTINUE
0024008           DO 3,M=1,2
0024038           DO 3,N=1,2
0024068           A(M,N)=0.0
0024138           DO 3,K=1,24
0024208           A(M,N)=A(M,N)+FUNT(M,K)*FUN(K,N)
0024218     3     CONTINUE
0024618           DO 4,M=1,2
0024638           B(M)=0.0
0024678           DO 4,K=1,24
0024738           B(M)=B(M)+FUNT(M,K)*Y(K)
0024738     4     CONTINUE
0025318           DO 8,N=1,2
0025338           IF(A(N,N).EQ.0.0)STOP
0025448           DO 5,NN=1,2
0025468           IF(NN.EQ.N)GO TO 6
0025508           DO 5,JN=1,2
0025538           IF(JN.EQ.N)GO TO 5
0025558           A(NN,JN)=A(NN,JN)-A(NN,N)*A(N,JN)/A(N,N)
0026008     5     CONTINUE
0026048     6     CONTINUE
0026108           DO 7,KN=1,2
0026128           IF(KN.EQ.N)GO TO 7
0026148           A(N,KN)=A(N,KN)/A(N,N)
0026248           A(KN,N)=A(KN,N)/A(N,N)
```

```
0026328    7     CONTINUE
0026368          A(N,N)=-1.0/A(N,N)
0026408    8     CONTINUE
0026448          DO 81,I=1,2
0026468          DO 81,K=1,2
0026518          A(I,K)=-A(I,K)
0026518    81    CONTINUE
0026748          DO 11,M=1,2
0026768          C(M)=0.0
0027028          DO 9,K=1,2
0027058          C(M)=C(M)+A(M,K)*B(K)
0027058    9     CONTINUE
0027418          PRINT 10,C(M)
0027548    10    FORMAT(2X,F20.6)
0027548    11    CONTINUE
0027578          REWIND 5
0027618          DO 13,N=1,24
0027638          READ 1,P,CO
0027748          P=P/1.34
0027758          CO=CO*39.4
0027778          CON=29303.35-11484.05*EXP(-0.0184*P)
0030078          ERROR=CO-CON
0031108          PRINT 12,P,CO,CON,ERROR
0030238    12    FORMAT(2X,4F20.6)
0030338    13    CONTINUE
                 STOP
                 END
```

Table A7.1: Input to Computor program of appendix 7.

PX1.34 $= (\frac{KWX10^3}{N_s})$	Q → 39.4 (Amp. Cond./m.)
10	470
15	500
20	522.5
30	557.5
35	572.5
40	585
50	603.75
60	620
70	637.5
80	648.75
90	660
100	671.1
110	678.95
120	686.84
130	693.42
140	700.00
150	705.00
160	710.00
170	715.00
180	717.50
190	720.0
200	722.50
210	725.0
220	725.75

APPENDIX 8

PROGRAM FOR FITTING CURVE OF OUTPUT CONSTANT FOR SPLIT-PHASE AND CAPACITOR START INDUCTION MOTORS

```
Y OF MINNESOTA FORTRAN COMPILER (VERSION 5.0 - 77/03/24) ON THE CYBER

      MNF,I=PEXF2CC,B=AA,J,T.

0000008B          PROGRAM CURFIT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
0021218          DIMENSION FUN(13,2),FUNT(2,13),A(2,2),B(2),C(2),Y(13)
0021218          DO 2,N=1,13
0022348          READ 1,P,CO
0022458    1     FORMAT(F4.2,F7.2)
0022458          FUN(N,1)=FUNT(1,N)=1.0
0022568          FUN(N,2)=FUNT(2,N)=-EXP(-P*3.514)
0022768          Y(N)=CO
0023028    2     CONTINUE
0023068          DO 3,M=1,2
0023118          DO 3,N=1,2
0023148          A(M,N)=0.0
0023218          DO 3,K=1,13
0023268          A(N,N)=A(N,N)+FUNT(M,K)*FUN(K,N)
0023268    3     CONTINUE
0023708          DO 4,M=1,2
0023728          B(M)=0.0
0023768          DO 4,K=1,13
0024028          B(M)=B(M)+FUNT(M,K)*Y(K)
0024028    4     CONTINUE
0024408          DO 8,N=1,2
0024428          IF(A(N,N).EQ.0.0)STOP
0024538          DO 6,NN=1,2
0024558          IF(NN.EQ.N)GO TO 6
0024578          DO 5,JN=1,2
0024628          IF(JN.EQ.N)GO TO 5
0024648          A(NN,JN)=A(NN,JN)-A(NN,N)*A(N,JN)/A(N,N)
0025078    5     CONTINUE
0025138    6     CONTINUE
0025178          DO 7,KN=1,2
0025218          IF(KN.EQ.N)GO TO 7
0025238          A(N,KN)=A(N,KN)/A(N,N)
0025338          A(KN,N)=A(KN,N)/A(N,N)
0025418    7     CONTINUE
0025458          A(N,N)=-1.0/A(N,N)
```

```
0025478   8     CONTINUE
0025538         DO 81,I=1,2
0025558         DO 81,K=1,2
0025638         A(I,K)=-A(I,K)
0025738   81    CONTINUE
0026038         DO 11,M=1,2
0026058         C(M)=0.0
0026118         DO 9,K=1,2
0026148         C(M)=C(M)+A(M,K)*B(K)
0026148   9     CONTINUE
0026538         PRINT 10,C(M)
0026638   10    FORMAT(2X,F20.6)
0026638   11    CONTINUE
0026668         REWIND 5
0026708         DO 13,N=1,13
0026728         READ 1,P,CO
0027038         CON=429.7-332.35*EXP(-3.514*P
0027138         ERROR=CO-CON
0027148         PRINT 12,P,CO,CON,ERROR
0027278   12    FORMAT(2X,4F20.6)
0027278   13    CONTINUE
0027328         STOP
0027338         END
```

Table AC.1: Input to Computer program of appendix 8.

$P = (\frac{Watts}{N_s})$	σ_o
0.06	155
0.08	177.5
0.10	197.5
0.12	215.0
0.14	230.0
0.16	242.5
0.18	255.0
0.20	265.0
0.22	275.0
0.24	286.4
0.26	295.5
0.28	303.75
0.30	312.5

APPENDIX 9

PROGRAM FOR FITTING CURVE OF CORE-PATH SHORTENING

FACTOR (2-POLES)

```
 OF MINNESOTA FORTRAN COMPILER (VERSION 5.0 - 77/03/24) ON THE CYZ2 UI

       MNF,I=PEXP2KC,B,J,T.

0000008          PROGRAM CURFIT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
0021218          DIMENSION FUN(24,2),FUNT(2,24),A(2,2),B(2),C(2),Y(24)
0021218          DO 2,N=1,24
0023238          READ 1,P,CO
0023348  1       FORMAT(2F5.1)
0023348          P=P*1.0155
0023358          FUN(N,1)=FUNT(1,N)=EXP(2.69*P)
0023538          FUN(N,2)=FUNT(2,N)=-1.0
0023638          Y(N)=CO
0023678  2       CONTINUE
0023738          DO 3,M=1,2
0023768          DO 3,N=1,2
0024018          A(M,N)=0.0
0024068          DO 3,K=1,24
0024138          A(M,N)=A(M,N)+FUNT(M,K)*FUN(K,N)
0024138  3       CONTINUE
0024548          DO 4,M=1,2
0024568          B(M)=0.0
0024628          DO 4,K=1,24
0024668          B(M)=B(M)+FUNT(M,K)*Y(K)
0024668  4       CONTINUE
0025248          DO 8,N=1,2
0025268          IF(A(N,N).EQ.0.0)STOP
0025378          DO 6,NN=1,2
0025418          IF(NN.EQ.N)GO TO 6
0025438          DO 5,JN=1,2
0025468          IF(JN.EQ.N)GO TO 5
0025508          A(NN,JN)=A(NN,JN)-A(NN,N)*A(N,JN)/A(N,N)
0025738  5       CONTINUE
0025778  6       CONTINUE
0026038          DO 7,KN=1,2
0026058          IF(KN.EQ.N)GO TO 7
0026078          A(N,KN)=A(N,KN)/A(N,N)
0026178          A(KN,N)=A(KN,N)/A(N,N)
0026258  7       CONTINUE
0026318          A(N,N)=-1.0/A(N,N)
```

```
0026338  8      CONTINUE
0026378          DO 81,I=1,2
0026418          DO 81,K=1,2,1
0026448          A(I,K)=A(I,K)
0026448  81     CONTINUE
0026678          DO 11,M=1,2
0026718          C(M)=0.0
0026758          DO 9,K=1,2
0027008          C(M)=C(M)+A(M,K)*B(K)
0027008  9      CONTINUE
0027348          PRINT 10,B(M)
0027478  10     FORMAT(2X,F20.6)
0027478  11     CONTINUE
0027528          REWIND 5
0027548          DO 13,N=1,24
0027568          READ 1,P,CO
0027678          P=P*0.0155
0027708          CON=1.87*(140.0345*EXP(2.69*P))
0027778          ERROR=CO-CON
0030018          PRINT 12,P,CO,CON,ERROR
0030148  12     FORMAT(2X,4F20.6)
0030148  13     CONTINUE
0030178          STOP
0030205          END
```

Table A9.1: Input to Computer program of appendix 9.

B (Tesla) ±0.0155	K_c (2-pole)
30	2.0
43	2.2
52.5	2.4
60.0	2.6
64.0	2.8
68.0	3.0
72.5	3.2
75.5	3.4
78.5	3.6
81.0	3.8
83.0	4.0
85.25	4.2
87.0	4.4
89.0	4.6
94.0	5.2
98.0	5.8
102.5	6.6
105.5	7.2
110.0	8.2
113.0	9.0
115.0	9.6
117.0	10.4
110.0	10.8
120.0	11.8

APPENDIX 10

PROGRAM FOR FITTING CURVE OF CORE-PATH SHORTENING

FACTOR (k-POLES)

```
/ OF MINNESOTA FORTRAN COMPILER (VERSION 5.0 - 77/03/24)
      MNF,I=PEXP4KC,B=Q,J,T.
0000008       PROGRAM CURFIT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
0021218       DIMENSION FUN(15,2),FUNT(2,15),A(2,2),B(2),C(2),Y(15)
0021218       DO 2,N=1,15
0022468       READ 1,P,CO
0022578  1    FORMAT(2F5.1)
0022578       P=P*0.0155
0022608       FUN(N,1)=FUNT(1,N)=EXP(2.33*P)
0022768       FUN(N,2)=FUNT(2,N)=-1.0
0023068       Y(N)=CO
0023128  2    CONTINUE
0023168       DO 3,M=1,2
0023218       DO 3,N=1,2
0023248       A(M,N)=0.0
0023318       DO 3,K=1,15
0023368       A(M,N)=A(M,N)+FUNT(M,K)*FUN(K,N)
0023368  3    CONTINUE
0024018       DO 4,M=1,2
0024038       B(M)=0.0
0024078       DO 4,K=1,15
0024138       B(M)=B(M)+FUNT(M,K)*Y(K)
0024138  4    CONTINUE
0024518       DO 8,N=1,2
0024538       IF(A(N,N).EQ.0.0)STOP
0024648       DO 6,NN=1,2
0024668       IF(NN.EQ.N)GO TO 6
0024708       DO 5,JN=1,2
0024738       IF(JN.EQ.N)GO TO 5
0024758       A(NN,JN)=A(NN,JN)-A(NN,N)*A(N,JN)/A(N,N)
0025208  5    CONTINUE
0025248  6    CONTINUE
0025308       DO 7,KN=1,2
0025328       IF(KN.EQ.N)GO TO 7
0025348       A(N,KN)=A(N,KN)/A(N,N)
0025448       A(KN,N)=A(KN,N)/A(N,N)
0025528  7    CONTINUE
0025568       A(N,N)=-1.0/A(N,N)
```

```
0025600  6      CONTINUE
0025640        DO 81,I=1,2
0025560        DO 81,K=1,2
0025710        A(I,K)=-A(I,K)
0025710  81    CONTINUE
0026140        DO 11,M=1,2
0026160        C(M)=0.0
0026220        DO 9,K=1,2
0026250        C(M)=C(M)+A(M,K)*B(K)
0026250  9     CONTINUE
0026610        PRINT 10,C(M)
0026740  10    FORMAT(2X,F20.6)
0026740  11    CONTINUE
0026770        REWIND 5
0027010        DO 13,N=1,15
0027030        READ 1,P,CO
0027140        P=P*0.0165
0027150        CON=1.685*(1+0.029*EXP(2.33*P))
0027200        ERROR=CO-CON
0027250        PRINT 12,P,CO,CON,ERROR
0027410  12    FORMAT(2X,4F20.6)
0027410  13    CONTINUE
0027440        STOP
0027450        END
```

Table A10.1: Input to Computer program of appendix 10.

B=0.0155 (TESLA)	K_c (4-pole)
50	2.0
65	2.2
75	2.4
82	2.6
87	2.8
91	3.0
95	3.2
98	3.4
101	3.6
104	3.8
109	4.2
111	4.4
113	4.6
115	4.8
117	5.0

APPENDIX 11

PROGRAM FOR FITTING CURVE OF CORE-PATH SHORTENING FACTOR (6-FOLDS & OVER)

```
Y OF MINNESOTA FORTRAN COMPILER (VERSION 5.0 - 77/03/24) ON THE CYBER
      MNF,I=PEXP6KC,B=W,J,T.

0000008          PROGRAM CURFIT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
0021218          DIMENSION FUN(11,2),FUNT(2,11),A(2,2),B(2),C(2),Y(11)
0021218          DO 2,N=1,11
0022228          READ 1,P,CO
0022338    1     FORMAT(2F5.1)
0022338          P=P*0.0155
0022348          FUN(N,1)=FUNT(1,N)=EXP(2.83*P)
0022528          FUN(N,2)=FUNT(2,N)=-1.0
0022628          Y(N)=CO
0022768    2     CONTINUE
0022728          DO 3,M=1,2
0022758          DO 3,N=1,2
0023008          A(M,N)=0.0
0023058          DO 3,K=1,11
0023128          A(M,N)=A(M,N)+FUNT(M,K)*FUN(K,N)
0023128    3     CONTINUE
0023548          DO 4,M=1,2
0023568          B(M)=0.0
0023628          DO 4,K=1,11
0023668          B(M)=B(M)+FUNT(M,K)*Y(K)
0023668    4     CONTINUE
0024248          DO 8,N=1,2
0024268          IF(A(N,N).EQ.0.0)STOP
0024378          DO 6,NN=1,2
0024418          IF(NN.EQ.N)GO TO 6
0024438          DO 5,JN=1,2
0024468          IF(JN.EQ.N)GO TO 5
0024508          A(NN,JN)=A(NN,JN)-A(NN,N)*A(N,JN)/A(N,N)
0024738    5     CONTINUE
0024778    6     CONTINUE
0025038          DO 7,KN=1,2
0025058          IF(KN.EQ.N)GO TO 7
0025078          A(N,KN)=A(N,KN)/A(N,N)
0025178          A(KN,N)=A(KN,N)/A(N,N)
0025258    7     CONTINUE
0025318          A(N,N)=-1.0/A(N,N)
```

```
0025338   8      CONTINUE
0025378          DO 81,I=1,2
0025418          DO 81,K=1,2
0025448          A(I,K)=-A(I,K)
0025448   81     CONTINUE
0025678          DO 11,M=1,2
0025718          C(M)=0.0
0025758          DO 9,K=1,2
0026008          C(M)=C(M)+A(M,K)*B(K)
0026008   9      CONTINUE
0026348          PRINT 10,C(M)
0026478   10     FORMAT(2X,F20.6)
0026478   11     CONTINUE
0026528          REWIND 5
0026548          DO 13,N=1,11
0026568          READ 1,P,CO
0026678          P=P*0.0155
0026778          CON=1.62*(1+).0781*EXP(2.83*P))
0026778          ERROR=CO-CON
0027118          PRINT 12,P,CO,CON,ERROR
0027148   12     FORMAT(2X,4F20.6)
0027148   13     CONTINUE
0027178          STOP
0027208          END
```

Table A11.1: Input to Computor program of appendix 11.

B=0.0155 (TESLA)	K_c (6-pole & over)
75	2.0
87.5	2.2
93	2.4
98	2.6
103	2.8
106	3.0
109.5	3.2
112	3.4
114	3.6
116.5	3.8
118.5	4.0

APPENDIX 12

PROGRAM FOR FITTING MAGNETIZATION CURVE OF LOHYS ORDINARY

```
NESOTA FORTRAN COMPILER (VERSION 5.0 = 77/03/24) ON THE CY72 UNDER

    NNF,I=BHC11,B=PL,J,T.

      PROGRAM BETSY(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      DIMENSION FUN(27,2),FUNT(2,27),A(2,2),B(2),C(2),Y(27),EI@0
      CONV=(0.1E-7)/(0.0254**2)
      DO 2,N=1,27
      READ 1,P,C0
      P=P/0.0254
      C0=C0*1000*CONV
1     FORMAT(F5.1,F7.1)
      FUN(N,1)=FUNT(1,N)=1.0/P
      FUN(N,2)=FUNT(2,N)=1.0
      Y(N)=1.0/C0
2     CONTINUE
      DO 3,M=1,2
      DO 3,N=1,2
      A(M,N)=0.0
      DO 3,K=1,27
      A(M,N)=A(M,N)+FUNT(M,K)*FUN(K,N)
3     CONTINUE
      DO 4,K=1,2
      B(M)=0.0
      DO 4,K=1,27
      B(M)=B(M)+FUNT(M,K)*Y(K)
4     CONTINUE
      DO 8,N=1,2
      IF(A(N,N).EQ.0.0)STOP
      DO 6,NN=1,2
      IF(NN.EQ.N)GO TO 6
      DO 5,JN=1,2
      IF(JN.EQ.N)GO TO 5
      A(NN,JN)=A(NN,JN)-A(NN,N)*A(N,JN)/A(N,N)
5     CONTINUE
6     CONTINUE
      DO 7,KN=1,2
      IF(KN.EQ.N)GO TO 7
      A(N,KN)=A(N,KN)/A(N,N)
      A(KN,N)=A(KN,N)/A(N,N)
7     CONTINUE
      A(N,N)=1.0/A(N,N)
```

```
CONTINUE
DO 61,I=1,2
DO 61,K=1,2
A(I,K)=-A(I,K)
CONTINUE
DO 11,M=1,2
C(M)=0.0
DO 9,K=1,2
C(M)=C(M)+A(M,K)*B(K)
CONTINUE
PRINT 10,C(M)
FORMAT(2X,F20.6)
CONTINUE
TERROR=0.
J=0
REWIND 5
DO 13,N=1,27
READ 1,P,CO
P=P/0.0254
CO=CO*1000*CONV
J=J+1
CON=P/(C(1)+C(2)*P)

ERROR(N)=ABS(CO-CON)
TERROR=TERROR+ERROR(N)
PERROR=(ERROR(N)*100.0)/CO
PRINT 12,P,CO,CON,ERROR(N),PERROR
FORMAT(2X,5F20.3)
CONTINUE
DEVM=TERROR/J
STERROR=0.
DO 14,NN=1,27
STERROR=STERROR+((ERROR(NN)-DEVM)**2)
CONTINUE
DEVS=SQRT(STERROR/(J-1))
PRINT 15,DEVM,DEVS
FORMAT(10X,'MEAN DEVIATION=',F20.3/10X,'STANDARD DEVIATIO=',F20.
STOP
END
```

Table A12.1: Input to computer Program of Appendix 12.

B * 0.0155 (Tesla)	H * 0.0254 (AT/M)
1.0	20.0
2.0	30.0
2.5	44.0
3.5	60.0
4.0	62.0
5.0	67.0
6.0	72.0
9.0	80.0
10.0	82.0
13.0	88.0
15.0	90.0
20.0	94.0
25.0	96.0
31.0	98.0
41.0	100.0
53.0	102.0
70.0	104.0
85.0	106.0
105.0	108.0
128.0	110.0
155.0	112.0
189.0	114.0

Table A12.1 (Continued)

228.0	116.0
280.0	118.0
342.5	120.0
395.0	122.0

PROGRAM FOR FITTING CURVES OF FUNDAMENTAL-FREQUENCY LOSSES

```
CSOTA FORTRAN COMPILER (VERSION 5.0 - 77/03/24) ON THE CY72 UNDER

NOF,I=LOSS,O=KM,J,T.

      PROGRAM BETSY(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      DIMENSION FUN(20,3),FUNT(3,20),A(3,3),B(3),C(3),Y(20),P(20),CO
     1         ,ERROR(20)
      DO 16,L=1,3
      DO 2,N=1,20
      READ 1,P(N),CO(N)
1     FORMAT(2F7.3)
      P(N)=P(N)+0.0155
      CO(N)=CO(N)/(0.0254**3)
      FUN(N,1)=FUNT(1,N)=1.0
      FUN(N,2)=FUNT(2,N)=ALOG(P(N))
      FUN(N,3)=FUNT(3,N)=P(N)
      Y(N)=ALOG(CO(N))
2     CONTINUE
      DO 3,M=1,3
      DO 3,N=1,3
      A(M,N)=0.0
      DO 3,K=1,20
      A(M,N)=A(M,N)+FUNT(M,K)*FUN(K,N)
3     CONTINUE
      DO 4,M=1,3
      B(M)=0.0
      DO 4,K=1,20
      B(M)=B(M)+FUNT(M,K)*Y(K)
4     CONTINUE
      DO 6,N=1 3
      IF(A(N,N).EQ.0.0)STOP
      DO 6,NN=1,3
      IF(NN.EQ.N)GO TO 6
      DO 5,JN=1,3
      IF(JN.EQ.N)GO TO 5
      A(NN,JN)=A(NN,JN)-A(NN,N)*A(N,JN)/A(N,N)
5     CONTINUE
6     CONTINUE
      DO 7,KN=1,3
      IF(KN.EQ.N)GO TO 7
      A(N,KN)=A(N,KN)/A(N,N)
      A(KN,N)=A(KN,N)/A(N,N)
7     CONTINUE
      A(N,N)=-1.0/A(N,N)
```

```
      CONTINUE
      DO 61,I=1,3
      DO 61,K=1,3
      A(I,K)=-A(I,K)
   61 CONTINUE
      DO 11,M=1,3
      C(M)=0.0
      DO 9,K=1,3
      C(M)=C(M)+A(M,K)*B(K)
    9 CONTINUE
      IF(P.EQ.1)C(M)=EXP(C(M))
      PRINT 10,C(M)
   10 FORMAT(2X,F20.6)
   11 CONTINUE
      TERROR=0.
      J=0
      DO 13,N=1,20
      J=J+1
      CON=C(1)*(P(N)**C(2))*EXP(C(3)*P(N))
      ERROR(N)=ABS(CO(N)-CON)


      TERROR=TERROR+ERROR(N)
      PERROR=(ERROR(N)*100.0)/CO(N)
      PRINT 12,P(N),CO(N),CON,ERROR(N),PERROR
   12 FORMAT(2X,5F20.3)
   13 CONTINUE
      DEVN=TERROR/J
      STERROR=0.
      DO 14,NN=1,20
      STERROR STERROR+((ERROR(NN)-DEVN)**2)
   14 CONTINUE
      DEVS=SQRT(STERROR/(J-1))
      PRINT 15,DEVN,DEVS
   15 FORMAT(10X,'MEAN DEVIATION=',F20.3/10X,'STANDARD DEVIATION=',
     1       F20.3)
   16 CONTINUE
      STOP
      END
```

Table A13.1: Input to Computer Program of Appendix 13.

B_m + 0.0155 (Tesla)	P_{CL} + $(0.0254)^3$ (Watts/cu.m.)
10.0	0.042
20.0	0.100
30.0	0.165
40.0	0.233
50.0	0.308
60.0	0. 4
70.0	0.517
76.67	0.6
86.67	0.8
94.17	1.0
100.0	1.2
105.47	1.4
109.17	1.6
113.17	1.8
115.83	2.0
119.17	2.2
121.67	2.4
124.17	2.6
126.67	2.8
129.17	3.0

Table A13.1 (continued)

10.0	0.06
20.0	0.137
30.0	0.225
40.0	0.317
50.0	0.417
60.0	0.533
70.0	0.7
65.0	0.6
75.83	0.8
83.75	1.0
89.83	1.2
95.0	1.4
99.17	1.6
103.17	1.8
106.67	2.0
110.0	2.2
112.08	2.4
115.0	2.6
117.50	2.8
120.0	3.0
10.0	0.075
20.0	0.14

Table A13.1 (continued)

30.0	0.283
40.0	0.397
50.0	0.533
60.0	0.7
70.0	0.9
55.07	0.6
65.83	0.8
74.17	1.0
80.42	1.2
85.47	1.4
90.0	1.6
93.75	1.8
97.5	2.0
100.83	2.2
103.33	2.4
105.83	2.6
108.33	2.8
110.47	3.0

List of Symbols or Abbreviations Used

in the Computer Programs of Appendixes 6-13

A - Elements of matrix A in appendix 3.

B - Elements of matrix b in appendix 3.

C - Elements of matrix C in appendix 3.

CO - Ordinate values of selected points on the curve to be fittod.

CON - Ordinate Values obtained from the resulting equation.

CONV - Unit conversion factor, usually for CO input in old unit.

DEVM - Mean deviation of ERROR

DEVS - Standard deviation of ERROR

ERROR - Absolute of the difference of CON from CO.

FUN - Elements of matrix F in appendix 3.

FUNT - Elements of matrix F^T in appendix 3.

P - Abscissa values of selected points on the curve to be fitted.

PERROR- Percent of ratio of ERROR to CO.

STERROR- Total sum of squares of deviations of ERROR from DEVM.

TERROR - Total sum of ERROR.

Y - Elements of matrix Y in appendix 3.

DISTRIBUTION FACTOR AND HARMONIC CONTENT OF CONCENTRIC WINDING

Dist. No.	Slots per pole	Distribution												Fund. K_d	Ratio harmonic mmf /fundamental mmf									
		1	2	3	4	5	6	7	8	9	10	11	12		3	5	7	9	11	13	15	17	19	21	23	25
1	4	1	1	x	1	1								.9856	.0478	.0542	.1429	.1111	.0135	.0132	.0667	.0588	.0090	.0082	.0435	.0400
2	4	1	2	x	2	1								.9473	-.0872	-.0769	.1429	.1111	-.0135	.0132	.0667	.0588	-.0090	-.0082	.0435	.0400
3	4	1	x	x	x	1								1.0000	.0333	.0000	.1429	.1111	.0000	.0769	.0667	.0588	.0526	.0476	.0435	.0400
4	6	1	2	x	x	x	1							.9598	.0440	.0256	-.0588	-.0843	-.0909	-.0769	-.0435	-.0156	.0141	.0349	.0435	.0400
5	6	1	1	x	x	1	1							.9831	.0440	.0256	-.0588	.0000	-.0909	-.0769	.0000	.0158	-.0141	.0000	.0435	.0400
6	6	1	1	1	x	1	1							.9598	-.1299	.0256	-.0588	.0407	-.0909	-.0769	.0244	-.0158	.0141	-.0174	.0435	.0400
7	6	1	2	1	x	1	2	1						.9330	.0000	-.0144	-.0588	.0000	.0909	.0769	.0000	-.0042	-.0038	.0000	.0435	.0400
8	9	1	1	1	x	1	1	1						.9957	.0000	.0030	.0588	.0000	.0909	.0769	.0000	.0158	.0141	.0000	.0435	.0400
9	9	1	2	2	1	x	x	1	2	2	1			.9726	.0220	-.0256	.0588	.0000	.0038	-.0114	.0000	.0588	.0526	.0000	-.0084	.0026
10	9	1	2	2	x	x	x	x	2	2	1			.9526	.0756	-.0256	-.0588	-.0000	.0252	.0025	-.0214	.0151	.0588	.0526	.0108	-.0017
11	9	1	2	1	x	x	x	x	1	2	1			.9436	.1212	-.0157	-.0147	.0000	-.0082	-.0061	.0274	.0588	.0526	.0195	-.0034	-.0039
12	9	1	1	1	x	x	x	1	1	1				.9542	.1299	-.0241	-.0404	.0000	.0257	.0092	-.0342	-.0588	-.0526	-.0235	.0053	.0114
13	9	3	2	x	x	x	x	2	3					.9378	.1645	.0084	-.0715	.0000	.0137	-.0022	-.0370	-.0588	-.0526	-.0064	-.0018	.0060
14	9	2	2	1	x	x	x	2	2	1				.9598	.0866	-.0303	-.0001	.0000	.0013	.0140	-.0133	-.0588	-.0526	-.0095	.0079	.0006
15	9	1	1	1	x	x	x	1	1	1				.9436	.0909	-.0433	.0324	.0000	-.0165	.0174	.0000	-.0588	-.0526	.0000	.0090	-.0074
16	9	3	3	2	x	x	x	3	3	2				.9347	.0433	-.0606	.0081	.0000	-.0053	.0152	-.0035	-.0588	-.0526	-.0000	.0086	-.0023
17	9	6	6	5	x	x	x	5	6	6				.9481	.0433	-.0888	.0068	.0000	-.0037	.0149	-.0090	-.0588	-.0526	-.0089	.0084	-.0016
18	12	2	1	1	x	x	x	x	x	x	1	1	2	.9903	.1665	.0115	.0000	.0030	.0120	-.0101	-.0135	-.0026	-.0030	-.0028	-.0435	-.0400
19	12	2	2	1	1	x	x	x	x	1	1	2	2	.9713	.0833	-.0115	.0000	-.0115	-.0120	.0101	.0000	-.0026	.0030	-.0119	-.0435	-.0400
20	12	1	1	1	1	x	x	x	x	1	1	1	1	.9903	.0000	-.0429	.0000	.0030	-.0120	.0101	.0000	-.0097	.0119	.0000	-.0435	-.0400
21	12	1	1	1	1	1	x	x	x	1	1	1	1	.9709	-.0833	.0115	.0000	-.0115	-.0120	-.0101	.0000	-.0026	-.0030	.0119	-.0435	-.0400
22	12	3	3	2	2	3	x	x	3	3	2	3	3	.9769	-.0184	.0179	.0000	-.0136	.0070	-.0060	.0094	-.0001	-.0047	.0028	-.0435	-.0400
23	12	2	2	2	1	1	x	x	x	1	1	2	2	.9837	.0401	-.0144	-.0010	-.0134	.0092	.0078	-.0090	-.0004	-.0038	.0057	.0435	.0400
24	12	2	2	1	1	x	x	x	x	x	1	1	2	.9009	.1299	-.0025	.0103	.0072	-.0156	-.0132	.0043	.0042	-.0006	.0180	.0435	.0400
25	12	1	2	2	2	1	x	x	x	1	2	2	1	.8228	.0000	-.0433	.0144	.0000	-.0016	-.0013	.0000	.0059	-.0090	.0000	.0435	.0400
26	12	1	2	1	x	x	x	x	x	x	1	2	1	.9497	.0119	.0043	-.0144	-.0120	-.0016	-.0013	-.0073	-.0059	.0090	.0303	.0435	.0400
27	12	15	30	24	24	13	x	x	x	13	24	24	30	15	.9238	.0286	-.0192	.0161	-.0028	-.0028	-.0039	-.0017	.0066	-.0061	.0084	.0435	.0400

APPENDIX 15[1]

CALCULATING SHEET FOR STARTING PERFORMANCE OF A SPLIT-PHASE INDUCTION MOTOR

Starting Performance for Single-phase Motors

	Calculation		1	2	3	4	5	6	7
	(20) = either sin (16) or $\frac{(19)}{(5) \times (13)}$ $K_r = 0.959$ $r_2/X = 0.420$ $r_2/X_0 = 0.01739$ $C_r = 0.959$ $C_R = 1.007$		Max. Ts/I_L winding 19 × 19 38 19 No. 23 SCC En.	Alternate-form. Wdg. 16 × 16 32 16 No. 24 SCC En.					
	Resistance	Capacitor							
1	r_1	r_1	0.512						
2	$r_2' = r_2 C_r$	$r_2' = r_2 C_r$	0.698						
3	R_m	R_m	1.210						
4	$X_m' = X_m C_R$	$X_m' = X_m C_R$	1.710						
5	Z_m	Z_m	2.09						
6	—	R_c							
7	r_{1a}	r_{1a}	9.81	10.41					
8	r_{2a}'	r_{1a}'	2.47	1.76					
9	R_a	R_a	12.28	12.17					
10	—	$-X_{ac}$							
11	X_a'	X_a'	6.06	1.30					
12	—	$-X_c$							
13	Z_a	Z_{ac}	13.69	12.91					
14	θ_m	θ_m	54.7						
15	θ_a	$-\theta_{ac}$	26.3						
16	(14) − (15)	(14) + (15)	28.4						
17	$X_m R_a$	$X_m R_a$	21.00	20.82					
18	$R_m X_a$	$-R_m X_a$	7.33	5.20					
19	(17) − (18)	(17) + (18)	13.67	15.62					
20	$\sin(\theta_m - \theta_a)$	$\sin(\theta_m - \theta_{ac})$	0.478	.579					
21	× a	× a	1.882	1.586					
22	× $1.88P/f$	× $1.88P/f$	.0627	.0627					
23	× r_1'	× r_1'	0.698	0.698					
24	× I_m	× I_m	55.0	55.0					
25	× I_a	× I_{ac}	8.40	8.91					
26	= T_d	= T_d	18.18	19.09					
27	R_{ma}	R_{ma}	13.49	13.38					
28	X_{ma}	X_{ma}	7.77	6.01					
29	Z_{ma}	Z_{mac}	15.57	14.67					
30	$I_L = I_m Z_{ma}/Z_a$	$I_L = I_m Z_{mac}/Z_{ac}$	62.6	62.5					
31	C.M./T_d	$E_c = I_{ac} f_c$	69.6	45.3					
32		$VA_c = I_{ac}^2 X_c$							
33									
34	T_d in % of F.L.T.		75	82					
35									
36									
37									

APPENDIX 16

PROGRAM FOR DRAWING D^2L SEPARATION CHART (2-POLES)

```
Y OF MINNESOTA FORTRAN COMPILER (VERSION 5.0 - 77/03/24) ON THE CY72 UNDE
          MNF,I=ADUK,L=PLO.
0000008           PROGRAM SIMS(INPUT,OUTPUT,TAPE2,TAPE5=INPUT,TAPE6=OUTPUT)
0041718           DIMENSION X(220),Y(220)
0041718           CALL PLOTS(0,0,2)
0050638           CALL AXIS(0.,0.,6HLENGTH,-6,20.,0.,0.,1.)
0050658           CALL AXIS(0.,0.,8HDIAMETER,+8,20.,90.,0.,1.)
0050678           DO 2,M=1,4
0050708           W=0.
0050708           DO 2,I=1,10
0050738           W=W+1.
0050748           V=W*(10.**(M-1))
0051058           II=0
0051068           XX=0.4
0051078           DO 1,J=1,196
0051138           XX=XX+0.1
0051140           VV=SQRT(V/XX)
0051218           IF(VV.GT.20.)GO TO 1
0051238           II=II+1
0051248           Y(II)=VV
0051268           X(II)=XX
0051268   1       CONTINUE
0051328           IF(II.EQ.0)GO TO 2
0051338           X(II+1)=0.
0051338           X(II+2)=1.
0051358           Y(II+1)=0.
0051368           Y(II+2)=1.
0051370           DO 22,N=1,3
0051428           CALL LINE(X,Y,II,1,0,N)
0051458   22      CONTINUE
0051478   2       CONTINUE
0051550           CALL PLOT(0.0,0.0,3)
0051578           PI=3.14159
0051578           C=PI/2.0
0051618           CON=0.0
0051628           DELTA=0.05
0051638           DO 4,K=1,30
0051698           CON=CON+DELTA
0051668           IF(CON.EQ.1.0)DELTA=DELTA*4.0
0051728           IF(CON.EQ.2.0)DELTA=DELTA*2.5
0051768           IF(CON.EQ.3.0)DELTA=DELTA*2.0
0052008           IF(CON.EQ.5.0)DELTA=DELTA*5.0
0052038           LL=0
0052038           XX=-0.1
0052048           DO 3,L=1,201
0052078           XX=XX+0.1
0052108           VV=XX/(C*CON)
0052128           IF(VV.GT.20.)GO TO 3
0052158           LL=LL+1
0052168           Y(LL)=VV
0052170           X(LL)=XX
0052218   3       CONTINUE
0052248           X(LL+1)=0.
0052248           X(LL+2)=1.
0052268           Y(LL+1)=0.
```

```
      7(LL+2)=1.
      DO 4,N=1,3
      CALL LINE(X,Y,LL,1,0,0)
    4 CONTINUE
      CALL PLOT(0.0,0.0,3)
      XX=0.0
      DO 6,I=1,20
      XX=XX+1.0
      X(1)=XX
      Y(1)=0.
      DO 5,J=1,20
      Y(J+1)=Y(J)+1.
      X(J+1)=XX
    5 CONTINUE
      X(22)=Y(22)=0.
      X(23)=Y(23)=1.
      CALL LINE(X,Y,21,1,0,0)
    6 CONTINUE
      CALL PLOT(0.0,0.0,3)
      YY=0.
      DO 8,I=1,20
      YY=YY+1.0
      Y(1)=YY
      X(1)=0.0
      DO 7,J=1,20
      Y(J+1)=YY
      X(J+1)=X(J)+1.0
    7 CONTINUE
      X(22)=Y(22)=0.
      X(23)=Y(23)=1.
      CALL LINE(X,Y,21,1,0,0)
    8 CONTINUE
      CALL PLOT(0.,0.,999)
      STOP
      END
```

APPENDIX 17

PROGRAM FOR DRAWING D^2L SEPARATION CHART (4-POLES)

```
OF MINNESOTA FORTRAN COMPILER (VERSION 5.0 + 77/03
      MNF,I=ADUK4,L=PK.
000000B          PROGRAM SIMB(INPUT,OUTPUT,TAPE6,TAPE
041718B          DIMENSION X(420),Y(420)
041718B          CALL PLOTS(0,0,4)
057038B          CALL AXIS(0.,0.,6HLENGTH,+6,20.,90.,0.,2.)
057058B          CALL AXIS(0.,0.,8HDIAMETER,+8,20.,90.,0.,2.)
057078B          DO 2,M=1,5
057108B          W=0.
057108B          DO 2,I=1,10
057138B          W=W+1.
057148B          V=W*(10.**(M-1))
057258B          II=0
057268B          XX=0.2
057278B          DO 1,J=1,199
057338B          XX=XX+0.2
057348B          VV=SQRT(V/XX)
057418B          IF(VV.GT.40.)GO TO 1
057438B          II=II+1
057448B          Y(II)=VV
057458B          X(II)=XX
057468B  1       CONTINUE
057528B          IF(II.EQ.0)GO TO 2
057538B          X(II+1)=0.
057538B          X(II+2)=2.
057558B          Y(II+1)=0.
057568B          Y(II+2)=2.
057578B          DO 22,N=1,3
057628B          CALL LINE(X,Y,II,1,0,0)
057658B  22      CONTINUE
057678B  2       CONTINUE
057758B          CALL PLOT(0.0,0.0,3)
057778B          PI=3.14159
057778B          C=PI/4.0
060018B          CON=0.0
060028B          DELTA=0.05
060038B          DO 4,K=1,32
060058B          CON=CON+DELTA
060068B          IF(CON.EQ.1.0)DELTA=DELTA*4.0
060128B          IF(CON.EQ.2.0)DELTA=DELTA*2.5
060158B          IF(CON.EQ.3.0)DELTA=DELTA*2.0
060208B          IF(CON.EQ.5.0)DELTA=DELTA*5.0
060238B          LL=0
060238B          XX=0.4
060248B          DO 3,L=1,101
060278B          XX=XX+0.4
060308B          VV=XX/(C*CON)
060328B          IF(VV.GT.40.)GO TO 3
060358B          LL=LL+1
060368B          Y(LL)=VV
060378B          X(LL)=XX
060418B  3       CONTINUE
060448B          X(LL+1)=0.
060448B          X(LL+2)=2.
060468B          Y(LL+1)=0.
```

```
0060478          Y(LL+2)=2.
0060508          DO  4,N=1,3
0060538          CALL LINE(X,Y,LL,1,0,0)
0060568      4   CONTINUE
0060638          CALL PLOT(0.0,0.0,3)
0060658          XX=0.0
0060658          DO  6,I=1,20
0060678          XX=XX+2.0
0060708          X(1)=XX
0060708          Y(1)=0.
0060718          DO  5,J=1,20
0060748          Y(J+1)=Y(J)+2.
0060758          X(J+1)=XX
0060768      5   CONTINUE
0061008          X(22)=Y(22)=0.
0061018          X(23)=Y(23)=2.
0061028          CALL LINE(X,Y,21,1,0,0)
0061058      6   CONTINUE
0061078          CALL PLOT(0.0,0.0,3)
0061118          YY=0.
0061118          DO  8,I=1,20
0061138          YY=YY+2.0
0061148          Y(1)=YY
0061148          X(1)=0.0
0061158          DO  7,J=1,20
0061208          Y(J+1)=YY
0061208          X(J+1)=X(J)+2.0
0061238      7   CONTINUE


0061248          X(22)=Y(22)=0.
0061258          X(23)=Y(23)=2.
0061268          CALL LINE(X,Y,21,1,0,0)
0061318      8   CONTINUE
0061338          CALL PLOT(0.,0.,999)
0061358          STOP
0061368          END
```

APPENDIX 18

PROGRAM FOR DRAWING D^2L SEPARATION CHART (6-POLES)

```
 ...OF MINNESOTA FORTRAN COMPILER (VERSION 5.0 - 77/03/24) ON THE CY...
        MNF,I=ADUK6,B=LGO,L=IJN,T.
0000008          PROGRAM SIMB(INPUT,OUTPUT,TAPE8,TAPE5=INPUT,TAPE6=O...
0041718          DIMENSION X(420),Y(420)
0041718          CALL PLOTS(0,0,8)
0057048          CALL AXIS(0.,0.,6HLENGTH,-6,20.,0.,0.,2.)
0057078          CALL AXIS(0.,0.,8HDIAMETER,+8,20.,90.,0.,2.)
0057128          DO 2,M=1,5
0057148          W=0.
0057148          DO 2,I=1,10
0057208          W=W+1.
0057218          V=W*(10.**(M-1))
0057328          II=0
0057338          XX=0.2
0057348          DO 1,J=1,199
0057418          XX=XX+0.2
0057428          VV=SQRT(V/XX)
0057508          IF(VV.GT.40.)GO TO 1
0057528          II=II+1
0057538          Y(II)=VV
0057578          X(II)=XX
0057648    1     CONTINUE
0057718          IF(II.EQ.0)GO TO 2
0057728          X(II+1)=0.
0057778          X(II+2)=2.
0060038          Y(II+1)=0.
0060108          Y(II+2)=2.
0060148          DO 22,N=1,3
0060178          CALL LINE(X,Y,II,1,0,0)
0060238    22    CONTINUE
0060268    2     CONTINUE
0060358          CALL PLOT(0.0,0.0,3)
0060408          PI=3.14159
0060408          C=PI/6.0
0060428          CON=0.0
0060438          DELTA=0.05
0060448          DO 4,K=1,32
0060478          CON=CON+DELTA
0060508          IF(CON.EQ.1.0)DELTA=DELTA*4.0
0060548          IF(CON.EQ.2.0)DELTA=DELTA*2.5
0060578          IF(CON.EQ.3.0)DELTA=DELTA*2.0
0060628          IF(CON.EQ.5.0)DELTA=DELTA*5.0
0060658          LL=0
0060668          XX=-0.4
0060668          DO 3,L=1,101
0060728          XX=XX+0.4
0060738          VV=XX/(C*CON)
0060758          IF(VV.GT.40.)GO TO 3
0061008          LL=LL+1
0061018          Y(LL)=VV
0061068          X(LL)=XX
0061138    3     CONTINUE
0061208          X(LL+1)=0.
0061258          X(LL+2)=2.
0061318          Y(LL+1)=0.
```

```
      Y(LL+2)=2.
      DO 4,N=1,3
      CALL LINE(X,Y,LL,1,0,0)
    4 CONTINUE
      CALL PLOT(0.0,0.0,3)
      XX=0.0
      DO 6,I=1,20
      XX=XX+2.0
      X(1)=XX
      Y(1)=0.
      DO 5,J=1,20
      Y(J+1)=Y(J)+2.
      X(J+1)=XX
    5 CONTINUE
      X(22)=Y(22)=0.
      X(23)=Y(23)=2.
      CALL LINE(X,Y,21,1,0,0)
    6 CONTINUE
      CALL PLOT(0.0,0.0,3)
      YY=0.
      DO 8,I=1,20
      YY=YY+2.0
      Y(1)=YY
      X(1)=0.0
      DO 7,J=1,20
      Y(J+1)=YY
      X(J+1)=X(J)+2.0
    7 CONTINUE

      X(22)=Y(22)=0.
      X(23)=Y(23)=2.
      CALL LINE(X,Y,21,1,0,0)
    8 CONTINUE
      CALL PLOT(0.,0.,999)
      STOP
      END
```

List of Symbols or Abbreviations used in the

Computer Programs of Appendixes 16-18

C - $\pi/2p$; ratio of π to number of poles.

CON - Constant K of equation (7.6).

DELTA - Incremental for CON.

II,LL - Total number of points available for plotting a curve.

V - Value of D_1^2L product, CM^3

VV - Diameter, cm

X - Array of abscissa points for plotting a curve.

XX - Length, cm

Y - Array of ordinate points for plotting a curve.

APPENDIX 19

DESIGN ANALYSIS PROGRAM

```
GOTA FORTRAN COMPILER (VERSION 5.0 - 77/03/24) ON THE CY72 UNDER  N O S

UNF,I=BIMEO,O=JIMMY,J.

      PROGRAM GBEMI(INPUT,OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT)
      COMMON/ONE/PH,PF,EFF,WF1,SCCN
      COMMON/TWO/FREQ,O,F,T1,NPP,NSS,NRS,AL,IBS,IRS,SSPEED
      COMMON/THREE/CQ,W10,D1,DY1,W11,W13,R13,C14,C11,D10,T10
      COMMON/FUR/AST,ASC,ARC,ART,BAG,SCL,RCL,STL,RTL,AGL,PLAMDA1,PLAMDA2
      COMMON/FIVE/AG,DR,D2,W20,DY2,T2,DS2,R21
      COMMON/SIX/D20,D24,W23,W21,T20,DB,WB,D21,DC
      COMMON/SEVN/SKA,NW,KD(10),LC,NCPIS,KKC,NCSPS,WF,VMIN,LSPP,NCAIS,N
      COMMON/EIGHT/X,NEC,RS,RKA,BSC,EST,BAG,XC,PKA,DMEAN,GAMMA,RRDC,
     1      D2N
      COMMON/NINE/D5,D2,RSHCT,RRHCT,TORQ,D1,D3,D4,X11,TCLOSS,PFW,RRHOTP
      COMMON/TEN/WIREL,RSHOTA,RM,XMP,ZM,RRHOTPA,AA,THETAM,CLR,CM,XAPA
      READ 1,PW,FREQ,PF,EFF,WF1,SCON,F,NPP,NSS,NRS
    1 FORMAT(7F6.2,3I2)
      PRINT 2,PW,FREQ,PF,EFF,WF1,SCCN,F,NPP,NSS,NRS
    2 FORMAT(/10X,*SOME OF THE SPECIFICATIONS:*,
     1       /15X,*RATED POWER(WATTS)*,27X,*=*,F13.6,
     2       /15X,*FREQUENCY*,36X,*=*,F13.6,
     3       /15X,*POWER FACTOR*,33X,*=*,F13.6,
     4       /15X,*EFFICIENCY*,35X,*=*,F13.6,
     5       /15X,*FUNDAMENTAL WINDING FACTOR *,18X,*=*,F13.6,
     6       /15X,*DIAMETER AND LENGTH SEPARATION CONSTANT*,6X,*=*,
     7       F13.6,/15X,*STACKING FACTOR*,30X,*=*,F13.6,
     8       /15X,*NUMBER OF POLE PAIRS*,25X,*=*,I6,
     9       /15X,*NUMBER OF STATOR SLOTS*,23X,*=*,I6,
     A       /15X,*NUMBER OF ROTOR SLOTS*,24X,*=*,I6)
      CALL D2L
      CALL SPUNCH
      CALL RPUNCH
      CALL MAGCIR
      CALL MW1
      CALL MW2
      CALL MW3
      CALL PERFCAL
      CALL AUX1
      CALL AUX2
      CALL COWNDPC
      STOP
      END
```

```
      SUBROUTINE D2L
      COMMON/ONE/PW,PF,EFF,WF1,SCON
      COMMON/TWO/FREQ,O,F,T1,NPP,NSS,NRS,AL,IBS,IRS,SSPEED
      COMMON/THREE/DO,W10,D1,DY1,W11,W13,R13,D14,D11,D10,T10
      COMMON/FUR/AST,ASC,ARC,ART,AAG,SCL,RCL,STL,RTL,AGL,PLAMDA1,PLAMDA2
      COMMON/FIVE/AG,DR,D2,W20,DY2,T2,DS2,R21
      COMMON/SIX/C20,D24,W23,W21,T20,DB,WB,D21,CC
      COMMON/SEVN/SWA,NW,KD(10),LD,NCP1S,KKD,NCSPS,WF,VMIN,LSPP,NCA1S,NP
      COMMON/EIGHT/X,NEC,RS,RKA,BSC,EST,BAG,XO,PKA,CMEAN,GAMMA,RROC,
     1      D2N
      COMMON/NINE/O5,O2,RSHOT,RRHOT,TORQ,O1,O3,C4,X11,TCLOSS,PFW,RRHOTP
      COMMON/TEN/WIREL,RSHOTA,RM,XMF,ZM,RRHOTPA,AA,THETAM,CLR,CM,XAPA
      SSPEED=60.*FREQ/NPP
      XX=FW/SSPEED
      C=429.7-332.35*EXP(-3.514*XX)
      DDL=1.0E+6*XX/C
C
C SEPARATING D & L FROM DDL.
C
      PI=3.14159
      D=(2.)*NPP*DDL/(SCON*PI))**(0.3333)
      AL=DDL/(D*D)
C
C EVALUATING MAXIMUM AIR-GAP FLUX DENSITY.
C
      Q=29303.35-11484.05*EXP(-0.0184*XX)
      BG=C*30/(PI*1.11*WF1*C*PF*EFF)
C
C O U T P U T.
C
      PRINT 1,D,AL,Q,BG
1     FORMAT(1//25X,'***VOLUME OF ACTIVE MATERIALS***',
     1      //10X,'STATOR INSIDE DIAMETER(CM)',24X,'=',F13.6,
     2      /10X,'STATOR AND ROTOR AXIAL LENGTH(CM)',17X,'=',F13.6,
     4       /10X,'AMPERE-CONDUCTOR PER METRE',24X,'=',F13.6,
     3      /10X,'MAXIMUM AIR-GAP FLUX DENSITY(TESLA)',15X,'=',F13.6)
      RETURN
      END
```

```
      SUBROUTINE SPUNCH
      COMMON/ONE/PW,PF,EFF,WF1,SCON
      COMMON/TWO/FREQ,D,F,T1,NPP,NSS,NRS,AL,IBS,IRS,SSPEED
      COMMON/THREE/CO,W10,D1,DY1,W11,W13,R13,D14,D11,D10,T10
      COMMON/FUR/AST,ASC,ARC,ART,AAG,SCL,RCL,STL,RTL,AGL,PLAMDA1,PLAMDA2
      COMMON/FIVE/AG,DR,D2,W20,DY2,T2,DS2,R21
      COMMON/SIX/D20,D24,W23,W21,T20,D8,W8,D21,CC
      COMMON/SEVN/SNA,NW,KD(10),LC,NCP1S,KKD,NCSPS,WF,VMIN,LSPP,NCA1S,NN
      COMMON/EIGHT/X,NEC,RS,RKA,BSC,EST,BAG,XC,PKA,CMEAN,GAMMA,RROC,
     1      D2N
      COMMON/NINE/D5,D2,RSHCT,RRHOT,TORQ,D1,D3,D4,X11,TCLOSS,PFW,RRHOTP
      COMMON/TEN/HIREL,RSHOTA,RM,XMP,ZM,RRHOTPA,AA,THETAM,CLR,CM,XAPA
      READ 1,IBS
    1 FORMAT(I2)
      DO=(D*(1.175+1.03/(2.*NPP)))+1.6434
      IF(NSS.LE.24)W10=0.068+0.0175*D
      IF(NSS.EQ.36)W10=0.038+0.0175*D
      IF(NSS.GE.48)W10=0.0175*D
      D10=0.08
      D11=1.3*D10
      IF(NPP.EQ.1)T1=(1.10+0.0315*D)*D/NSS
      IF(NPP.GT.1)T1=(1.27+0.0354*D)*D/NSS
      PI=3.14159
      DY1=1.15*NSS*T1/(2.0*PI*NPP)
      HSAR=PI/NSS
       HSAD=180./NSS
C
C FLAT-BOTTOM SLOTS.
C
      IF(IBS.EQ.1)GO TO 2
      W11=(PI*(D+2.0*(D10+D11))/NSS)-T1
      D14=0.5*(DO-D)-(D10+D11+DY1)
      W13=W11+2.0*D14*TAN(HSAR)
      D1=D10+D11+D14
      GO TO 3
C
C ROUND-BOTTOM SLOTS.
```

```
      C
B     2      A=(C*SIN(HSAR)-T1)/2.0
B            B=0.5*(DO-C)-DY1
B            D1=(B*(1.+SIN(HSAR))+0.2*A)/(1.+0.8*SIN(HSAR))
B            R13=(A+B*SIN(HSAR))/(1.0+0.8*SIN(HSAR))
B            D14=D1-(R13+D10+D11)
B            W11=2.0*(R13-D14*SIN(HSAR))/COS(HSAR)
B            W13=2.0*R13
      C
      C O U T P U T .
      C
B     3      PRINT 4,DO,W10,D10,D11,T1,DY1,HSAD
B     4      FORMAT(1//30X,***STATOR PUNCHING***,
     1       //10X,*STATOR OUTER DIAMETER,DO(CM)*,22X,*=*,F13.6,
     2       /10X,*STATOR SLOT OPENING,W10(CM)*,23X,*=*,F13.6,
     3       /10X,*STATOR DEPTH OF TIP,D10(CM)*,23X,*=*,F13.6,
     4       /10X,*STATOR DEPTH OF MOUTH,D11(CM)*,21X,*=*,F13.6,
     5       /10X,*STATOR TOOTH WIDTH,T1(CM)*,25X,*=*,F13.6,
     6       /10X,*STATOR YOKE DEPTH,DY1(CM)*,25X,*=*,F13.6,
     7       /10X,*STATOR HALF SLOT ANGLE(DEGREES)*,19X,*=*,F13.6)
3            IF(IBS.EQ.0)PRINT 5
3            IF(IBS.EQ.1)PRINT 6
3     5      FORMAT(/10X,*TYPE OF STATOR SLOT IS FLAT-BOTTOM*)
3     6      FORMAT(/10X,*TYPE OF STATOR SLOT IS ROUND-BOTTOM*)
3            PRINT 7,D1, W11,D14,W13
3     7      FORMAT(/10X,*D1*,48X,F13.6,/10X,*W11*,47X,F13.6,/10X,*D14*,47X,
     1       F13.6,/10X,*W13*,47X,F13.6)
1            RETURN
1            END
```

```
      SUBROUTINE RPUNCH
      DIMENSION RCCBD(16),RECCBW(9),RECCBD(12)
      COMMON/ONE/PW,PF,EFF,WF1,SCON
      COMMON/TWO/FREQ,D,F,T1,NPP,NSS,NRS,AL,IBS,IRS,SSPEED
      COMMON/THREE/CO,W1O,D1,DY1,W11,W13,R13,D14,D11,D10,T10
      COMMON/FUR/AST,ASC,ARC,ART,AAG,SCL,RCL,STL,RTL,AGL,PLAMDA1,PLAMDA2
      COMMON/FIVE/AG,DR,D2,W2O,DY2,T2,DS2,R21
      COMMON/SIX/C2O,D24,W23,W21,T2O,DB,WB,D21,CC
      COMMON/SEVN/SWA,NW,KD(10),LO,NCP1S,KKO,NCSPS,WF,VMIN,LSPP,NCA1S,NN
      COMMON/EIGHT/X,NEC,RS,RKA,ESC,EST,BAG,XO,FKA,ONEAN,GAMMA,RROC,
     1      D2N
      COMMON/NINE/D5,D2,RSHCT,RRHCT,TORQ,C1,O3,O4,X11,TCLOSS,PFW,RRHOTP
      COMMON/TEN/WIREL,RSHOTA,RM,XMF,ZM,RRHOTPA,AA,THETAM,CLR,CM,XAPA
      READ 1,(ROCBO(I),I=1,16)
      READ 111,(RECCBW(I),I=1,9),(RECCBD(I),I=1,12)
111   FORMAT(21F6.4)
1     FORMAT(16F6.4)
      DO 112,M=1,16
      ROCBO(M)=ROCBD(M)*2.54
      IF(M.GT.12)GO TO 112
      RECCBD(M)=RECCBD(M)*2.54
      IF(M.GT.9)GO TO 112
      RECCBW(M)=RECCBW(M)*2.54
112   CONTINUE
      READ 2,IRT,IRS
2     FORMAT(2I2)
      PI=3.14159
      AG=(0.013+0.0042*D/(SQRT(2.*NPP))
      D2=C-2.*AG
      T2=0.95*NSS*T1/NRS
      W2O=0.68
      D2O=0.08
      IF(IRS.EQ.1)GO TO 8

ROUND SLOTS.

      R21=(PI*(C2-2.*D2O)-NRS*T2)/(2.*(NRS+PI))
      DC=2.0*R21-0.038
      IF(IRT.NE.0)GO TO 7
      IF(DC.GT.ROCBO(1))GO TO 3
      DC=ROCBO(1)
      GO TO 6
```

```
      3     DO 5,J=1,15
            IF(ROCBD(J).GE.DC.OR.DC.GE.ROCBD(J+1))GO TO 5
            IF(DC-ROCBC(J).LT.ROCBC(J+1)-DC)GO TO 4
            DC=ROCBD(J+1)
            GO TO 5
      4     DC=ROCBD(J)
      5     CONTINUE
            IF(DC.GT.ROCBD(16))DC=RCCBD(16)
      6     R21=(DC+0.038)/2.0
      7     T2=((PI*(D2-2.0*D20-2.0*R21))/NRS)-2.0*R21
            DS2=2.*R21+D20
            GO TO 19
C
C TRAPEZOIDAL SLOT.
C
      8     CR=0.035
            CT=0.03
            D21=1.3*D20
            D24=((D2-2.*(D20+D21+CR))/4.)-(NRS*(T2+CT)/(4.*PI))
            DB=D24-CR
            IF(IRT.NE.0)GO TO 13
            IF(DB.GT.RECCBD(1))GO TO 9
            DB=RECCBD(1)
            GO TO 12
      9     DO 11,J=1,11
            IF(RECCBD(J).GE.DB.OR.DC.GE.RECCBD(J+1))GO TO 11
            IF(DC-RECCBD(J).LT.RECCBD(J+1)-DB)GO TO 10
            DB=RECCBD(J+1)
            GO TO 11
     10     DB=RECCBD(J)
     11     CONTINUE
            IF(DB.GT.RECCBD(12))DB=RECCBD(12)
     12     D24=DB*CR
     13     DS2=D24+D21+D20
            W23=(PI*(D2-2.0*DS2)/NRS)-T2
            WB=W23-CT
            IF(IRT.NE.0)GO TO 18
            IF(WB.GT.RECCBW(1))GO TO 14
            WB=RECCBW(1)
            GO TO 17
```

```
   14     DO 16,J=1,9
          IF(RECCBW(J).GE.WB.OR.WB.GE.RECCBW(J+1))GO TO 16
          IF(WB-RECCBW(J).LT.RECCBW(J+1)-WB)GO TO 15
          WB=RECCBW(J+1)
          GO TO 16
   15     WB=RECCBW(J)
   16     CONTINUE
          IF(WB.GT.RECCBW(9))WB=RECCBW(9)
   17     W23=WB+CT
   18     W21=W23+2.0*D24*TAN(PI/NRS)
          T2=(PI*(D2-2.0*DS2)/NRS)-W23
C
C YOKE DEPTH AND VENT HOLES.
C
   19     DY2=0.95*DY1
          DR=D-2.0*(DS2+DY2)
C
C O U T P U T .
C
          PRINT 20,AG,D2,T2,W20,D20
   20     FORMAT(1//31X,***ROTOR PUNCHING***
         1       //10X,*AIR-GAP LENGTH(CM)*,32X,*=*,F13.6,
         2       /10X,*ROTOR OUTER DIAMETER,D2(CM)*,23X,*=*,F13.6,
         3       /10X,*ROTOR TOOTH WIDTH,T2(CM)*,26X,*=*,F13.6,
         4       /10X,*ROTOR SLOT OPENING,W20(CM)*,24X,*=*,F13.6,
         5       /10X,*ROTOR DEPTH OF TIP,D20(CM)*,24X,*=*,F13.6)
          IF(IRS.EQ.0)PRINT 21,R21,DC
          IF(IRS.EQ.1)PRINT 22,D21,D24,D8,DS2,W23,WB,W21
   21     FORMAT(/10X,*TYPE OF ROTOR SLOT IS ROUND*,
         1       /10X,*R21*,47X,*=*,F13.6,/10X,*DC*,48X,*=*,F13.6)
   22     FORMAT(/10X,*TYPE OF ROTOR SLOT IS TRAPEZOIDAL*,
         1       /10X,*D21*,47X,*=*,F13.6,/10X,*D24*,47X,*=*,F13.6,
         2       /10X,*D8*,48X,*=*,F13.6,/10X,*DS2*,47X,*=*,F13.6,
         3       /10X,*W23*,47X,*=*,F13.6,/10X,*WB*,48X,*=*,F13.6,
         4       /10X,*W21*,47X,*=*,F13.6)
          RETURN
          END
```

```
      SUBROUTINE MAGCIR
      COMMON/ONE/PH,PF,EFF,WF1,SCON
      COMMON/TWO/FREQ,D,F,T1,NPP,NSS,NRS,AL,IBS,IRS,SSPEED
      COMMON/THREE/CO,W10,D1,DY1,W11,W13,R13,D14,D11,D10,T10
      COMMON/FOUR/AST,ASC,ARC,ART,AAG,SCL,RCL,STL,RTL,AGL,PLANDA1,PLANDA2
      COMMON/FIVE/AG,DR,D2,W20,DY2,T2,DS2,R21
      COMMON/SIX/C20,D24,W23,W21,T20,DB,WB,D21,DC
      COMMON/SEVN/SWA,NW,KD(10),LC,N(P1S,KKD,NCSPS,WF,VMIN,LSPP,NCAIS,NN
      COMMON/EIGHT/X,NEC,RS,RKA,ESC,EST,BAG,XO,PKA,DMEAN,GAMMA,RRDC,
     1      D2N
      COMMON/NINE/D5,D2,RSHOT,RRHOT,TORQ,D1,D3,D4,X11,TCLOSS,PFW,RRHOTP
      COMMON/TEN/WIREL,RSHOTA,RM,XMP,ZM,RRHOTPA,AA,THETAM,CLR,CH,XAPA
      PI=3.14159
      PLANDA1=D*PI/ASS
      T10=PLANDA1-W10
      X1=PLANDA1*(5.0*AG+W10)
      CF1=X1/(X1-W10*W10)
      PLANDAP=PI*(D2+AG)/(2.0*NPP)
      PLANDA2=PI*D2/NRS
      T20=PLANDA2-W20
      X1=PLANDA2*(5.0*AG+W20)
      CF2=X1/(X1-W20*W20)
      CF=CF2*CF2
      ASC=2.0*F*AL*DY1
      AST=F*AL*NSS*T1/(2.0*NPP)
      ARC=2.0*F*AL*DY2
      ART=F*AL*NRS*T2/(2.0*NPP)
      AAG=AG*PLANDAP
      SCL=PI*(DO-DY1)/(4.0*NPP)
      RCL=PI*(DR+DY2)/(4.0*NPP)
      AGL=AG*CF
      STL=D1
      IF(IRS.EQ.0)RTL=2.0*R21/3.
      IF(IRS.EQ.1)RTL=DS2
C
C O U T P U T .
C
```

```
      PRINT 1,PLAMDA1,T10,CF1,PLAMDAF,PLAMDA2,T20,CF2,CF,A
     1        ARC,ART,AAG,SCL,RCL,AGL,STL,RTL
    1  FORMAT(1//25X,***MAGNETIC-CIRCUIT CALCULATIONS***,
     1       //10X,*STATOR TOOTH PITCH(CM)*,28X,*=*,F13.6,
     2       /10X,*STATOR TOOTH FACE(CM)*,29X,*=*,F13.6,
     3       /10X,*STATOR GAP CONSTANT*,31X,*=*,F13.6,
     4       /10X,*POLE PITCH(CM)*,36X,*=*,F13.6,
     5       /10X,*ROTOR TOOTH PITCH(CM)*,29X,*=*,F13.6,
     6       /10X,*ROTOR TOOTH FACE(CM)*,31X,*=*,F13.6,
     7       /10X,*ROTOR GAP CONSTANT*,32X,*=*,F13.6,
     8       /10X,*TOTAL GAP CONSTANT*,32X,*=*,F13.6,
     9       /10X,*STATOR CORE AREA(CMXCM)*,27X,*=*,F13.6,
     1       /10X,*STATOR TEETH AREA(CMXCM)*,26X,*=*,F13.6,
     1       /10X,*ROTOR CORE AREA(CMXCM)*,28X,*=*,F13.6,
     2       /10X,*ROTOR TEETH AREA(CMXCM)*,27X,*=*,F13.6,
     3       /10X,*AIR-GAP AREA(CMXCM)*,31X,*=*,F13.6,
     4       /10X,*STATOR CORE LENGTH(CM)*,28X,*=*,F13.6,
     5       /10X,*ROTOR CORE LENGTH(CM)*,29X,*=*,F13.6,
     6       /10X,*AIR-GAP LENGTH(CM)*,32X,*=*,F13.6,
     7       /10X,*STATOR TEETH LENGTH(CM)*,27X,*=*,F13.6,
     8       /10X,*ROTOR TEETH LENGTH(CM)*,28X,*=*,F13.6)
      RETURN
      END
```

```
      SUBROUTINE MW1
      COMMON/ONE/PW,PF,EFF,WF1,SCCN
      COMMON/TWO/FREQ,O,F,T1,NPP,NSS,NRS,AL,IBS,IRS,SSPEED
      COMMON/THREE/CO,W10,D1,CY1,W11,W13,R13,C14,C11,D10,T10
      COMMON/FUR/AST,ASC,ARC,ART,AAG,SCL,RCL,STL,RTL,AGL,PLAMDA1,PL M
      COMMON/FIVE/AG,DR,D2,WE2,CY2,T2,DS2,R21
      COMMON/SIX/C20,D24,W23,W21,T20,DE,WE,D21,CC
      COMMON/SEVN/SWA,NW,KD(10),LC,NCP1S,KKC,NCSPS,WF,VMIN,LSPP,NC
      COMMON/EIGHT/X,NEC,RS,RKA,BSC,EST,BAG,XO,PKA,CMEAN,GAMMA,RPOC
     1      D2N
      COMMON/NINE/DS,D3,RSHCT,RRHCT,TORQ,C1,C3,C4,X11,TCLOSS,PFW,EP
      COMMON/TEN/WIREL,RSHOTA,RM,XMF,ZM,RRHOTPA,AA,THETAM,CLR,CM,XA
      READ 1,VMIN,VMAX,BT,TTW,TSC,TFS,SLFULL,NCSPS,NN
    1 FORMAT(7F7.3,2I2)
      READ 2,LO,(KO(J),J=1,NN)
    2 FORMAT(10I2)
      LSPP=NSS/(2*NPP)
      FT=1.637*AST*BT/1.E4
      CKW1=0.45016*0.97*VMIN/(FT*FREQ)
      PI=3.14159
      KKC=0
      WFO=0.
      LLC=LC
      DO 3,I=1,NN
      KKC=KKC+KO(I)
      WFC=WFO+KO(I)*SIN((LLC-I)*PI/(2.0*LSPP))
      LLC=LLO-1
    3 CONTINUE
      WF=WFO/KKO
      NC=CKW1/WF
      NCP1S=NC/(KKO*4*NPP)
      NCPS=NCP1S*NCSPS

C NET-SLOT WINDING AREA.

      ASG1=(D11*(W10+W11)+D14*(W11+W13))/2.0
      ARB=(PI*(R13**2))/2.0
      IF(IBS.EQ.0)ASG=ASG1
      IF(IBS.EQ.1)ASG=ASG1+ARB
      ASCE1=TSC*(W11-W10+2.0*C14)
      IF(IBS.EQ.0)ASCE=ASCE1+TSC*W13
      IF(IBS.EQ.1)ASCE=ASCE1+TSC*ARB
      ATW=TTW*W11*1.5
      SWA=ASG-ATW-ASCE-0.5*(NCSPS-1)*TFS*(W11+W13)
```

```
WIRE SIZE.

      IF(VMIN.EQ.VMAX)NW=NCPS
      IF(VMIN.NE.VMAX)NW=VMAX*NCPS/VMIN
      DIAM=SQRT(SLFLL*SWA/(100.*NW))

C
C O U T P U T .
C
      PRINT 4,BT,VMIN,VMAX,FT,LSPP,CKW1,WF,NC,NCP1S,ASG,SWA,NW,DIAM
    4 FORMAT(1//33X,***MAIN WINDING***,
     1       //10X,*ASSUMED STATOR TOOTH DENSITY(TESLA)*,15X,*=*,F13.
     2       /10X,*SUPPLY VOLTAGE(VOLTS)*,29X,*=*,F7.3,*/*,F7.3,
     3       /10X,*FLUX PER POLE(WEBERS)*,29X,*=*,F13.6,
     4       /10X,*NUMBER OF SLOTS PER POLE*,26X,*=*,I6,
     5       /10X,*EFFECTIVE CONDUCTORS*,30X,*=*,F13.6,
     6       /10X,*WINDING FACTOR*,36X,*=*,F13.6,
     7       /10X,*TOTAL CONDUCTORS*,34X,*=*,I6,
     8       /10X,*NUMBER OF CONDUCTORS IN A "1" SLOT*16X,*=*,I6,

     9       /10X,*GROSS SLOT AREA(CMXCM)*,28X,*=*,F13.6,
     1       /10X,*NET SLOT-WINDING AREA(CMXCM)*,22X,*=*,F13.6,
     1       /10X,*TOTAL NUMBER OF WIRES IN THE SLOT*,17X,*=*,I6,
     2       /10X,*DIAMETER OF WIRE WITH INSULATOR(CM)*,15X,*=*,F10
      RETURN
      END
```

```
      SUBROUTINE MW2
      DIMENSION DIACT(5)
     COMMON/ONE/PN,PF,EFF,WF1,SCCN
     COMMON/TWO/FREQ,D,F,T1,NPP,NSS,NRS,AL,IBS,IRS,SSPEED
     COMMON/THREE/DC,W10,D1,DY1,W11,W13,R13,C14,D11,D10,T10
     COMMON/FOUR/AST,ASC,ARC,ART,AAG,SCL,RCL,STL,RTL,AGL,PLAMDA1,P
     COMMON/FIVE/AG,D3,D2,W21,DY2,T2,DS2,R21
     COMMON/SIX/C20,D24,W23,W21,T20,DB,WB,D21,CC
     COMMON/SEVN/SWA,NW,KD(10),LC,NCP1S,KKC,NCSPS,WF,VMIN,LSPP,NCA1
     COMMON/EIGHT/X,NEC,RS,RKA,DSC,EST,BAG,XC,PKA,CMEAN,GAMMA,RRC,
    1      D21
     COMMON/NINE/D5,D2,RSHCT,RRHCT,TORQ,C1,D3,C4,X11,TCLOSS,PFW,RR
     COMMON/TEN/WIREL,RSHOTA,RM,XMP,ZM,RRHCTPA,AA,THETAM,CLR,CN,XA
      READ 1,RES,NCW,MPP
      FORMAT(F7.3,2I2)
      READ 2,(DIACT(I),I=1,NCW)
     FORMAT(5F10.6)
      D2N=0.
      DO 3,J=1,NCW
      D2N=D2N+NW*DIACT(J)*DIACT(J)
      CONTINUE
      SLFULLA=D2N*100.0/SWA
```

A V E R A G E C O I L T H R O W.

```
      KKC2=0
      MCT=0
      MC=0
      MLC=LC
      DO 4,K=1,NN
      MCT=MCT+(MLC-K)*NCP1S*KD(K)
      MC=KD(K)*NCP1S+MC
      MLC=MLC-1
      KKC2=KKC2+(KD(K)**2)
      CONTINUE
     AMCT=MCT
     AMC=MC
      ACT=AMCT/AMC
```

M E A N D I A M E T E R O F S T A T O R S L O T S.


```
C
      DMEAN=D+D1+D13+D11
C
C  LENGTH  MEAN  CONDUCTORS
C
      PI=3.14159
      IF(NPP.EQ.1)GAMMA=1.3
      IF(NPP.EQ.2)GAMMA=1.5
      IF(NPP.GT.2)GAMMA=1.7
      CONLMN=AL+PI*DMEAN*GAMMA*ACT/NSS
C
C  NUMBER  OF  CONDUCTORS
C
      NCC=MC*4.0*NPP
C
C  STATOR  WINDING  RESISTANCE  AT  AMBIENT  TEMPERATURE
C
      RS=CONLMN*NCC*RES/(100*MPP*1000)
C
C  RESISTANCE  PER  COIL  SIDE.
C
      RSPS=NCSPS*RS
C
C
C  EFFECTIVE  CONDUCTORS.
C
      NCC=NCC*WF
C
C  STATOR  SLOT  CONSTANT
C
      FZ3=C13/W11
      FZ4=3.0*C11/(W10+W11)
      IF(IBS.EQ.2) GO TO 5
      FZ1=0.311*C14/W11
```

```
C
C
C  S A T U R A T I O N   F A C T O R
C
      FPF=0.463016*1.37*VMIN/(NEC*FREQ)
      PK=1.0-2.0*NPP/100.0
      PK=0.94
      CK=PK/(2.0-PK)
      BSC=FPF*1.0E4/ASC
     IF((2*NPP).EQ.2)CCRK=1.97*(1.0+0.0346*EXP(2.69*BSC))
     IF((2*NPP).EQ.4)CCRK=1.686*(1.0+0.029*EXP(2.33*BSC))
     IF((2*NPP).GT.4)CCRK=1.62*(1.0+0.0081*EXP(2.83*BSC))
     HSC=CCRK*103.72*BSC/(1.0-0.532*BSC)
      BST=FPF*1.0E4/(0.637*AST)
      HST=103.72*BST/(1.-0.532*BST)
      BRC=CK*FPF*1.0E4/ARC
     IF((2*NPP).EQ.2)CCRK=1.97*(1.0+0.0346*EXP(2.69*BRC))
     IF((2*NPP).EQ.4)CCRK=1.686*(1.0+0.029*EXP(2.33*BRC))
     IF((2*NPP).GT.4)CCRK=1.62*(1.0+0.0081*EXP(2.83*BRC))
     HRC=CCRK*103.72*BRC/(1.0-0.532*BRC)
      BRT=CK*FPF*1.0E4/(0.637*ART)
      HRT=103.72*BRT/(1.-0.532*BRT)
      BAG=FPF*1.0E4/AAG
      HAG=BAG*1.0E7/(4.0*PI)
      HTOT=(HST*SCL+HST*STL+HRC*SCL+HRT*RTL+HAG*AGL)/100.
      SFM=100.*HTOT/(HAG*AGL)
C
C  LEAKAGE  AND  MAGNETIZING  REACTANCES
      CX=KKC2*NSS/(KKD*KKD*WF*WF*8.0*NPP)
      FZ=F2S*CX+(NSS/NRS)*FZR
      ZZK=((T10+T20)**2.0)/(4.0*(PLAMDA1+PLAMDA2))
      NSF=(NSS+NRS)/(4.0*NPP)
      BK=(11.25/NSF)+0.48
      SSKEW=360/NSS
     SSKEWR=2.0*PI/NSS
      D=0.25*((SSKEW/100.0)**2.0)
      CSKEW=360.0*SIN(SSKEWR/2.0)/(PI*SSKEW)
      GMK=AAG/(AGL*SFM*2.0*NPP)
      XK=2.0*PI*FREQ*NEC*NEC*0.1E-7
      SLOT=3.19*2.0*FZ*AL/NSS
      ZIGZAG=1.065*2.0*AL*ZZK/(NSS*AG)
      END=1.57*3.0*DMEAN*ACT/(NSS*2.0*NPP)
      BELT=0.00114*2.0*G1K*BK
      SKEW=0.3234*2.0*GMK*FK*Q
      PL=SLOT+ZIGZAG+END+BELT+SKEW
      PM=0.3234*3.0*GMK*CSKEW
     XOM=XK*PM
      PC=PM+PL/2.0
      X=XK*PL
      XO=XK*PO
```

```
      RKA=(XO-X)/XC
      RKA=SQRT(RKA)

C  O  U  T  P  U  T

      PRINT 8,(CIACT(I),I=1,NOW),SLFULLA,ACT,OMEAN,CONLMN,NOC,RS,RSP,
     1        NEC,FZS,FZR,FPP,PSC,PST,PRC,PRT,PAG,HSC,HST,HRC,HRT,HAG,
     2        HTCT,SFM,CX,FZ,ZZK,NSP,BK,SSKEW,D,CSKEW,GMK,XK,SLCT,
     3        ZIGZAG,END,BELT,SKEW,PI,XOM,X,XC
    8 FORMAT(/10X,*DIAMETERS OF WIRE(CM)*,29X,*=*,F13.6,
     1      /10X,*ACTUAL SLOT FULLNESS*,30X,*=*,F13.6,
     2      /10X,*AVERAGE COIL THROW*,32X,*=*,F13.6,
     3      /10X,*MEAN DIAMETER OF STATOR SLOTS(CM)*,17X,*=*,F13.6,
     4      /10X,*LENGTH MEAN CONDUCTOR(CM)*,25X,*=*,F13.6,
     5      /10X,*NUMBER OF CONDUCTORS*,30X,*=*,I6,
     6      /10X,*STATOR WINDING RESISTANCE(OHMS)*,19X,*=*,F13.6,
     7      /10X,*STATOR RESITANCE PER SECTION(OHMS)*,16X,*=*,F13.6,
     8      /10X,*EFFECTIVE CONDUCTORS*,30X,*=*,I6,
     9      /10X,*STATOR SLOT CONSTANT*,30X,*=*,F13.6,
     1      /10X,*ROTOR SLOT CONSTANT*,31X,*=*,F13.6,
     1      /10X,*FLUX PER POLE(WEBERS)*,29X,*=*,F13.6,
     2      /10X,*FLUX DENSITIES(TESLA):*,/15X,*STATOR CORE*,34X,*=*
     3     F13.6,/15X,*STATOR TEETH*,33X,*=*,F13.6,
     4      /15X,*ROTOR CORE*,35X,*=*,F13.6,
     5      /15X,*ROTOR TEETH*,34X,*=*,F13.6,
     6      /15X,*AIR GAP*,38X,*=*,F13.6,/10X,*AMPERE-TURNS PER METRE
     7      /15X,*STATOR CORE*,34X,*=*,F13.6,
     8      /15X,*STATOR TEETH*,33X,*=*,F13.6,
     9      /15X,*ROTOR CORE*,35X,*=*,F13.6,
     1      /15X,*ROTOR TEETH*,34X,*=*,F13.6,
     1      /15X,*AIR GAP*,38X,*=*,F13.6,/10X,*TOTAL AMPERE-TURNS*,31X,
     2      *=*,F13.6,/10X,*SATURATION FACTOR*,33X,*=*,F13.6,
     3      /10X,*DISTRIBUTION FACTOR FOR SLOT LEAKAGE*,14X,*=*,F13.6,
     4      /10X,*TOTAL SLOT CONSTANT*,31X,*=*,F13.6,
     5      /10X,*ZIG-ZAG CONSTANT*,34X,*=*,F13.6,
     6      /10X,*AVERAGE NUMBER OF SLOTS PER POLE*,18X,*=*,I6,
     7      /10X,*BELT LEAKAGE CONSTANT*,29X,*=*,F13.6,
     8      /10X,*SKEW ANGLE (DEGREES)*,30X,*=*,F13.6,
     9      /10X,*SKEW LEAKAGE FACTOR*,31X,*=*,F13.6,
     1      /10X,*SKEW FACTOR*,39X,*=*,F13.6,
     1      /10X,*DIFFERENTIAL LEAKAGE CONSTANT*,21X,*=*,F13.6,
     1      /10X,*REACTANCE CONSTANT*,32X,*=*,F13.6,
     2      /10X,*LEAKAGE REACTANCES:*,/15X,*SLOT*,41X,*=*,F13.6,
     3      /15X,*ZIG-ZAG*,38X,*=*,F13.6,/15X,*END*,42X,*=*,F13.6,
     4      /15X,*BELT*,41X,*=*,F13.6,/15X,*SKEW*,41X,*=*,F13.6,
     5      /12X,*TOTAL*,43X,*=*,F13.6,
     6      /10X,*MAGNETIZING REACTANCE*,29X,*=*,F13.6,
     7      /10X,*IDEAL SHORT-CIRCUIT REACTANCE*,21X,*=*,F13.6,
     8      /10X,*OPEN-CIRCUIT REACTANCE*,29X,*=*,F13.6)
      RETURN
      END
```

```
      SUBROUTINE ANS
      COMMON/ONE/PN,PF,SFF,WF1,SCCN
      COMMON/TWO/FREQ,O,F,T1,NPP,ISS,NRS,AL,IBS,IRS,SSPEED
      COMMON/THREE/CC,W10,C1,CY1,W11,W13,R13,C14,C11,O10,T1C
      COMMON/FOUR/AST,ASC,APC,APT,AAG,SCL,RCL,STL,RTL,AGL,PLAMDA1,PLAM
      COMMON/FIVE/AC,OR,O2,W20,CY2,T2,OS2,P21
      COMMON/SIX/C2L,O24,W33,W21,T3C,OB,WB,C21,CC
      COMMON/SEVA/SWA,WN,KC(10),LC,NCP1S,KKC,NCSPS,WF,VMIN,LSPP,NCP1S
      COMMON/EIGHT/X,NCC,PS,WKA,BSC,BST,BAG,XC,RKA,DMEAN,GAMMA,RPCC,
     1     O2N
      COMMON/NINE/OS,O2,RSHCT,ARHCT,TORQ,C1,C3,C4,X11,TCLOSS,PFW,RPMSE
      COMMON/TEN/WIREL,RSHCTA,RM,XMF,ZM,PRHCTPA,AA,THETAM,CLR,CM,XMFS
C
C**INITIAL DESIGN OF ROTOR CAGE**
C
C
      READ 1,RCPC
1     FORMAT(E14.3)
      RPCK=0.45*X
      RPCC=RPCK/1.15
      RESCON=RCPC*2.*NFC*NSC
      BARNG=RPCC/RESCON
      PI=3.14159
      SK=PI*D2/NSS
      IF(IRS.EQ.1)AEAR=PI*((.5*CC)**2.)
      IF(IRS.EQ.1)AEAR=OB*WB
      BAR=OMPT(AL*AL+SK*SK)/(PIBAR*NRS)
      RING=BARING-BAR
      IF(IRS.EQ.1)DRR=D2-2.*(O2Y+Y21)
      IF(IRS.EQ.2)DRR=D2-2.0*(O21+O21)-O24
      DIC=DR/DRR
      DICP=DIC**(NPP*2)
      RINGK=NPP*(1.0-DIC)*(1.0+DICP)/(1.0-DICP)
      NP=2*NPP
      ARING=63.7*CPC*RINGK/(RING*NP*NP*100.)
      THICK=ARING/(0.5*(D2-DR))
C
C OUTPUT
C
      PRINT 2,PRCC,RESCON,ABAR,DR,D2,THICK
2     FORMAT(1//34X,***ROTOR CAGE***,/
     1       /10X,*ROTOR RESISTANCE (OHM)*,29X,*=*,F13.6,
     2       /10X,*RESISTANCE CONSTANT*,31X,*=*,F13.6,
     3       /10X,*CROSS-SECTIONAL AREA OF 1 ROTOR BAR (CMXCM)*,7X,*=*,
     4       F13.6,/10X,*INTERNAL DIAMETER OF RING(CM)*,21X,*=*,F13.6,
     5       /10X,*OUTER DIAMETER OF RING(CM)*,24X,*=*,F13.6,
     6       /10X,*THICKNESS OF RING(CM)*,29X,*=*,F13.6)
      RETURN
      END
```

```
      SUBROUTINE PERFCAL
      COMMON/ONE/PH,PF,EFF,WF1,SCON
      COMMON/TWO/FREQ,D,F,T1,NPP,NSS,NRS,AL,IBS,IRS,SSPEED
      COMMON/THREE/DO,W10,D1,DY1,W11,W13,R13,D14,D11,D10,T10
      COMMON/FUR/AST,ASC,ARC,ART,AAG,SCL,RCL,STL,RTL,AGL,PLAMDA1,PLAMDA
      COMMON/FIVE/AG,DR,D2,W20,DY2,T2,DS2,R21
      COMMON/SIX/C20,D24,W23,W21,T20,DB,WB,D21,DC
      COMMON/SEVN/SWA,NW,KD(10),LO,NCP1S,KKD,NCSPS,WF,VMIN,LSPP,NCA1S,N
      COMMON/EIGHT/X,NEC,RS,RKA,BSC,BST,BAG,XO,PKA,DMEAN,GAMMA,RROC,
     1      D2N
      COMMON/NINE/D5,D2,RSHOT,RRHOT,TORQ,D1,D3,D4,X11,TCLOSS,PFW,RRHOTP
      COMMON/TEN/WIREL,RSHOTA,RM,XMF,ZM,RRHOTPA,AA,THETAM,CLR,CM,XAPA
      READ 1,GSF,CJCUR,ITE,IL
1     FORMAT(2F6.3,2I2)
C
C BREAKDOWN TORQUE USING VEINOTT FORMULA
C
      R=RROC+RS
      RHOT=1.15*R
      U=345-9.2*((RHOT/X)**2)
      VR=((VMIN/115)**2)
      TBD=0.08474*VR*NPP*60.0*U*RKA/(2.0*FREQ*(RHOT+X))
C
C CORE  LOSSES AND FRICTION
C
      IF(IL.EQ.0)PLOSS1=7355.534*(BSC**0.604)*EXP(1.357*BSC)
      IF(IL.EQ.1)PLOSS1=10568.037*(BSC**0.615)*EXP(1.292*BSC)
      IF(IL.EQ.2)PLOSS1=14595.578*(BSC**0.711)*EXP(1.217*BSC)
      PLOSSSC=PLOSS1*ASC*2.0*NPP*SCL*1.0E-6
      IF(IL.EQ.0)PLOSS2=7355.534*(BST**0.604)*EXP(1.357*BST)
      IF(IL.EQ.1)PLOSS2=10568.037*(BST**0.615)*EXP(1.292*BST)
      IF(IL.EQ.2)PLOSS2=14595.037*(BST**0.711)*EXP(1.217*BST)
      PLOSSST=PLOSS2*AST*2.0*NPP*STL*1.0E-6
      BAG1=BAG**2.3
      FREQ15=(FREQ/(2.0*NPP))**1.55
      W10AG=(W10/AG)**1.22
      BNSS=NSS
      SQN=SQRT(BNSS)
      PLOSSSL=8.463E-6*GSF*BAG1*FREQ15*(D**2.45)*SQN*AL*W10AG
      PLOSSC=PLOSSSC+PLOSSST
      TCLOSS=PLOSSC+PLOSSSL
      PFW=1.25*((DJCUR/2.54)**3)*SSPEED/100.
      IF(ITE.EQ.1)PFW=PFW*2.0
C
C PERFORMANCE CALCULATION USING REVOLVING FIELD THEORY
C
```

```
      RSHOT=1.15*RS
      RRHOT=RROC*1.15
      X11=X/(1.0+PKA)
      01=0.5*RKA*RRHOT
      02=RRHOT/XC
      03=0.5*PKA*X0
      04=0.5*PKA*X11
      05=RRHOT/X
      SPC=0.7+0.3*EXP(-1.69*C5)
      SLIPBO=1-SPC
      M=1
      SLIP=0.019
3     IF(M.EQ.50)GO TO 33
      SLIP=SLIP+0.001
      GO TO 34
33    PRINT 111
111   FORMAT(////10X,"E R R O R ! !"///)

      GO TO 4
34    Y1=2.0-SLIP
      Y1BO=2.0-SLIPBO
      Y2=01/SLIP
      Y2BO=01/SLIPBO
      Y3=01/Y1
      Y3BO=01/Y1BO
      Y4=(02/SLIP)**2
      Y4BO=(02/SLIPBO)**2
      Y5=(02/Y1)**2
      Y5BO=(02/Y1BO)**2
      Y6=1.0+Y4
      Y6BO=1.0+Y4BO
      Y7=1.0+Y5
      Y7BO=1.0+Y5BO
      RF=Y2/Y6
      RFBO=Y2BO/Y6BO
      RB=Y3/Y7
      RBBO=Y3BO/Y7BO
      RT=RF+RB+RSHOT
      RTBO=RFBO+RBBO+RSHOT
      Y8=03*Y4
      Y8BO=03*Y4BO
      Y9=03*Y5
      Y9BO=03*Y5BO
      Y10=Y9+04
      Y10BO=Y8BO+04
      Y11=Y9+04
      Y11BO=Y9BO+04
```

```
2     FORMAT(1//26X,***PERFORMANCE CALCULATIONS***,/
     1       /10X,*BREAKDOWN TORQUE(VEINOTT FORMULA)(N.M)*,12X,*=*,F13.6
     2       /10X,*LOSSES(WATTS):*,/15X,*STATOR CORE*,34X,*=*,F13.6,
     3       /15X,*STATOR TEETH*,33X,*=*,F13.6,
     4       /15X,*SURFACE LOSS*,33X,*=*,F13.6,
     5       /15X,*TOTAL CORE LOSS*,30X,*=*,F13.6,
     6       /10X,*JOURNAL OUTER DIAMETER(CM)*,24X,*=*,F13.6,
     7       /10X,*GRADE OF STEEL FACTOR*,29X,*=*,F13.6,
     8       /10X,*FRICTION AND WINDAGE LOSSES(WATTS)*,16X,*=*,F13.6,
     9       /10X,*SLIP*,46X,*=*,F13.6,
     1       /10X,*BREAK DOWN SLIP*,35X,*=*,F13.6,
     1       /10X,*RESISTANCES (OHMS):*,
     2       /15X,*APPARENT TO FORWARD FIELD*,20X,*=*,F13.6,
     3       /15X,*APPARENT TO FORWARD FIELD(BREAKDOWN)*,9X,*=*,F13.6,
     4       /15X,*APPARENT TO BACKWARD FIELD*,19X,*=*,F13.6,
     5       /15X,*APPARENT TO BACKWARD FIELD(BREAKDOWN)*,8X,*=*,F13.6,
     6       /15X,*TOTAL*,40X,*=*,F13.6,
     7       /15X,*TOTAL(BREAKDOWN)*,29X,*=*,F13.6,
     8       /10X,*REACTANCES(OHMS):*,
     9       /15X,*APPARENT TO FORWARD FIELD*,20X,*=*,F13.6,
     1       /15X,*APPARENT TO FORWARD FIELD(BREAKDOWN)*,9X,*=*,F13.6,
     1       /15X,*APPARENT TO BACKWARD FIELD*,19X,*=*,F13.6,
     2       /15X,*APPARENT TO BACKWARD FIELD(BREAKDOWN)*,8X,*=*,F13.6,
     3       /15X,*TOTAL*,40X,*=*,F13.6,
     4       /15X,*TOTAL(BREAKDOWN)*,29X,*=*,F13.6,
     5       /10X,*TOTAL IMPEDANCE(OHMS)*,29X,*=*,F13.6,
     6       /10X,*TOTAL IMPEDANCE(BREAKDOWN)(OHMS)*,18X,*=*,F13.6,
     7       /10X,*CURRENT(AMP)*,38X,*=*,F13.6,
     8       /10X,*BREAKDOWN CURRENT*,33X,*=*,F13.6,
     9       /10X,*CORRECTED CURRENT*,33X,*=*,F13.6,
     1       /10X,*NO-LOAD CURRENT*,35X,*=*,F13.6,
     1       /10X,*PRIMARY LOSS (WATTS)*,30X,*=*,F13.6,
     2       /10X,*NO-LOAD PRIMARY LOSS*,30X,*=*,F13.6,
     3       /10X,*SECONDARY LOSS*,36X,*=*,F13.6,
     4       /10X,*NO-LOAD SECONDARY LOSS*,28X,*=*,F13.6,
     5       /10X,*POWER INPUT*,39X,*=*,F13.6,
     6       /10X,*NO-LOAD POWER INPUT*,31X,*=*,F13.6,
     7       /10X,*POWER OUTPUT*,38X,*=*,F13.6,
     8       /10X,*BREAKDOWN POWER OUTPUT*,28X,*=*,F13.6,
     9       /10X,*SPEED (RPM)*,39X,*=*,F13.6,
     1       /10X,*BREAKDOWN SPEED (RPM)*,29X,*=*,F13.6,
     1       /10X,*TORQUE (N.M)*,38X,*=*,F13.6,
     2       /10X,*BREAKDOWN TORQUE(N.M)*,29X,*=*,F13.6
     3       /10X,*EFFICIENCY*,40X,*=*,F13.6,
     4       /10X,*POWER FACTOR*,38X,*=*,F13.6,
     5       /10X,*APPARENT EFFICIENCY*,31X,*=*,F13.6,
     6       /10X,*PERCENTAGE FULLOAD*,32X,*=*,F13.6)
      RETURN
      END
```

```
      XF=Y12/Y6
      XFBD=Y12BD/Y6BD
      XB=Y11/Y7
      XBBD=Y11BD/Y7BD
      XT=XF+XB+X11
      XTBD=XFBD+XBBD+X11
      Z=SQRT((RT**2)+(XT**2))
      ZBD=SQRT((RTBD**2)+(XTBD**2))
      C=VMIN/Z
      CBD=VMIN/ZBD
      CC=C+PLOSSC*RT/(VMIN*Z)
      CNL=2.0*VMIN/(XD+X)
      Y12=RF-RB
      Y12BD=RFBD-RBBD
      PLS=(CC**2)*RSHOT
      PLSNL=(CNL**2)*RSHOT
      PLRF=(C**2)*SLIP*RF
      PLRFNL=0.0
      PLRB=(C**2)*Y1*RB
      PLRBNL=(CNL**2)*D1
      PLR=PLRF+PLRB
      PLRNL=PLRFNL+PLRBNL
      Y13=(C**2)*Y12*(1.0-SLIP)
      Y13NL=(CNL**2)*Y12*(1.0-SLIP)
      Y13BD=(CBD**2)*Y12BD*(1.0-SLIP)
      PIN=PLS+PLR+PLOSSC+Y13
      PINNL=PLSNL+PLRNL+PLOSSC+Y13NL
      PLOSSFW=PLOSSSL+PFW
      POUT=Y13-PLOSSFW
      POUTBD=Y13BD-PLOSSFW
      SPEED=(1.0-SLIP)*SSPEED
      SPEEDBD=(1.0-SLIPBD)*SSPEED
      TORQ=112.7*POUT*0.08474/SPEED
      TORQBD=112.7*POUTBD*0.08474/SPEEDBD
      EFFD=POUT/PIN


      PFD=PIN/(CC*VMIN)
      EFFAPP=EFFD*PFD
      FULCAD=POUT*100.0/PW
      IF(FULCAD.GT.99.0.AND.FULCAD.LT.101.0)GO TO 4
      M=M+1
      GO TO 3
C
C O U T P U T
C
    4 PRINT 2,TBD,PLOSSSC,PLOSSST,PLOSSSL,TCLOSS,DJOUR,GSF,
     1      PFW,SLIP,SLIPBD,RF,RFBD,RB,RBBD,RT,RTBD,XF,XFBD,XB,
     2      XBBD,XT,XTBD,Z,ZBD,C,CBD,CC,CNL,PLS,PLSNL,PLR,PLRNL,
     3      PIN,PINNL,POUT,POUTBD,SPEED,SPEEDBD,TORQ,TORQBD,
     4      EFFD,PFD,EFFAPP,FULCAD
```

```
      SUBROUTINE AUX1
      DIMENSION KCA(10)
      COMMON/ONE/PM,PF,EFF,WF1,SCCN
      COMMON/TWO/FREQ,O,F,T1,NPP,NSS,NRS,AL,IBS,IRS,SSPEED
      COMMON/THREE/CO,W10,O1,CY1,W11,W13,R13,O14,O11,O10,T10
      COMMON/FUR/AST,ASC,ARC,ART,AAG,SCL,RCL,STL,RTL,AGL,PLAMDA1,PLAMDA
      COMMON/FIVE/AG,OR,O2,W20,CY2,T2,OS2,R21
      COMMON/SIX/C20,O24,W23,W21,T20,OB,WB,O21,CC
      COMMON/SEVN/SWA,NW,KD(10),LC,NCPIS,KKC,NCSPS,WF,VMIN,LSPP,NCA1S,N
      COMMON/EIGHT/X,NEC,RS,RKA,ESC,EST,BAG,XO,PKA,OMEAN,GAMMA,RROC,
     1     O2N
      COMMON/NINE/O5,O2,RSHCT,RRHCT,TORQ,O1,O3,O4,X11,TCLOSS,PFW,RRHCTP
      COMMON/TEN/WIREL,RSHCTA,RM,XMP,ZM,RRHCTPA,AA,THETAM,CLR,CM,XAPA
      READ 1,NNA,LDA,CL
1     FORMAT (2I2,F7.3)
      READ 2,(KDA(J),J=1,NNA)
2     FORMAT (10I2)
      CSR=RKA/(1.0+(O2*O2))
      CLR=1.0+O5*C2/(1.0+(O2*C2))
      RRHCTP=RRHCT*CSR
      RM=RSHCT+RRHCTP
      XMP=X*CLR
      ZM=SQRT(RM*RM+XMP*XMP)
      CM=VMIN/ZM
      THETAM=ATAN(XMP/RM)
      CCLM=CL/CM
      RA=(RM+ZM*CCLM)/(CCLM*CCLM-1.0)
      XAP=XMP/(CCLM*CCLM-1.0)
      A=SQRT(XAP/XMP)
      NECA=NEC*A
C
C     W I N D I N G   F A C T O R
C
      PI=3.14159
      KKCA=0
      WFCA=0.
      LLO=LDA
      DO 3,I=1,NNA
      KKDA=KKDA+KCA(I)
      WFCA=WFDA+KCA(I)*SIN((LLO-I)*PI/(2.[illegible]
      LLO=LLO-1
3     CONTINUE
      WFA=WFCA/KKDA
      NCA=NECA/WFA
      NCA1S=NCA/(KKDA*4*NPP)
      NCAA=NCA1S*KKCA*4*NPP
      NECAA=NCAA*WFA
      ANECAA=NECAA
      ANEC=NEC
      AA=ANECAA/ANEC
```

```
C
C AVERAGE COIL THROW
C
      MCTA=0
      MCA=0
      MLOA=LOA
      DO 4, K=1,NAA
      MCTA=MCTA+(MLOA-K)*NCA1S*KOA(K)
      MCA=KOA(K)*NCA1S+MCA
      MLOA=MLOA-1
4     CONTINUE
      AMC1A=MCTA
      AMCA=MCA

      ACTA=AMCTA/AMCA
C
C LENGTH OF A MEAN CONDUCTOR
C
      CONLMNA=AL+PI*DMEAN*GAMMA*ACTA/NSS
      WIREL=NCAA*CONLMNA/100.
C
C REQUIRED VALUE OF STATOR AUXILLIARY WINDING RESISTANCE
C
      RRHOTPA=RRHOTP*AA*AA
      RSHOTA=RA-RRHOTPA
      RSCOLDA=RSHOTA/1.15
      RWIREL=1000.*RSCOLDA/WIREL
C
C O U T P U T .
C
      PRINT 5,WFA,NCA1S,NCAA,NECAA,ACTA,CONLMNA,WIREL,RWIREL
5     FORMAT(1//29X,***AUXILIARY WINDING***,
     1       //10X,*WINDING FACTOR*,36X,*=*,F13.6,
     2      /10X,*NUMBER OF CONDUCTORS IN A "1" SLOT*,16X,*=*,
     3      /10X,*TOTAL CONDUCTORS*,34X,*=*,I6,
     4      /10X,*EFFECTIVE CONDUCTORS*,30X,*=*,I6,
     5      /10X,*AVERAGE COIL THROW*,32X,*=*,F13.6,
     6      /10X,*LENGTH MEAN CONDUCTOR (CM)*,24X,*=*,F13.6,
     7      /10X,*WIRE LENGTH ( M)*,34X,*=*,F13.6,
     8      /10X,*RESISTANCE PER 1000 METRES (OHMS)*,17X,*=*,F
      RETURN
      END
```

```
      SUBROUTINE AUX2
      COMMON/ONE/PW,PF,EFF,WF1,SCCN
      COMMON/TWO/FREQ,D,F,T1,NPP,NSS,NRS,AL,IBS,IRS,SSPEED
      COMMON/THREE/DO,W10,D1,DY1,W11,W13,R13,D14,D11,D18,T10
      COMMON/FUR/AST,ASC,ARC,ART,AAG,SCL,RCL,STL,RTL,AGL,PLAMDA1,PU
      COMMON/FIVE/AG,DR,D2,W20,DY2,T2,DS2,R21
      COMMON/SIX/C20,D24,W23,W21,T20,D8,W8,C21,CC
      COMMON/SEVN/SWA,NN,KD(10),LD,NCP1S,KKD,NCSPS,WF,VMIN,LSPP,NCAA
      COMMON/EIGHT/X,NEC,RS,RKA,BSC,BST,BAG,XO,PKA,CMEAN,GAMMA,RRO
     1      D2N
      COMMON/NINE/D5,D2,RSHCT,RRHCT,TORQ,C1,C3,C4,X11,TCLOSS,PFW,RR
      COMMON/TEN/WIREL,RSHOTA,RM,XMP,ZM,RRHOTPA,AA,THETAM,CLR,CM,YA
      READ 1,NM,DIAA,RWIRELA,ACM
      FORMAT(I2,F10.6,2F10.4)
      SAFULL=NCA1S*NM*DIAA*DIAA
      TD2N=D2N + SAFULL
      PCFULL = TD2N *100.0/SWA
      IF(PCFULL.LT.65.0) GO TO 3
      PRINT 2
      FORMAT (10X,*AUXILLIARY WINDING IS NOT SATISFACTORY*/)
      GO TO 6
      PRINT4
      FORMAT (/10X,*AUXILLIARY WINDING IS SATISFACTORY*/)
      RSCCLDA = WIREL*RWIRELA/1000
      RSHCTA = 1.15*RSCCLDA
      RAA = RSHOTA + RRHOTPA
      XAPA = AA*AA*XMP
      ZA = SQRT(RAA*RAA + XAPA*XAPA)
      THETAA = ATAN(XAPA/RAA)
      YA1 = THETAM - THETAA
      YA5 = SIN(YA1)
      YA6 = VMIN/ZA
      TS = YA5*AA*3.76*NPP*RRHOTP*CM*YA6*0.08474/FREQ
      RMA = RM + RAA
      XMA = XMP + XAPA
      ZMA = SQRT((RMA*RMA) + (XMA*XMA))
      CLA = CM*ZMA/ZA
      CURCEN = ACM/YA6
      PTSFULL = TS*100.0/TORQ
```

```
 OUTPUT

 PRINT 5,DIAA,RWIRELA,PCFULL,RM,XMP,ZM,CM,THETAM,RAA,XAPA,ZA,
1      YA6,THETAA,TS,CLA,CURDEN,PTSFULL
 FORMAT(10X,*DIAMETER OF CHOSEN WIRE (CM)*,22X,*=*,F13.6,
1      /10X,*RESISTANCE PER 1000 METRES (OHM)*,18X,*=*,F13.6,
2      /10X,*PER CENT SLOT FULLNESS*,28X,*=*,F13.6,
3      /10X,*CONSTANTS FOR LOCKED-ROTOR CONDITIONS:*,
4      /15X,*MAIN WINDING*,
5      /20X,*REAL COMPONENT OF TOTAL IMPEDANCE*,7X,*=*,F13.6,
6      /20X,*APPARENT REACTANCE*,22X,*=*,F13.6,
7      /20X,*TOTAL IMPEDANCE*,25X,*=*,F13.6,
8      /20X,*CURRENT IN ONE PHASE*,20X,*=*,F13.6,
9      /20X,*PHASE ANGLE BETWEEN CURRENT AND VOLTAGE*,1X,*=*,F13.
1      /15X,*AUXILLIARY WINDING*,
1      /20X,*REAL COMPONENT OF TOTAL IMPEDANCE*,7X,*=*,F13.6,
2      /20X,*APPARENT REACTANCE*,22X,*=*,F13.6,
3      /20X,*TOTAL IMPEDANCE*,25X,*=*,F13.6,
4      /20X,*CURRENT IN ONE PHASE*,20X,*=*,F13.6,
5      /20X,*PHASE ANGLE BETWEEN CURRENT AND VOLTAGE*,1X,*=*,F13.
6      /10X,*STARTING TORQUE (N.M.)*,28X,*=*,F13.6,
7      /10X,*ACTUAL LOCKED-ROTOR CURRENT*,23X,*=*,F13.6,
8      /10X,*CURRENT DENSITY*,35X,*=*,F13.6,
9      /10X,*PER CENT STARTING TO FULL-LOAD TORQUE*,13X,*=*,F13.6
 RETURN
 END
```

```
      SUBROUTINE COWNOPC
      COMMON/ONE/FW,PF,EFF,WF1,SCON
      COMMON/TWO/FREQ,D,F,T1,NPP,NSS,NRS,AL,IBS,IRS,SSPEED
      COMMON/THREE/CO,W10,D1,DY1,W11,W13,R13,C14,D11,D10,T10
      COMMON/FUR/AST,ASC,ARC,ART,AAG,SCL,RCL,STL,RTL,AGL,PLAMDA1,PLAMDA
      COMMON/FIVE/AG,DR,D2,W20,DY2,T2,DS2,R21
      COMMON/SIX/D20,D24,W23,W21,T20,DB,WB,D21,DC
      COMMON/SEVN/SWA,NW,KD(10),LD,NCP1S,KKD,NCSPS,WF,VMIN,LSPP,NCASES,
     1      D2N
      COMMON/NINE/C5,C2,RSHCT,RRHCT,TORQ,C1,C3,C4,X11,TCLOSS,PFW,RRLOSS
      COMMON/TEN/WIREL,RSHCTA,RM,XMP,ZM,RRHOTPA,AA,THETAM,CLR,CM,XAPA
      DIMENSION TNE(35)
      COMPLEX ZF,ZB,H10,H11,Z1,H12,H13,Z1A,ZT,ZTA,H14,H15,
     1H16,H17,H18,H19,H20,H21,H22,H23,H24,CUM,CA,CL
      READ 1,VA
    1 FORMAT(F10.4)
C
C EVALUATION OF APPARENT IMPEDANCES: TO FORWARD FIELD(ZF),
C AND TO BACKWARD FIELD(ZB),
C
      JM=1
      M=3
      TNE(1)=TNE(2)=0.
      SLIP=0.04
      IF(M.EQ.33)GO TO 33
      SLIP=SLIP+0.01
      GO TO 34
   33 PRINT 111
  111 FORMAT(////10X,*E R R O R ! !*///)
      GO TO 6
   34 H1=((C2/SLIP)**2)
      HH1=C3*H1
      H2=C1/SLIP
      HH2=C4 + HH1
      H3=1.+H1
      H4=2.-SLIP
      H5=((C2/H4)**2)
      H55=C3*H5
      H6=C1/H4
      H66=C4 + H55
      H7=1. + H5
      H8=H2/H3
      H88=HH2/H3
      H9=H6/H7
      H99=H66/H7
      ZF=CMPLX(H8,H88)
      ZB=CMPLX(H9,H99)
```

```
C
C EVALUATION OF PRIMARY CURRENTS IN VECTOR FORM
C
      H10=ZF*ZB
      H11=AA*H10
      Z1=CMPLX(RSHOT,X11)
      H12=ZF +ZB
      H13=AA*AA*H12
      XA=XAPA/CLR
      X11A=XA/(1. + PKA)
      Z1A=CMPLX(RSHOTA,X11A)
      ZT=Z1 + H12
      ZTA=H13 + Z1A
      H14=ZT*ZTA
      H15=H11**2

      H16=H14-H15
      H17=VMIN/H16
      EPSK=VA/VMIN
      H18=CMPLX(0.0,EPSK)
      H19=H18*H11
      H20=ZTA+H19
      H21=EPSK*ZT
      H22=(0.0,-1.0)
      H23=H22*H11
      H24=H21+H23
      CUM=H20*H17
      CA=H24*H17
      CL=CUM+CA
      A=REAL(CUM)
      B=AIMAG(CUM)
      GS=REAL(CA)
      HS=AIMAG(CA)
      H25=A*HS
      H26=B*GS
      H27=H25-H26
C
C COMPUTATION OF INPUTS
C
```

```
      CMS=CABS(CUM)
      CAS=CABS(CA)
      CLS=CABS(CL)
      PMP=VMIN*A
      PAP=VA*GS
      PL=PMP+PAP
C
C FORWARD,BACKWARD,AND NET TORQUE:(FRICTION AND WINDAGE INCLUDED)
C
      H28=CMS**2
      H29=(AA*CAS)**2
      H30=H28+H29
      H31=2.0*AA*H27
      H32=H30+H31
      H33=H30-H31
      TF=H32*H8
      TB=H33*H9
      IF(JM.EQ.1)GO TO 6
      TNE(M)=TF-TB
      IF(TNE(M-1).GT.TNE(M-2).AND.TNE(M-1).GT.TNE(M))GO TO 4
      M=M+1
      GO TO 3
4     SLIP=SLIP-0.01
      JM=1
      GO TO 34
6     TNET=TF-TB
      H34=1.0-SLIP
      H35=TNET*H34
      H36=(TCLOSS+PFW)*H34
      POUT=H35-H36
      EFF=POUT/PL
      PFC=PL/(VMIN*CLS)
      RPM=H34*SSPEED
      T=TNET/(2.0*3.14159*SSPEED)
      PCLRF=TF*SLIP
      PCLRB=TB*H4
      PMWCL=RSHOT*H28
      PAWCL=RSHOT*CAS*CAS
      TLOSS=PCLRF+PCLRB+PMWCL+PAWCL+H36
      H37=POUT+TLOSS
C
```

```
C PULSATING TORQUE
C
      TP=CABS(H10)*SQRT(H32*H33)
C
C O U T P U T
C
      PRINT 2, SLIP,VA,ZF,ZE,Z1,Z1A,ZT,ZTA,CUM,CA,CL,PMP,PAP,PL,
     1      TF,TB,TNET,POUT,EFFC,PFC,RPM,T,PCLRF,PCLRB,PMWCL,PAWCL,
     2      TLOSS,H37,TP
2     FORMAT(//17X,***COMBINED-WINDING PERFORMANCE CALCULATIONS***,
     1      //10X,*SLIP OF PERFORMANCE*,31X,*=*,F13.6,
     2      /10X,*AUXILLIARY WINDING VOLTAGE(VOLT)*,18X,*=*,F13.6,
     3      /10X,*IMPEDANCES(OHMS):*,
     4      /15X,*APPARENT TO FORWARD FIELD*,20X,2F7.3,
     5      /15X,*APPARENT TO BACKWARD FIELD*,19X,*=*,2F7.3,
     6      /15X,*PRIMARY LEAKAGE OF MAIN WINDING*,14X,*=*,2F7.3,
     7      /15X,*PRIMARY LEAKAGE OF AUXILLIARY WINDING*,8X,*=*,2F
     8      /15X,*TOTAL OF MAIN WINDING*,24X,*=*,2F7.3,
     9      /15X,*TOTAL OF AUXILLIARY WINDING*,18X,*=*,2F7.3,
     1      /10X,*CURRENTS(AMP):*,
     1      /15X,*MAIN WINDING*,33X,*=*,2F7.3,
     2      /15X,*AUXILLIARY WINDING*,27X,*=*,2F7.3,
     3      /15X,*LINE*,41X,*=*,2F7.3,
     4      /10X,*INPUT POWERS(WATTS):*,
     5      /15X,*MAIN WINDING PHASE*,27X,*=*,F13.6,
     6      /15X,*AUXILLIARY WINDING PHASE*,21X,*=*,F13.6,
     7      /15X,*TOTAL OR LINE*,32X,*=*,F13.6,
     8      /10X,*TORQUES(SYNCHRONOUS WATTS):*,
     9      /15X,*FORWARD FIELD*,32X,*=*,F13.6,
     /      /15X,*BACKWARD FIELD*,31X,*=*,F13.6,
     1      /15X,*NET INCLUDING FRICTION AND WINDAGE*,11X,*=*,F13.
     2      /10X,*OUTPUT POWER(WATTS)*,31X,*=*,F13.6,
     3      /10X,*EFFICIENCY(%)*,37X,*=*,F13.6,
     4      /10X,*POWER FACTOR*,38X,*=*,F13.6,
     5      /10X,*SPEED(RPM)*,40X,*=*,F13.6,
     6      /10X,*TORQUE(N.M.)*,38X,*=*,F13.6,
     7      /10X,*POWER LOSSES(WATTS):*,
     8      /15X,*FORWARD FIELD*,32X,*=*,F13.6,
     9      /15X,*BACKWARD FIELD*,31X,*=*,F13.6,
     1      /15X,*MAIN WINDING COPPER*,26X,*=*,F13.6,
     1      /15X,*AUXILLIARY WINDING COPPER*,20X,*=*,F13.6,
     2      /15X,*TOTAL*,40X,*=*,F13.6,
     2     /10X,*OUTPUT POWER AND LOSSES(WATTS)*,20X,*=*,F13.6,
     3      /10X,*PULSATING TORQUE(SYNC. WATTS)*,21X,*=*,F13.6)
      RETURN
      END
```

List of Symbols or Abbreviations Used in the Computer Programs of Appendix 19

Subroutine D2L

AL - Axial Length of machine, CM

BG - Air-gap maximum flux density, Tesla.

C - Output constant.
D - Stator bore diameter, cm.
D2L - Name of subroutine.

DDL - D_1^2L product, cm^3

EFF - Efficiency

FREQ - Frequency, Hz

NPP - Number of pole-pairs.

PF - Power factor

PW - Power rating, Watts.

Q - Ampere conductor per metre.

SSPEED- Synchronous speed, r.p.m.

WF1 - Winding factor for fundamental

X - Ratio of power to the synchronous speed.

Subroutine SPUNCH

A - A defined in Table 20.

B - B defined in Table 20.

DO - Outer diameter of machine.

D1 - d_1 defined in Table 20.

D10 - d_{10} defined in Table 20.

D11 - d_{11} defined in Table 20.

D14 - d_{14} defined in Table 20.

DY1 - d_{y1} defined in Table 20.

HSAD - Half slot angle in degree.

HSAR - Half slot angle in radian.

IBS - Indicates the type of slot.

NSS - Number of stator slots.

R13 - r_{13} defined in Table 20.

SPUNCH- Name of subroutine.

T1 - t_1 defined in Table 20.

W10 - W_{10} defined in Table 20.

W11 - W_{11} defined in Table 20.

W13 - W_{13} defined in Table 20.

Subroutine RPUNCH

AG - Air-gap length, cm.

CR - C_r defined in Table 21.

CT - C_t defined in Table 21.

D2 - D_2 defined in Table 21.

D20 - d_{20} defined in Table 21.

D21 - d_{21} defined in Table 21.

D24 - d_{24} defined in Table 21.

DB - d_b defined in Table 21.

DC - d_c defined in Table 21.

DR - The effective internal diameter of rotor.

DS2 - d_2 defined in Table 21.

DY2 - Rotor yoke depth.

IRS - Indicates type of rotor slot.

IRT - Indicates rotor type.

NRS - Number of rotor slot.

R21 - r_{21} defined in Table 21.

RECCBD- Depth of available rectangular copper bars.

RECCBW- Width of available rectangular copper bars.

ROCBD - Diameter of available round copper bars.

RPUNCH- Name of subroutine.

T2 - t_2 defined in Table 21.

W20 - W_{20} defined in Table 21.

W21 - w_{21} defined in Table 21.

W23 - w_{23} defined in Table 21.

WB - w_b defined in Table 21

Subroutine MAGCIR

AAG - Air gap area.

AGL - Length of air gap, effective.

ARC - Rotor core area.

ART - Rotor teeth area.

ASC - Stator core area.

AST - Stator teeth area.

CF - K in Table 7.

CF1 - K_1 in Table 7.

CF2 - K_2 in Table 7.

F - F in Table 7.

MAGCIR- Name of subroutine

PLAMDA1- λ_1 in Table 7.

PLAMDA2- λ_2 in Table 7.

PLAMDAP λ_p in Table 7.

RCL - Length of rotor core

SCL - Length of stator core

STL - Length of stator teeth

T10 - t_{10} in Table 7.

T20 - t_{20} in Table 7.

Subroutine MW1

ASCE - Slot cell insulation area

ASG - Gross slot area.

ATW - Top wedge insulation area.

BT - Assumed stator tooth density

CKW1 - Effective Conductors

DIAM - Calculated diameter of the wire to be used.

FT - Flux per pole

KD - The array of the number of sides in one-half of a distribution.

KKD - Total sum of the array KD

LD - Slot number of the last slot in a given distribution.

LSPP - Slot per pole

MW1 - Name of the subprogram.

NC - Number of conductors.

NCPS - Number of conductors per slot.

NCP1S- Number of conductors per one side of a slot.

NCSPS- Number of sides per slot.

NN - Half the number of conductor-occupied slots.

NW - Total number of wires in the slot.

SLFULL - Specified slot fullness.

SWA - Slot-winding area.

TFS - Thickness of fuller-board separator.

TSC - Slot cell thickness.

TTW - Top wedge thickness.

VMAX - Maximum rated voltage.

VMIN - Minimum rated voltage.

WF - Winding factor.

Subroutine MW2

BAG - Air gap flux density.

BELT - Belt leakage reactance divided by reactance constant.

BK - Belt leakage constant.

BRC - Rotor core flux density.

BRT - Rotor tooth flux density.

BSC - Stator core flux density.

BST - Stator tooth flux density.

CONLMN- Length mean conductor of main winding

CORK - Core path shortening factor

CSKEW - Skew factor

CX - Equation (5.19).

DIACT- Actual diameter chosen from the wire table.

DMEAN - Mean diameter of stator slots.

END - End leakage reactance divided by reactance constant.

FPP - Flux per pole

FZ - Slot constant.

FZR - Rotor slot constant.

FZS - Stator slot constant.

GAMMA - as defined in 5.4.1

GMK - Equation (5.28)

HAG - Air gap ampere-turn per metre.

HRC - Rotor core ampere-turn per metre.

HRT - Rotor tooth ampere-turn per metre.

HSC - Stator core ampere-turn per metre.

HST - Stator tooth ampere-turn per metre.

HTOT - Total sum of ampere-turn per metre.

MACT - Average coil throw.

MPP - Number of parallel paths.

MW2 - Name of the subprogram.

NDW - Number of strands of chosen wire.

NEC - Effective conductors.

NOC - Number of conductors.

NSP - Average number of slots per pole.

PK - Assumed K_p

PKA - Actual K_p

Q - Skew leakage factor.

RES - Resistance of chosen wire per 1000 metre.

RK - Assumed K_r.

RKA - Actual K_r.

RS - Stator winding resistance.

RSPS - Stator winding resistance per section.

SFM - Saturation factor.

SLFULLA- Actual slot fullness.

SLOT - Slot leakage reactance divided by reactance constant

SKEW - Skew leakage reactance divided by reactance constant

SSKEW- Skew angle in radian

X - Short-circuit reactance.

XO - Open-circuit reactance

XK - Reactance constant.

ZIGZAG - Zig-zag leakage reactance divided by reactance constant.

Subroutine MW3

ABAR - Cross-section of a single rotor bar.

ARING - Cross-section of ring.

BAR - Equation (5.39).

BARING - BAR + RING

DR - Mean diameter of the end ring.

MW3 - Name of subprogram.

NP - Number of poles.

RCPC - Resistance of commercially pure copper.

RESCON - Resistance constant.

RING - Equation (5.41).

RINGK - Equation (5.42).

RRDC - Rotor winding resistance (cold)

RRDH - Rotor winding resistance (hot)

SK - Skew distance.

Subroutine PERFCAL

C - Primary current.

CBD - Primary current at breakdown.

CC - Corrected primary current.

CNL - No-load current.

-

DJOUR - Journal diameter.

EFFAPP - Apparent efficiency.

EFFD - Efficiency of the designed machine (calculated)

FULOAD - Percentage ratio of output at performance to rated full-load.

GSF - Grade of steel factor.

IL - Indicates type of lamination.

ITE - Indicates if machine is totally enclosed fan-cooled.

01,02,03,04, - M_1, M_2, M_3, M_4 respectively in appendix 1.

PERFCAL - Name of subprogram.

PFD - Power factor (calculated).

PFW - Friction and windage losses

PIN - Input power

PINNL - No-load input power.

PLOSSC - Sum of stator core and stator teeth losses.

PLOSSFW - Total sum of high frequency and friction and windage losses.

PLOSSSC - Stator core loss.

PLOSSSL - Surface loss.

PLOSSST - Stator teeth loss.

POUT	-	Output power
POUTBD	-	Break down output power.
PLR	-	Total secondary loss.
PLRB	-	Secondary loss due to backward field.
PLRBNL	-	No-load secondary loss due to backward field.
FLRF	-	Secondary loss due to forward field.
PLRFNL	-	No-load secondary loss due to forward field.
PLRNL	-	No-load total secondary loss.
PLS	-	Total primary loss.
PLSNL	-	No-load total primary loss.
R	-	Sum of primary and secondary windings resistance (cold)
RB	-	Apparent resistance to backward field.
RBBD	-	Breakdown apparent resistance to backward field.
RF	-	Apparent resistance to forward field.
RFBD	-	Breakdown apparent resistance to forward field.
RHOT	-	R (hot).
RT	-	Total resistance.
RTBD	-	Total breakdown resistances
SLIP	-	Slip of performance.
SLIPBD	-	Breakdown slip.
SPEED	-	Speed of performance.
SPEEDBD	-	Breakdown speed.
SPO	-	Ratio of breakdown speed to synchronous speed.

TBD - Breakdown torque using veinott empirical formula.

TCLOSS - Total core loss.

TORQ - Revolving field theory torque at performance.

TORQBD - Revolving field theory breakdown torque.

XB - Apparent reactance to backward field.

XBBD - XB at breakdown

XF - Apparent reactance to forward field.

XFBD - XF at breakdown.

XT - Total reactances.

XTBD - Total breakdown reactances.

Z - Impedance.

ZBD - Breakdown impedance.

Subroutine AUX1

A - Ratio of effective conductors in auxiliary winding to that in main windings.

AA - Actual A.

AUX1 - Name of subprogram.

CCLM - Ratio of locked rotor current to current in the main winding.

CL - Locked rotor current.

CLR - Equation (8.6)

CM - Current in the main winding.

CONLMNA - Length mean conductor of auxiliary winding.

CSR - Equation (8.5).

KDA - The array of the number of sides in one-half of a distribution.

LDA - Slot number of the last slot in a given distribution.

MACTA - Average coil throw.

NCA - Number of conductors.

NCAA - Actual number of conductors.

NCA1S - Number of conductors in one side of a slot.

NECA - Effective conductors.

NECAA - Actual effective conductors.

NNA - Half the number of conductor occupied slots.

RA - Equation (8.12)

RM - R_m in table 22.

RRHOTP - Apparent rotor resistance (hot).

RRHOTPA - Actual apparent rotor resistance (hot).

RSCOLDA - Auxiliary winding resistance (cold)

RSHOTA - Auxiliary winding resistance (hot).

RWIREL - Calculated resistance of the auxiliary winding per 1000 metre.

THETAM - θ_m in table 22.

WFA - Winding factor of auxiliary winding.

WIREL - Wire length.

XAP - X_a^1 in table 22.

XMP - X_m^1 in table 22.

ZM - Z_m in table 22.

Subroutine AUX2

ACM - Area of auxiliary wire.

AUX2 - Name of subprogram.

CLA - Actual (or designed) locked rotor current.

CURDEN - Current density

DIAA - Diameter of chosen wire.

NM - Number of sides in the fullest slot.

PCFULL - Slot fullness in the fullest slot.

PTSFULL - Percent ratio of starting torque to full-load torque.

RAA - Actual R_a

RMA - Actual R_m

RWIRLA - Resistance per 1000 metre of the chosen wire.

THETAA - θ_a in table 22.

TS - Starting torque.

XAPA - Actual X_a^1

XMA - Actual X_m^1

ZA - Z_a in table 22.

ZMA - Actual Z_m in table 22.

Subroutine COWNDPC

CA - Auxiliary winding current.

CL - Line current

CM - Main winding current.

COWNDPC - Name of subprogram

EFF	-	Efficiency
PAP	-	Auxiliary winding phase input power.
PAWCL	-	Auxiliary winding copper loss.
PCLRB	-	Backward field power loss.
PCLRF	-	Forward field power loss.
PF	-	Power Factor.
PL	-	Total or line power
PMP	-	Main winding phase input power
PMWCL	-	Main winding copper loss
POUT	-	Output power
RPM	-	Speed.
T	-	Torque (N.M.)
TB	-	Backward field torque.
TF	-	Forward field torque.
TLOSS	-	Total power loss.
TNET	-	Net torque including friction and windage.
TP	-	Pulsating torque
VA	-	Auxiliary winding supply voltage.
Z1	-	Primary leakage of main winding impedance.
Z1A	-	Primary leakage of auxiliary winding impedance.
ZB	-	Apparent to backward field impedance.
ZF	-	Apparent to forward field impedance.
ZT	-	Total impedance of main winding.
ZTA	-	Total impedance of auxiliary winding.

APPENDIX 20[1]

TABLE OF WIRE

(Compiled from Phelps-Dodge, General Electric, and Westinghouse sources)

Gage no.	Diameter, bare	Diameter over insulation								Weight, lb/1000 ft				Area in circular mils	Resistance in ohms/1000 ft at 25°C
		Enam. or single formvar	Double formvar	Quadruple formvar	Single paper enam.	Single cotton enam.	Single silk (or Nylon) enam.	Double glass bare	Single glass heavy formvar	Bare	Double formvar	Single cotton enam.	Double glass bare		
13	0.072	0.0738	0.0753	0.0779	0.077	0.0786	.....	0.0795	0.0803	15.66	15.9	16.0	16.3	5178	2.042
14	0.064	0.0659	0.0673	0.0699	0.0691	0.0707	.....	0.0716	0.0723	12.43	12.6	12.7	13.0	4107	2.575
15	0.057	0.0588	0.0602	0.0628	0.062	0.0639	0.0604	0.0646	0.0652	9.858	10.05	10.1	10.3	3257	3.247
16	0.051	0.0525	0.0539	0.0563	0.0557	0.0571	0.0541	0.0582	0.0589	7.818	7.98	8.06	8.24	2583	4.094
17	0.045	0.0469	0.0482	0.0506	0.0501	0.0515	0.0488	0.0528	0.0532	6.20	6.34	6.41	6.56	2048	5.163
18	0.040	0.0418	0.0429	0.0456	0.045	0.0466	0.0434	0.0478	0.0482	4.917	5.02	5.10	5.23	1624	6.51
19	0.036	0.0374	0.0386	0.0409	0.0406	0.0421	0.039	0.0434	0.0436	3.899	4.00	4.06	4.18	1288	8.21
20	0.032	0.0334	0.0346	0.0368	0.0366	0.038	0.035	0.0395	0.0396	3.092	3.17	3.24	3.34	1022	10.35
21	0.0285	0.0299	0.031	0.0331	0.0331	0.0345	0.0313	0.036	0.0360	2.452	2.51	2.57	2.67	810.1	13.05
22	0.0254	0.0267	0.0278	0.0298	0.0299	0.0313	0.0283	0.0328	0.0328	1.945	1.99	2.05	2.14	642.4	16.46
23	0.0226	0.0239	0.0249	0.0269	0.027	0.0284	0.0254	0.0301	0.0299	1.542	1.58	1.63	1.72	509.5	20.76
24	0.0201	0.0213	0.0224	0.0243	0.0245	0.0259	0.0229	0.0276	0.0274	1.223	1.26	1.31	1.39	404.0	26.17
25	0.0179	0.0191	0.0201	0.022	0.0215	0.0233	0.0207	0.0252	0.0233	0.9699	0.998	1.04	1.12	320.4	32.60
26	0.0159	0.0170	0.018	0.0198	0.0194	0.021	0.0186	0.0212	0.0218	0.7692	0.793	0.827	0.900	254.1	41.02
27	0.0142	0.0153	0.0161	0.0178	0.0177	0.0193	0.0169	0.0195	0.0194	0.610	0.850	0.662	0.727	201.5	52.48
28	0.0126	0.0136	0.0145	0.016	0.016	0.0178	0.0152	0.0179	0.0177	0.4837	0.501	0.532	0.588	159.8	66.17
29	0.0113	0.0122	0.013	0.0145	0.0146	0.0164	0.0138	0.0166	0.0162	0.3836	0.396	0.427	0.477	126.7	83.44
30	0.0100	0.0109	0.0116	0.0131	0.0133	0.0151	0.0125	0.0153	0.0149	0.3042	0.315	0.344	0.387	100.5	105.2
31	0.0089	0.0098	0.0105	.....	.....	0.0139	0.0113	0.0142	0.0137	0.2413	0.251	0.278	0.314	79.7	132.7
32	0.0080	0.0088	0.0094	.....	.....	0.013	0.0104	0.0133	0.0126	0.1913	0.198	0.224	0.255	63.21	167.3
33	0.0071	0.0079	0.0085	.....	.....	0.0119	0.0094	0.0124	0.0117	0.1517	0.158	0.182	0.208	50.13	211.0
34	0.0063	0.0071	0.0078	.....	.....	0.0111	0.0086	0.0116	0.0108	0.1203	0.126	0.148	0.169	39.75	266.0
35	0.0056	0.0063	0.0067	.....	.....	0.0102	0.0078	0.0109	0.0100	0.0954	0.0996	0.120	0.138	31.52	335.5
36	0.0050	0.0057	0.0060	.....	.....	0.0093	0.0072	0.0103	0.0093	0.0757	0.0791	0.100	0.113	25.00	423.0
37	0.0045	0.0051	0.0055	.....	.....	0.0087	0.0066	0.0098	0.0087	0.060	0.0628	0.080	.....	19.83	533.4
38	0.0040	0.0045	0.0049	.....	.....	0.0082	0.0061	0.0093	0.0081	0.0478	0.0498	0.065	.....	15.72	672.6
39	0.0035	0.0040	0.0043	.....	.....	.....	0.0055	0.0088	0.0076	0.0377	0.0397	0.060	.....	12.47	848.1

[1] Reproduced from C. G. Valeott, "Fractional Horsepower Electric Motors," McGraw-Hill Book Company, Inc., New York, 1948, p. 521.

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