DEVELOPMENT AND PERFORMANCE CHARACTERISTICS OF IMPROVED RELUCTANCE MOTOR

A DISSERTATION

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

By

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DEDICATED
TO
MY PARENTS

CANDIDATE'S DECLARATION

I hereby, certify that the work which is being presented in the dissertation entitled, DEVELOPMENT AND PERFORMANCE CHARACTERISTICS OF IMPROVED RELUCTANCE MOTOR, in partial fulfilment of the requirements for the award of the degree of MASTER OF ENGINEERING IN ELECTRICAL ENGINEERING with specialization in POWER APPARATUS AND ELECTRIC DRIVES, submitted in the Electrical Engineering Department, University of Roorkee, Roorkee (India), is an authentic record of my own work carried out for a period of about seven months from July 1988 to February 1989, under the supervision of Dr. Bhim Singh, Reader, Electrical Engineering Department, University of Roorkee and Sri S.P. Srivastava, Lecturer, Electrical Engineering Department, University of Roorkee, Roorkee (India).

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

Dated 23-8 ,1989

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

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ABSTRACT

The dissertation deals with the design, development and performance investigation of a polyphase reluctance motor. The investigations in the present work are made at normal supply frequency (50 Hz) as well as at variable frequency.

The whole work of dissertation has been catagorised as introduction, computer aided design, Development of machine and its parameter determination, performance characteristics and conclusions and suggestions for further work. In chapter 1, an introduction to reluctance motor and the literature review is given . In chapter 2 all the computational design aspects are described in detail. Chapter 3 deals with the details of developed machine as well as their method of determination. In chapter 4 various performance characteristics at different frequencies are drawn. Where as the concluding chapter 5 deals with the main conclusions and suggestions for further work in this field.

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CHAPTER - 1

INTRODUCTION

1.1 GENERAL

Reluctance motors were known to exists forover one and, a half century. But their principle of operation was less understood and they were comparatively to other a.c. motors, less popular because of their poor performance.

The reluctance motor operates on the principle of variable reluctance and has been defined by the ASA as "A synchronous motor, similar in construction to an Induction motor the which the member carrying the secondary circuit has salient pole without d.c. excitation, which starts as an induction motor and operates normally at synchronous speed'.

The progressive demand of constant speed drive in industries in recent years has resulted as a boon for the reluctance motors. Fresh efforts are under way to improve the design of these machines, with a view to obtain improved overall performance. Reluctance motors have recently stood on a competitive footing with other types of a.c. machines. This is mainly due to the various modern designs announced, which relived the motor from construction's complexity and proved to yield good performance levels.

Reluctance motors are usually built in small sizes and for low ratings. It is a normal practice to describe reluctance motor in terms of induction motor. Reluctance motors are very simple in construction and they have wound stator similar to an induction motor, the rotor being constructed to provide two axis, namely direct axis and quadrature axis, both of widely differing in magnetic reluctances. The periodic variation of reluctances in the magnetic circuit results in a 'Reluctance-torque' which finally causes the machine to rotate at a constant speed.

Many drives require perfectly constant speed operation in spite of fluctuation in load and/or supply conditions. A normal Induction motor can not maintain constant speed with respect to change in load while a normal synchronous motor requires a d.c. excitation involving the complexity of slip rings and brushes etc. to feed them. But a reluctance motor runs by the reaction torque due to pole saliency and it operates at synchronous speed, requires no d.c. excitation and is pulled into synchronism automatically. Thus a reluctance motor eliminates the disadvantages of both synchronous motor and induction motor for certain applications.

Recently, reluctance motors found numerous fields of applications. This is mainly owed to its simplicity in construction, robustness and speed constancy. Following are the main advantages offered by a reluctance motor:

(i) Reluctance motors are robust, reliable and cheap in construction.

(ii) Reluctance motors do not require d.c. excitation, as it is required by a synchronous motor for its field excitation.

(iii) Reluctance motors give constant speed, irrespective of load and/or supply conditions.

(iv) Using static frequency converters, these motors can be used in control systems for positioning or speed control, or for a combination of both.

(v) Minimum inspection, and maintenance are required for a reluctance motor.

Due to above advantages, reluctance motors now a days became a common part in several drives. Reluctance motors can be used in control systems and allied fields i.e. for positioning and speed control or for a combination of both. The reluctance motors are the best suited one amoung other a.c. motors in case of:

(a) Electric clocks,

(b) Precision control of machine tools,

(c) Textile industries,

(d) Fiber industries,

(e) Recording instruments,

(f) Glass factories,

(g) Drives for alternators supplying computer systems,

(h) Variable speed drives using variable frequency supply, for ex. in placing nuclear rods in reactors etc.

1.2 LITERATURE REVIEW

It is interesting to look into the cronology of development of reluctance motors, as a large number of attempts have been made by many investigators [1-30] on the design, development, theory and analysis of reluctance motors to improve their starting, steady state and transient performance.

The paper by Lawrenson et al [1] deals with a reluctance machine in which, the radial poles of a conventional machine are replaced by circumferential segments. Here working from the flux distribution in the air gap, general equations for the synchronous performance of reluctance machine were developed. These are then used in the comparision of new and conventional reluctance machine. Though the investigation is devoted chiefly to fixed, normal frequency operation, consideration is also given to machine performance under varying frequency condition. Additionally a new method for the experimental determination of the axis reactance of salient pole machine is described.

In an another paper Lawrenson et al have [3] described of some of the improvements that have been achieved both experimentally and theoritically, in reluctance motors with purely segmental rotors. Careful attention is given to the asynchronous performance characteristics. It also states that efficiencies upto 90 % may be expected even in relatively small reluctance machines. It further states that losses due to the generation of high frequency currents are small. The performance claimed here have been fully confirmed by tests on a commercial machine of 10 H.P. rating.

load current, and pullout current. A method is given by which the entire motor performance may be calculated through knowledge of machine admittance. Comparision of calculated and measured values are also made here.

A theoritical and practical studies are given to reluctance motors having rotors constructed from axially laminated anistropic cores, by Cruickshank and Anderson [10]. The experimental work has led to the development of a practical motor of high performance, capable of a large maximum output without detriment to overall performance or stability.

The nonlinear programming approach is used to predict an optimum design for a large reluctance motor of the flux guided type, in the paper presented by Nagrial [13]. The power method along with the SUMT technique is employed to optimize the design.

Lawrenson et al [15] had explored the theory of salient doubly electronically switched reluctance motors. It is demonstrated that the machine provides the basis for fully controllable variable speed system, which are shown to be superior to conventional system in many respects. The motor attains all the advantages normally associated with induction motors and brings sufficient economy in the drive electronics. The basic modes of operation, analysis, design consideration and experimental results from a range of prototype motors upto 15 KW at 750 rev/min are described.

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The principles and design methods of a new type of reluctance motor are described by Fong and Hetsui [4].They stated that the rotor of the new machine has one system of flux barriers per pole pair and is nonsegmented. The developed machine combines the advantages of simplicity of manufacture with a satisfactory performance.

Chalmers and Mulki [5], have described the design of reluctance motors, having unlaminated rotors and it gives test results for a range of motors. Here mainly two designs are considered, respectively, salient pole rotor and rotors with flux barriers.

Optimum steady state and transient performance of reluctance motor is explained in the investigation made by Nagrial and Lawrenson [6]. In their another companion paper [7], they have discussed about an improved reluctance motor.

Chalmers and Mulki [8] have reported preliminary performance attainments of robust and potentially in expensive prototypes which use unlaminated rotors eliminating the need for conventional squirrel cage Embedded windings. In their another paper they [11] have described regarding design and performance of reluctance motor with unlaminated rotors having considered two types of designs.

Honsinger [9] have analyzed the performance of reluctance motor using direct and quadrature axis components circle diagrams and machine admittance. Specific equations are deduced for pullout torque, maximum power factor, no load current, and pullout current. A method is given by which the entire motor performance may be calculated through knowledge of machine admittance. Comparision of calculated and measured values are also made here.

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Honsinger's [16] work has received the attention of many investigators because of its outstanding usefulness. Here equations for the self inductances L_d and L_q of a reluctance machine having flux barriers and cut outs are developed. An electromagnetic model of the reluctance machine is postulated. Flux densities are found proper in the air gap the cutouts, and the barriers. A comparision is also made between measured and calculated results.

Ramamoorthy and Rao [17] have solved the design optimization of reluctance motor as the nonlinear programming problem using Zangwill's exterior penalty function formulation and powell's unconstrained minimization technique. The performance characteristics of the optimally designed 2 H.P., 3 phase motor are also presented.

The tests described by Kadar [18], show that the reluctance machine may be operated as an independent or isolated generator at a predetermined voltage and frequency, with sinusoidal waveform and by means of capacitive excitation. The paper further states that practically a flat external load voltage characteristic can also be obtained by proper choice and arrangement of capacitors.

An adequate understanding of the close relation existing between performance characteristics and machine parameters is essential for designing any reluctance motor is stated by Uezato et al [19,20]. They have analyzed the effects of rotor structure and rotor constants on the synchronous and asynchronous operating characteristics of a solid rotor three phase reluctance motor with slits on the pole axis. The calculated characteristics are also compared with the measured ones. The effect of short circuit winding attached to the salient poles is also studied briefly here. Where as the second attempt deals mainly with, how the steady state stability of small solid rotor three phase reluctance motor is affected by the machine parameters. The effect of certain typical machine parameters have been quantitatively demonstrated which may be instrumental in designing the motor.

The performance characteristics of reluctance motors employing rotors with different shapes are presented by Hassan et al[21]. Here six rotors were considered, five of them were of conventional type while sixth one was of segmental type. It also gives a comparision between the different performance characteristics of the motor which leads to useful conclusion enabling designers to choose between the different types to fulfill different drive requirement.

Singh et al [22] have reported in a theoritical appraach to show improvement in the design for optimum steady state performance of a polyphase reluctance machine.

Hassan et al [23] have investigated the effect of motor indivisual parameters on number of pole slipping occuring when starting the motor. Useful conclusions have stemmed, which are considered to be of a good aid to both the designer and the user of these machines. The improved design of reluctance motors in which starting is achieved with no need for extra starting cage windings is shown in the another paper [25] by the same author. They have stated that starting in this type of motor is achieved by virtue of the induced currents in the rotors solid body.

Consideration of transient behaviour of reluctance machines focuses attention in the attempts made by Uezato et al [26] and Lawrenson et al [27]. The main object of these papers is to build up a general picture of basic features of the transient behaviour of reluctance machine it also gives proper attention to rotor windings, and digital solution of the differential equations of the machine, in which each rotor circuit is indivisually represented. Simple model is used to demonstrate initial switching transients, asynchronous torque pulsations and their relationship to the average asynchronous torque/speed curve.

The stability study of reluctance motors have been carried out using analogue computer by Cruickshank et al [28]. They have described how the limits of stability in reluctance machine are known to be narrow, especially in machines of improved design with high reactance ratio. Here the machine equations are developed using a frame of reference fixed with respect to the rotor. Machine performance is then simulated on an analogue computer. A large number of freely accelerating torque speed curves are then generated for different values of machine parameters. Then the stability limits are usefully be investigated with the aid of computed and measured freely accelrating torque/speed curves.

Some other attempts are also made on the stability studies of reluctance machines by Lawrenson [29] and by Honsinger [30]. Lawrenson has reported an experimental and theoretical study of rotor oscillations in reluctance machine, with particular reference to variable frequency system. Where as in the paper presented by Honsinger, stability criteria for reluctance motors are derived in terms of machine parameters, voltage, applied frequency, inertia etc. Simplified equations are also found that enable physical interpretation of the cause of instability.

1.3 SCOPE OF PRESENT WORK

Exhaustive literature survey reveals that little research work has been reported on the overall performance of the reluctance machine, and its variable frequency operation. Moreover, what ever concerned literature is available more theoritical approach is used to study the same. Therefore, a need is felt to develope a new approach for the design of three phase reluctance motor to give improved performance.

An attempt is, therefore, made in the present inves - tigation to study the steady state synchronous performance of a polyphase improved reluctance motor, at fixed frequency and at variable frequency.

The main objectives of the proposed work are -

i. To develope a computer algorithm to design a polyphase reluctance motor for its improved overall performance.

ii. To fabricate different rotors based upon the above obtained computer aided design results.

iii. To study experimentally the performance of developed reluctance machine operating at normal and at variable frequency.

Here, first of all a computer algorithm based upon three different criteria is developed to obtain the design for improved overall performance. Based upon computer aided design values, different rotors are fabricated using mild steel. The performance of the reluctance machine using above designed rotors is then studied experimentally at normal and at variable frequency.

<u>Outline of chapters</u>

In the first chapter, the importance of the reluctance motor is proved along with its exhaustive literature survey, and the main objectives of the propesed work are enlisted.

In the second chapter, a computer technique based upon three different criteria is developed to get design for improved overall performance of polyphase reluctance motor.

In the third chapter, the experimental machine is developed and various tests are conducted over it to find out its parameters.

In the fourth chapter, different performance characteristics at normal operating frequency and at variable frequencies are obtained and the effect of different parameters on the performance of the machine is also depicted.

In the last and concluding chapter, the main conclusions are discussed and suggestions for further work are enlisted.

CHAPTER -2

COMPUTER AIDED DESIGN

2.1 GENERAL

In this chapter an attempt is made on the development of an analytical technique to obtain the design of three phase reluctance motor for optimum steady state synchronous performance by selecting the rotor parameters with solid and simple rotor structure. Three different criteria are considered here, to achieve optimum rotor parameters. The computed design results are presented and discussed in detail.

2.2 THEORY

The stator of reluctance motor is normally similar to three-phase induction motor and most of the investigators [1-32] have suggested that there is no appreciable gain by changing the stator parameters of three phase reluctance motors. Therefore, in the present investigation, a wound stator of standard three phase, four pole cage induction motor is considered. However, there are three main rotor parameters which mainly affect its synchronous performance. First and the most important parameter is pole arc to pole pitch ratio (β), which affects its performance upto large extent and is considered as main variable. The second parameter is the depth of channel at quadrature axis of rotor (G), which effects the performance only upto some extent and a suitable value of it is considered here. The third main parameter is length of air gap which must be as minimum as possible and is normally limited by mechanical considera - tion and therefore it is taken same as of cage induction motor.

Taking pole arc to pole pitch ratio (β) as main parameter, as a variable, three criteria are considered in the present investigation to seek the improved design of polyphase reluctance motor:

Criterion 1 - The main aim, in this criterion, is to get minimum stator current for a given output power.

Criterion 2 - The main objective in this criterion, is to get the maximum output power for a given stator current which is specified by stator design.

Criterion 3 - The main goal in this criterion, is to obtain maximum output power for a given total losses of motor, which it may dissipate with safe tem - perature rise.

<u>Criterion 1</u>

In this criterion, main aim is to develope a high performance polyphase reluctance motor in terms of high efficiency and power factor. As reported by Lawrenson et al [1,3,6,7,15] that the reluctance motor may develope same output power as a three-phase cage induction motor by improving its rotor design. Therefore, in this criterion for a constant output power equal to the rating of an induction motor, the armature current is minimized by varying the rotor parameters. Being the input voltage constant it will result minimum input KVA for a specified output power. Inherently, the achieved design will provide high performance reluctance motor in terms of higher efficiency and power factor.

For this purpose, the mathematical formulation based upon two axis theory of salient pole synchronous machine under steady state condition is adopted [19]. From which the expression of input power (P_i) in terms of machine parameters and load angle (δ) is as

$$P_i = mV^2\{(X_d - X_q)\ \sin 2\delta + 2r_a\}/\{2(X_d . X_q + r_a^2)\} \qquad \ldots(2.1)$$

where

m = No. of phases,

V = Applied voltage/phase

X_d = Direct axis reactance

X_q = Quadrature axis reactance

δ = Load angle

r_a = Stator winding resistance/phase.

Here, expression for direct axis and quadrature axis reactances may be written as

$$X_d = X_\ell + X_{md} \qquad \text{and } X_{md} = X_c . CD$$

where,

$$CD = A + [\{\beta + \sin(\beta.\pi)\}/\pi].(1-A)$$

Therefore,

$$X_d = X_l + X_c[A + \{\beta + \sin(\beta.\pi)/\pi\}.(1-A)] \qquad ...(2.2)$$

Similarly,

$X_q = X_l + X_{mq}$, and

$X_{mq} = X_c . CQ$, where

$$CQ = A + [\{\beta - \sin(\beta \times \pi)\}/\pi].(1-A)$$

Therefore,

$$X_q = X_l + X_c[A + \{\frac{\beta - \sin(\beta \times \pi)}{\pi}\} \times (1-A)] \qquad ...(2.3)$$

where in (2.2) and (2.3) different parameters are defined as

$A = G1/G$

G = channel depth,

$G1$ = length of air gap,

β = Pole arc/pole pitch, and

X_c = Magnetising reactance/phase

The armature current (I), minimization of which is the aim, in this criterion, may be expressed as

$$I = V\{(X_q \cos\delta - r_a \sin\delta)^2 + (X_d \sin\delta + r_a(\cos\delta)^2\}^{1/2}/(X_d.X_q + r_a^2) \qquad ...(2.4)$$

The expression of output power (P_o) which is at motor shaft, may be obtained from input power (P_i), the armature ohmic loss (I^2ra), core loss and mechanical losses.Therefore, it may be expressed as

$$P_o = \left[\frac{mV^2(X_d - X_q)\{(X_d . X_q - r_a^2)\sin 2\delta + r_a(X_d + X_q)\cos 2\delta - r_a(X_d - X_q)\}}{\{2(X_d . X_q + r_a^2)^2\}} \right] - P_{LN}$$

...(2.5)

where,

P_{LN} = No load losses, which includes core losses and mechanical losses.

The above equation (2.5) may be simplified as

$$Po = A_1 \cos 2\delta + A_2 \sin 2\delta - A_3 \qquad ...(2.6)$$

or

$$P_o = A_4 \cos 2(\delta_{max} - \delta) - A_3 \qquad ...(2.7)$$

where

δ_{max} is the load angle for output power at pull out and may be expressed as below,

$$\delta_{max} = 0.5 \tan^{-1}(A_2/A_1) \qquad ...(2.8)$$

For a given output power (P_R), the load angle (δ_R) may be calculated from the expression derived from equations (2.6), (2.7) and (2.8).

$$\delta_R = \delta_{Max} - 0.5 \cos^{-1}\{(P_R + A_3)/A_4\} \qquad ...(2.9)$$

where different coefficients $A_1, A_2 \ldots A_5$ are

$$A_1 = A_5\ (X_d + X_q)\ r_a\ ,$$
$$A_2 = (X_d \cdot X_q - r_a^2) \cdot A_5,$$
$$A_3 = A_5 (X_d - X_q) \cdot r_a + P_{LN},$$
$$A_4 = (A_1^2 + A_2^2)^{1/2}, \text{ and}$$
$$A_5 = mV^2 (X_d - X_q) / \{2 (X_d \cdot X_q + r_a^2)^2\}$$

For the load angle (δR) at a specified power (P_R), the armature current (I_R) may be computed from equation (2.2) for a particular design.

Here, important point to be considered is that, if the developed power at pull out of a particular design is less than the specified power (P_R), then that design may be discarded during current (I) minimization process. The developed power at pull out (P_{PO}) may be obtained from equations (2.7) and (2.8) for any design.

Criterion 2

In the second criterion, main aim is to achieve optimum output power at a specified stator current (I_s).In the stator design of this type of motor, there are two loadings one being the magnetic loading and become fixed for the given voltage and frequency. The other one being the electric loading and for fixed stator structure, it is only dependent upon the current in the stator. The size of the conductor in stator winding is already decided for a given current (I_s). Therefore, the goal in this case, is to get maximum possible output power (P_{SI}) for a specified stator current (I_s) dictated by stator conductor.

For this purpose, it is essential to discard all those designs have no load current greater than and/or current at pull out less than the specified current (I_s). The no load and pull out currents may be easily computed from equation (2.4) by simply substituting suitable value of load angle.

For a particular design, to compute output power for a given stator current (I_s), first load angle (δ_s) may be obtained and then output power (P_{SI}) for that load angle (δ_s) may be computed. The stator current may be explicitly expressed in terms of load angle as follows:

$$I = B_1(B_2 \cos 2\delta + B_3 \sin 2\delta + B_4)^{1/2} \qquad (2.10)$$

where coefficients B_1, B_2 and B_3 are as follows

$$B_1 = \frac{V}{\{X_q(K_x + K_r^2)\}}$$

$$B_2 = 0.5\,(1-K_x^2),$$

$$B_3 = K_r\,(K_x-1),$$

$$B_4 = 0.5\,K_x^2 + K_r^2 + 0.5, \text{ and}$$

$$K_x = X_d/X_q,\; K_r = r_a/X_q$$

Equation (2.10) may be further solved for a specified current (I_s) to compute load angle (δ_s) in similar manner as done in criterion-1. From which load angle (δ_s) can be expressed as

$$\delta_s = \delta_{SMI} - \tan^{-1}[\{B_5^2 - (B_6 - B_4)^2\}^{1/2} / (B_6 - B_4)] \quad \ldots(2.11)$$

where,

$$\delta_{SMI} = 0.5 \tan^{-1} (B_3/B_2),$$

$$B_5 = (B_2^2 + B_3^2)^{1/2}, \text{ and}$$

$$B_6 = (I_s/B_1)^2$$

Using this load angle (δ_s) for a specified stator current (I_s), the output power (P_{SI}) may be calculated from equation (2.6).

Criterion 3

The main aim in the criterion is to get maximum (optimum) output power for a specified total losses (P_{LR}) equal to full load losses of the same rating cage induction motor. For which, the total losses may be expressed in terms of load angle as follows.

$$P_L = C_1 \cos 2\delta + C_2 \sin 2\delta - C_3 \quad \ldots(2.12)$$

where

$$C_1 = - A_1$$

$$C_2 = A_5(X_d.X_q + r_a^2) - A_2$$

$$C_3 = A_3 - 2A_5\, r_a(X_d.X_q + r_a^2)$$

The equation (2.12) may be solved for specified losses (P_{LR}) to compute load angle (δ_{LR}) in similar way as in first criterion and then corresponding output power (P_{SL}) from equation (2.6).

Here it is again important to curtail all those designs which have no load losses greater and/or losses at pull out less than specified losses (P_{LR}). These losses may be easily computed from equation (2.12) by substituting suitable values of load angle.

2.3 COMPUTATION

As the large number of computations are involved for obtaining the optimum design values of a threephase reluctance motor based upon above three described criteria, the use of computer becomes essential. Hence a computer algorithm is developed for this purpose.

In this approach the simple and easy incremental search method based on iterative procedure is employed to find out the required designs for different criteria. Using the above mathematical formulation, a general computer programme is developed and flow chart of which is shown in Fig. 2.1.

In the programme after reading the stator details and different specified parameters like rated power (P_R), rated voltage (V), leakage reactance (X_L), no load losses (P_{IN}), rated frequency (F_R), number of poles (P) and magnetising reactance (X_C), whose values are given in Appendix-1 for the motor considered. It selects the rotor parameters for a particular design and then it selects the particular criteria out of following three:

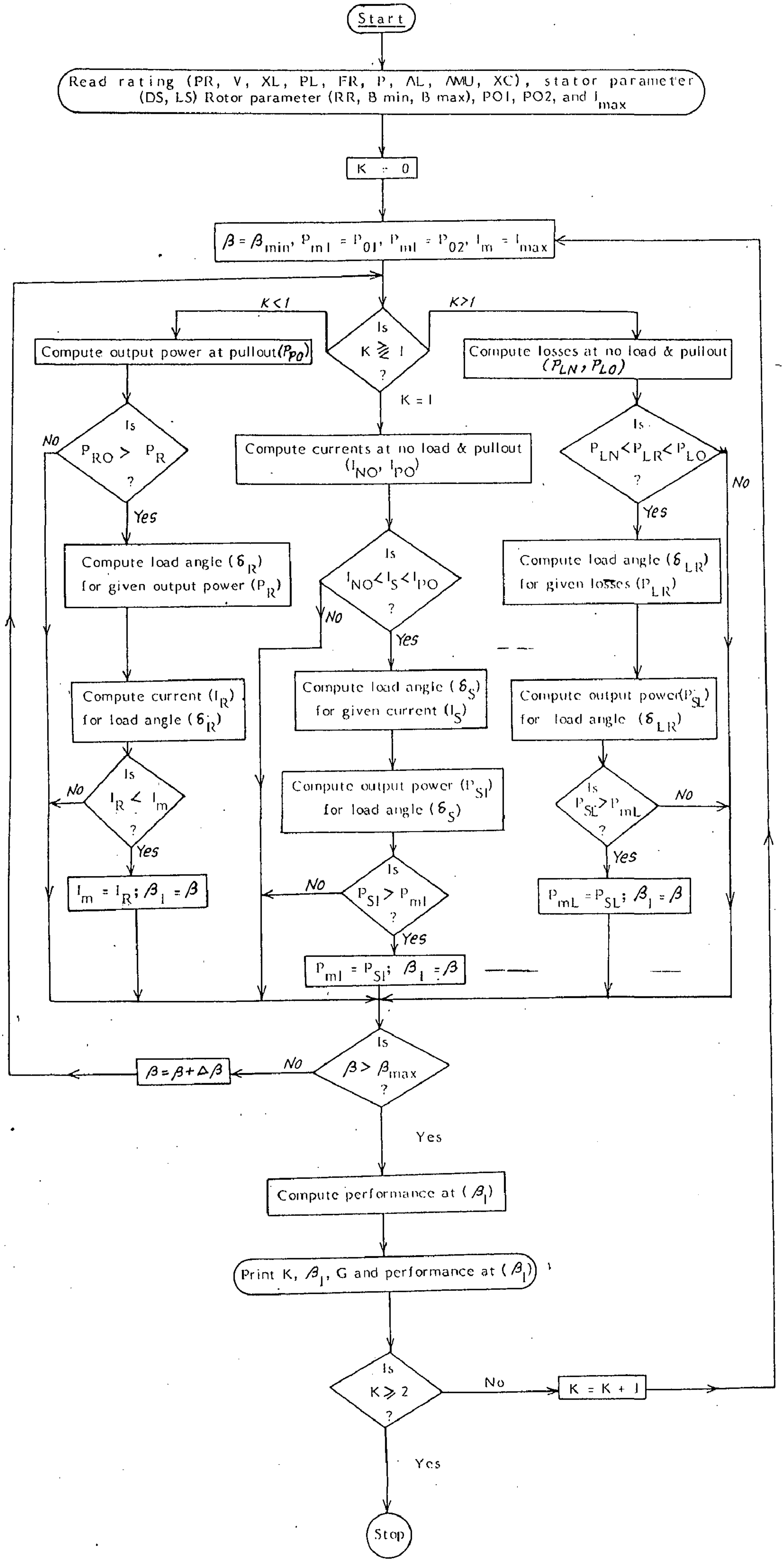

Fig. 2.1 - Flow Chart for Computer Algorithm

Criterion -1 To obtain the minimum stator current for a given output power (P_R).

Criterion -2 To obtain the maximum output power for a given stator current (I_S).

Criterion -3 To obtain the maximum output power for a given total losses (P_{LR}).

After selecting the criterion, then it checks of whether the design obtained is desirable or not. If it is yes, then it computes the load angle and other required parameters for the comparision with earlier improved accepted design for improvement. But, if the design is not acceptable it selects the next set of rotor parameters and re - peats all above steps. In this fashion, the design is im - proved one above another in steps for each individual criterion described above. The results obtained for motor considered are tabulated in Table 2.1 and are shown in Figs. 2.2-2.4.

Table -1

OPTIMUM DESIGN RESULTS

Item	Motor 3H.P., 400V, 50Hz, 4 Pole		
	Crn-1	Crn-2	Crn-3
Polea arc to pole pitch ratio (B)	0.31	0.39	0.31
Channel depth (G), mm	12.5	12.5	12.5
Length of air gap (Gl) mm	0.5	0.5	0.5
Output power (P_o), watts	2200	1450*	2215*
Stator current (At P_o), A	3.57*	2.59	3.59
Total losses (At P_o), watts	614.99	431.54	620.00
Power factor (At P_o)	0.656	0.655	0.621
Efficiency (At P_o)	0.732	0.759	0.756
Pull out power, watt	2762.87	2189.12	2762.87
Pull out current, A	3.59	2.59	3.59

Crn-1	(Criterion-1)	To obtain the minimum stator current for a given output power, (P_R).
Crn-2	(Criterion-2)	To obtain the maximum output power for a given stator current, (I_S).
Crn-3	(Criterion-3)	To obtain the maximum output power for a given total losses, (P_{LR}).

* Represents the optimum value of considered parameter.

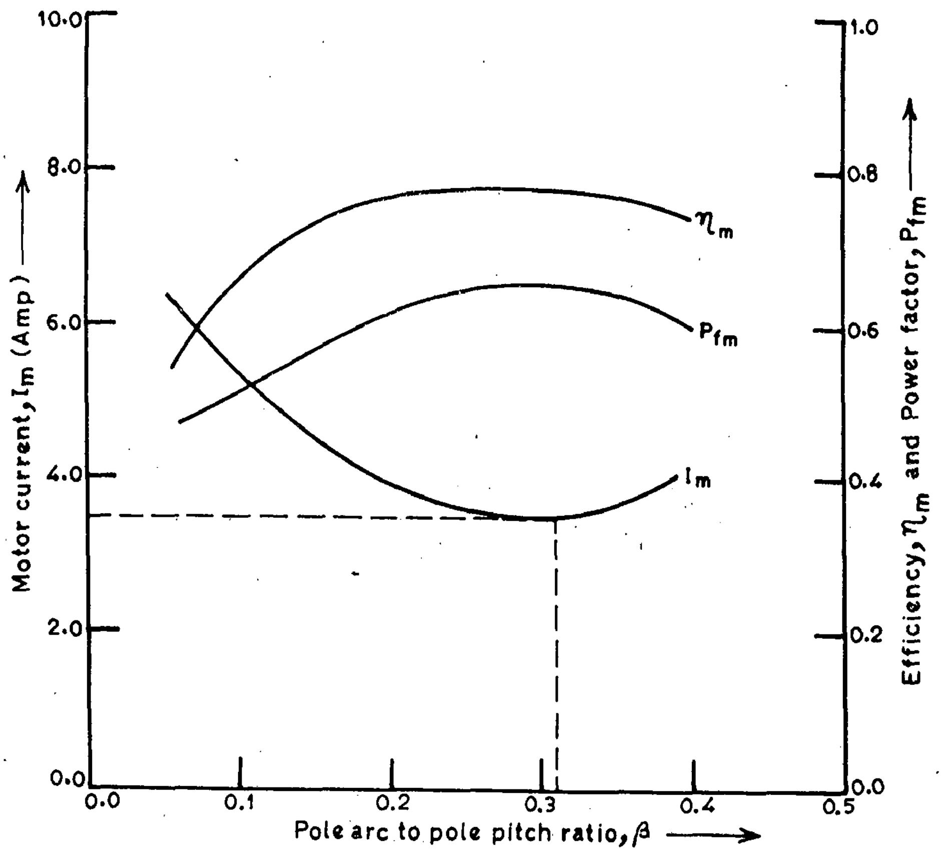

FIG.2.2: VARIATION OF STATOR CURRENT (I), EFFICIENCY AND POWER FACTOR WITH POLE ARC TO POLE PITCH RATIO (β) FOR SPECIFIED POWER OUTPUT (2200W).

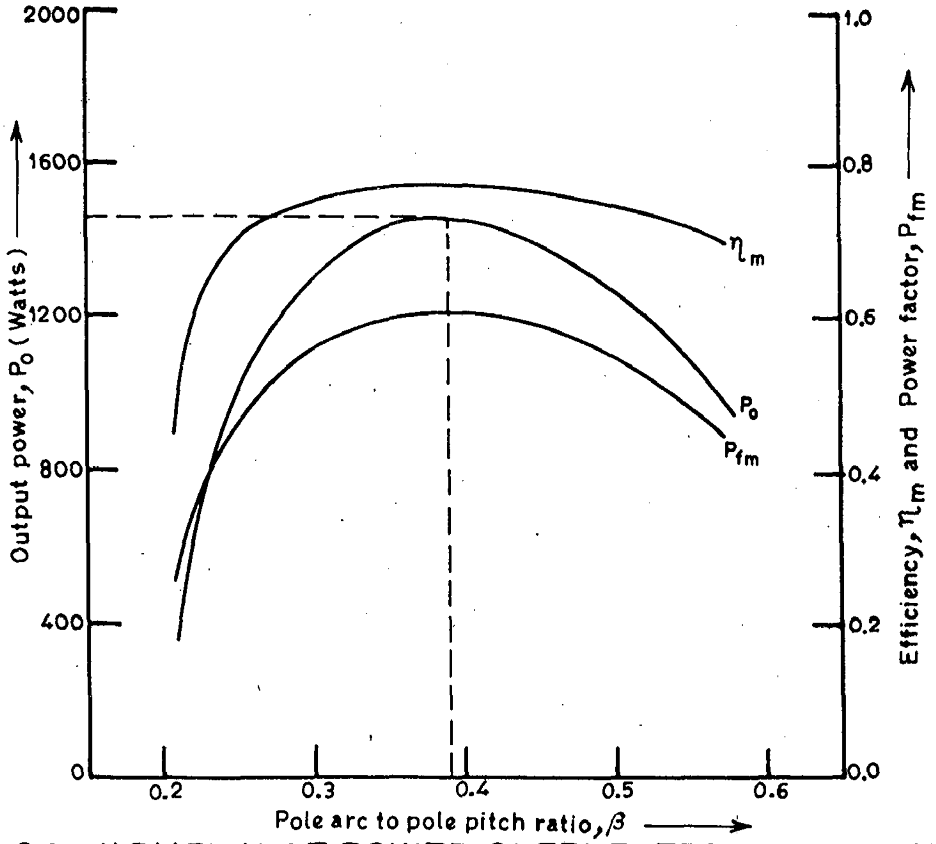

FIG.2.3: VARIATION OF POWER OUTPUT, EFFICIENCY AND POWER FACTOR WITH POLE ARC TO POLE PITCH RATIO (β) FOR SPECIFIED STATOR CURRENT (2.59A).

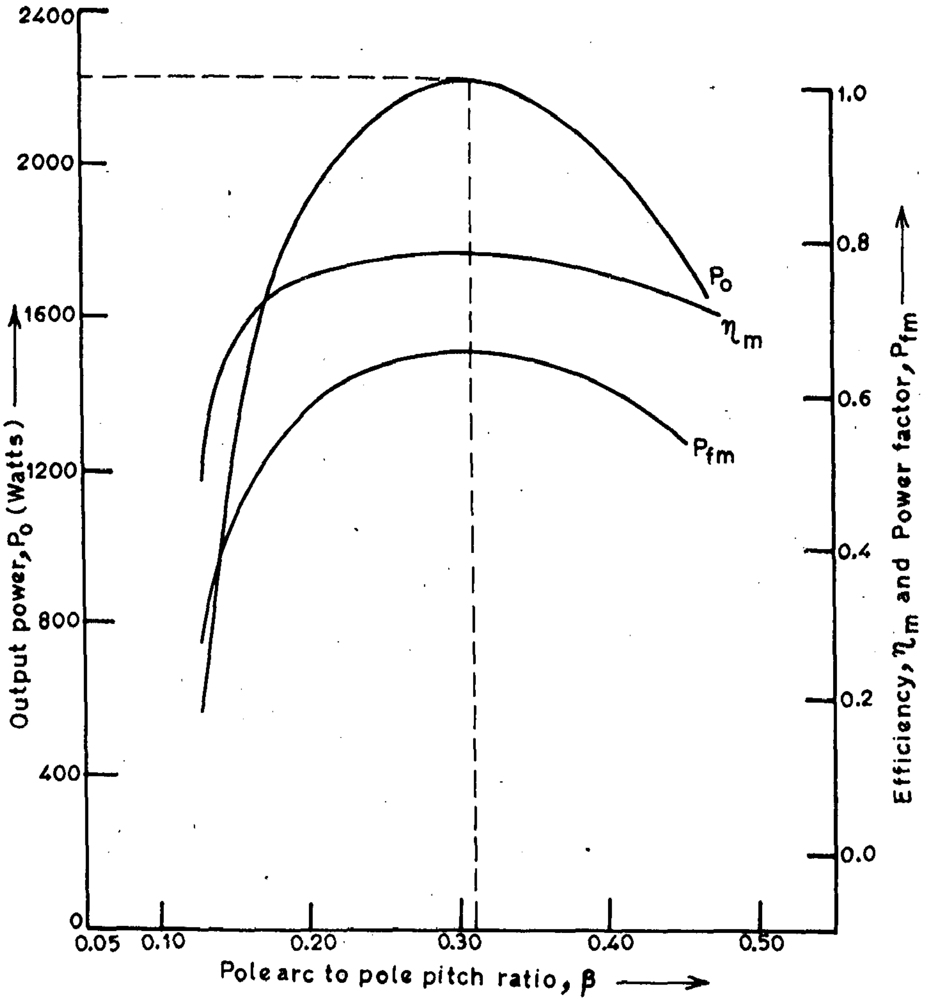

FIG. 2.4: VARIATION OF POWER OUTPUT, EFFICIENCY AND POWER FACTOR WITH POLE ARC TO POLE PITCH RATIO (β) FOR SPECIFIED TOTAL LOSSES (620 W).

2.4 DISCUSSION OF RESULTS

Using the developed computer algorithm, the obtained design results for the improved steady state synchronous performance of a polyphase reluctance motor show the following salient features.

1. The results of the considered motor for criterion-1 (i.e. minimum stator current for a given output power) are shown in Fig.2.2. It may be observed from these results that minimum stator current (3.57 Amp) is at pole arc to pole pitch ratio (β=0.31), and the feasible range of designs is $0.06 \leq \beta \leq 0.38$. Designs are not at all exhisting for the values B less than 0.06 where as for the values β greater than 0.38, the pull out power was less than P_R(2200W), and the Fig.2.2 shows that optimum results are obtained for β = 0.31.

2. Fig. 2.3 shows the results for the criterion-2, (i.e. maximum output power for a given stator current =2.59A) and it is observed that in this case designs are possible for the range of pole arc to pole pitch ratio (β), $0.21 \leq \beta \leq 0.56$. For the values pole arc to pole pitch ratio (β) less than 0.21, designs does not exhibit, where as for the pole arc to pole pitch ratio β greater than 0.56 also the designs are not feasible. The best motor performance according to Fig. 2.3 is obtained at β=0.39 for this criterion.

3. The results shown in Fig. 2.4 are for criterion 3 (i.e. maximum output power for a given total losses = 620.0W). The maximum possible output power obtained here is 2210 watts approximately at pole arc to pole pitch ratio (β = 0.31). This possible output power is even greater than the obtained in criterion-1. The designs here are possible for the range of pole arc to pole pitch ratio (β), $0.13 \leq \beta \leq 0.45$.

4. The results obtained for criterion-1 and criterion-3 are observed very close to each other and they provide the similar designs as reported by many investigators [11,20,22].

5. The designs obtained in this investigation has low losses, therefore, higher efficiency, low power factor and slightly higher no load current as compared to cage induction motor.

6. The developed computer programme based on the flow chart shown in Fig.2.1 requires small computation time and less memory storage of digital computer.

2.5 CONCLUSIONS

In this chapter, an analytical technique based upon three different criterions has been developed to design the three phase reluctance motor for optimum steady state synchronous performance. The developed computer programme is used to achieve optimum designs of different rotors. The values of the pole arc to pole pitch ratio (β=0.31 and 0.39) are therefore selected based upon criterion-1 and criterion-2 respectively for the fabrication and experimentation, where as the value of pole arc to pole pitch ratio (β=0.45) is selected for comparision.

The proposed design approach is simple and requires small computation time as well as memory requirements.

CHAPTER - 3

DEVELOPMENT OF MACHINE AND ITS PARAMETER DETERMINATION

3.1 GENERAL

In this chapter, based on the computer aided design results obtained for the optimum steady state synchronous performance of the machine, three rotors of different pole arc to pole pitch ratio (β) are fabricated using mild steel, and various tests are conducted to get different parameters of the machine.

3.2 DETAILS OF DEVELOPED MACHINE

It is experimentally observed and discussed by number of investigators [3,7,13] that there is no extra gain if the stator of a reluctance machine is designed seperately instead of using the stator of cage induction motor. According to Nagrial [13], In most of the cases the reluctance motor is manufactured using the same stator as for induction motor i.e. it is usual practice to have a common stator and inter changeable rotors. It has also been investigated experimentally that taking stator and rotor dimensions as variable will give the same output as given by taking only the rotor dimensions as variable. Therefore, second approach i.e. optimizing only rotor dimensions is considered superior.

Using the above mentioned concept, in the present work also, the stator of a standard polyphase cage induction motor is used as the stator of a reluctance motor. Where as, three rotors of different pole arc to pole pitch ratios (β) based on computer aided design, are fabricated using mild steel and various tests are conducted to get its various parameters.

The details of the stator (Induction moror) used for reluctance motor are as follows

Rated voltage	- 400/440V, 3H.P., 4 pole, 50 Hz. 3-phase, Delta connected.
Rated current (line)	- 4.5 (2.59A/phase)
Diameter of stator (D_s)	- 120.5 mm
Length of stator (L_s)	- 105.0 mm
Length of air gap (G)	- 0.5 mm

The computer aided design results obtained in previous chapter for optimized rotor design are based upon following three criteria.

Criterion 1 - To obtain the minimum stator current for a given output power (P_R= 2200 W)

Criterion 2 - To obtain the maximum output power for a given stator current (I_s = 2.59 A).

Criterion 3 - To obtain the maximum output power for a given total losses (P_{LR}= 620W).

Three main rotor parameters which mainly affect the steady state synchronous performance of polyphase reluctance motor are : Pole arc to pole pitch ratio (β), the channel depth (G), and length of air gap (Gl). The pole arc to pole pitch ratio (β) is the most important rotor parameter and it appreciably affect its performance. Hence, it is considered as the main parameter to obtain optimum design of the motor. The second parameter to affect the performance, is the depth of channel at quadrature axis of the rotor. There is an improvement by increasing the depth of channel, but after a certain value of its, the pull-in performance of the machine deteriotes drastically and there is also not much appreciable improvement in steady state performance. Hence this parameter is considered as fixed one with its suitable value. Where as the third parameter i.e. air gap length, have the tendency to have its reduced value as minimum as possible, but it is always resticted by mechanical considerations and most of the times it is considered equal to the length of the air gap of normal induction motor.

The following are the design parameters of the developed rotors.

Diameter of rotor (D_r) = 119.5 mm

Length of rotor (L_r) = 105 mm

Number of poles (P) = 4

Pole arc to pole pitch ratio (β)
i. 0.31 for first rotor,
ii. 0.39 for second rotor,
iii. 0.45 for third rotor.

The first rotor is fabricated with the parameters obtained based on first criterion of computer aided design results. Moreover, the computer aided design

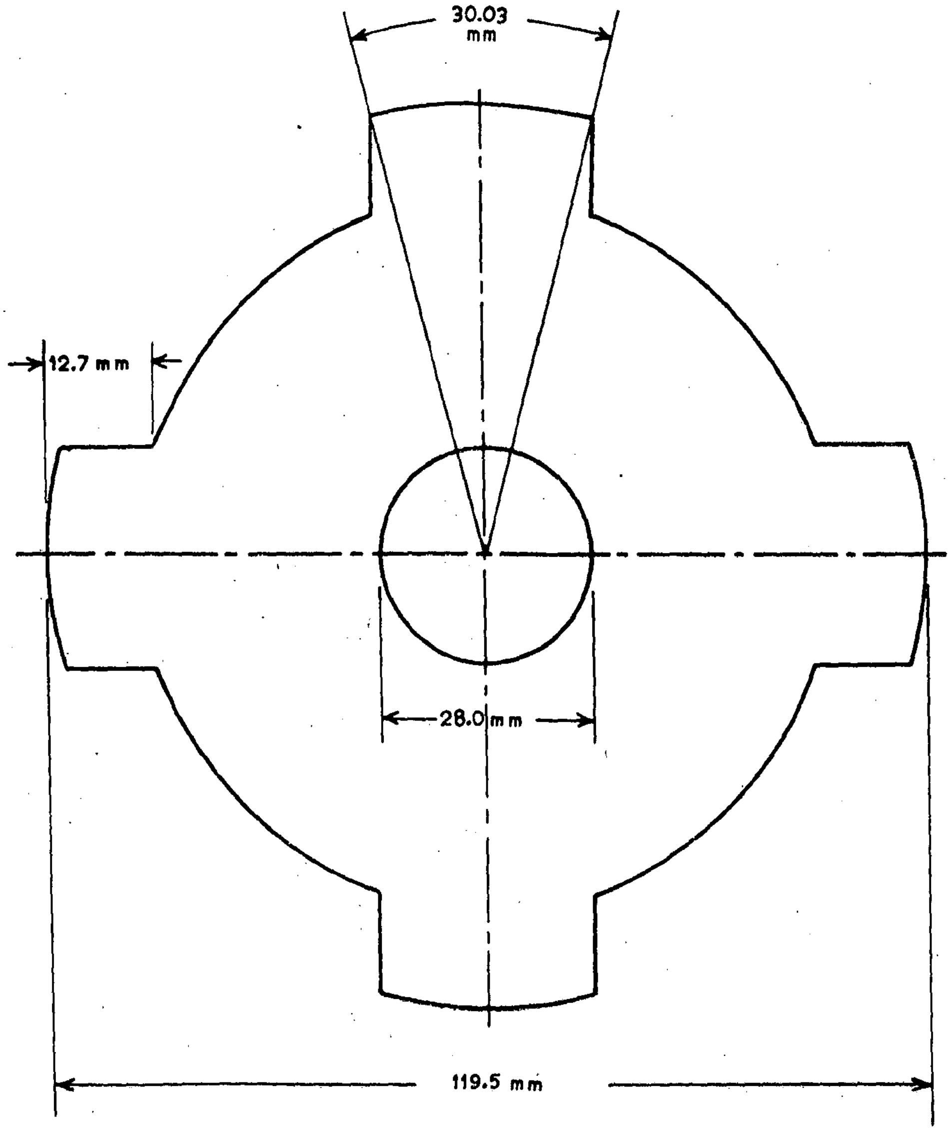

FIG.3.1: DIMENSIONAL SKETCH OF RELUCTANCE ROTOR FOR POLE ARC TO POLE PITCH RATIO (β = 0.31).

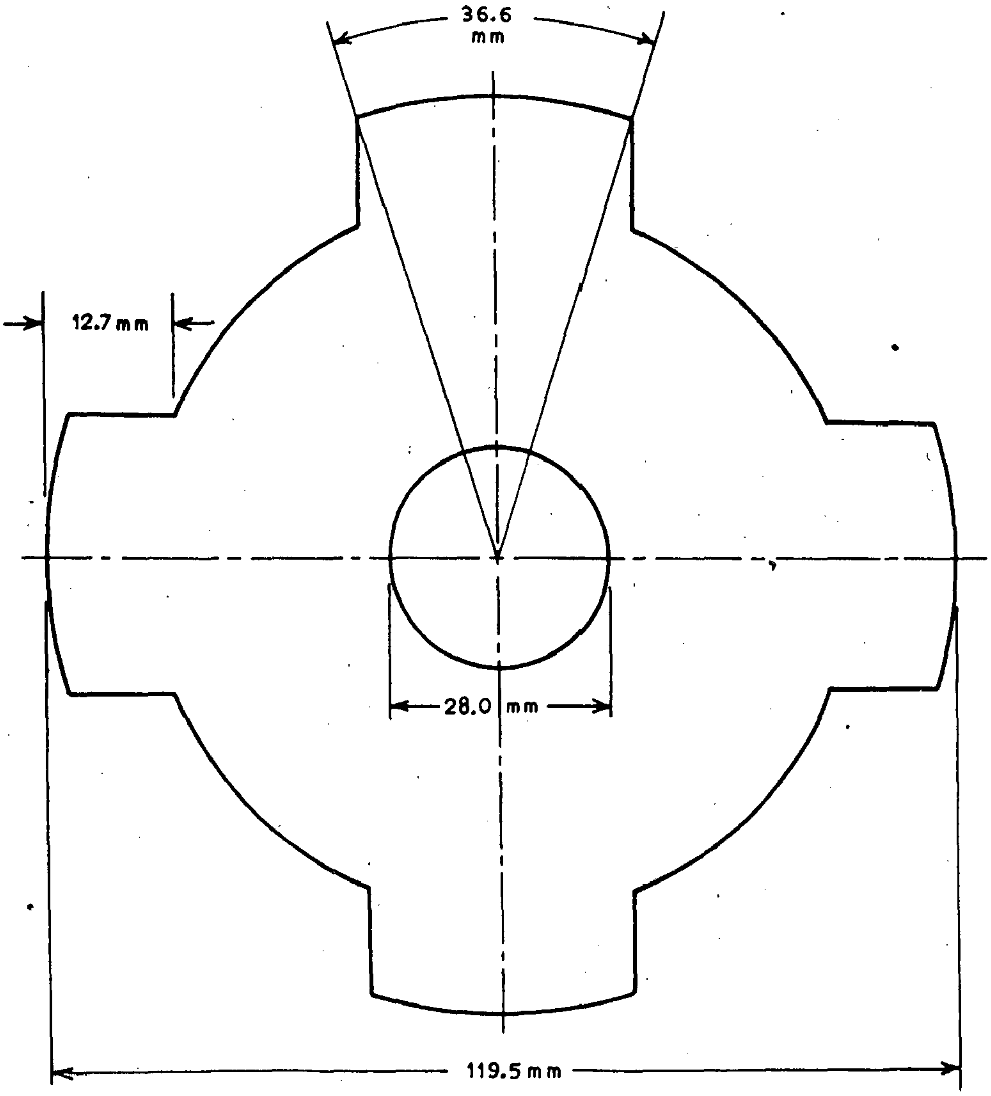

FIG.3.2: DIMENSIONAL SKETCH OF RELUCTANCE ROTOR FOR POLE ARC TO POLE PITCH RATIO ($\beta = 0.39$).

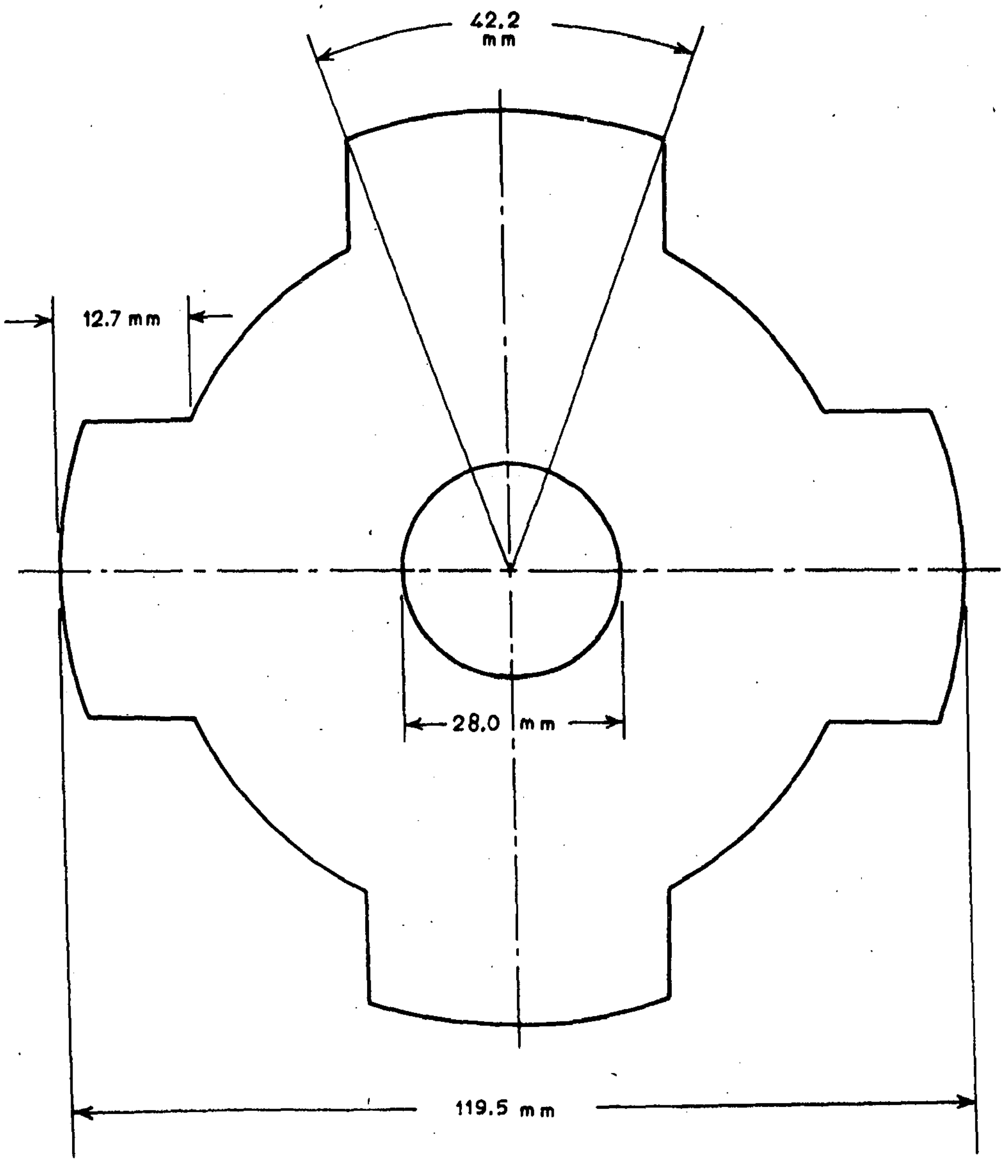

FIG.3.3: DIMENSIONAL SKETCH OF RELUCTANCE ROTOR FOR POLE ARC TO POLE PITCH RATIO ($\beta = 0.45$).

results of third criterion are also same as the results of first criterion. The second rotor is fabricated using the rotor parameters obtained based on the results for the second criterion of computer aided design. The third rotor is fabricated for comparision of performance and have the rotor parameters same as reported by many investigators [14,19,20 21].

The mode of geometry of these rotors is shown in Figs. 3.1, 3.2 and 3.3, respectively.

Additional mechanical design parameters of the developed rotors are

Diameter of the shaft	=	28 mm
Channel depth	=	12.5 mm
Bearings	=	IS 8 and IS 11
Material used	=	Mild steel

3.3 DETERMINATION OF PARAMETERS

In order to find out various stator details, block rotor test, no load test and stator winding resistance measurement tests were conducted on the polyphase cage induction motor of whose stator is considered for the reluctance motor.

For leakage reactance, the block rotor test is performed in which rated armature current is applied by gradually increasing the input voltage and all other corresponding datas are recorded.

For finding out no load losses and magnetising reactance (X_c), no load test is conducted. Here, input supply voltage is increased gradually and, other corresponding datas are recorded, the test is performed upto rated voltage of the machine.

Stator winding resistance test is conducted in order to find out the winding resistance of the cage induction motor and further this value is used while finding out the no load losses. The following results were obtained by performing the above mentioned tests.

(a) Stator winding resistance/phase (r_a) = 10.13 ohms per phase

(b) Magnetising reactance (X_c) = 305.99 ohms per phase

(c) No load losses (P_{LN}) = 226.41 Watts.

Figures 3.4 and 3.5 show the variation of no load current and no load losses with respect to voltage variation for different rotors having different pole arc to pole pitch ratio (β).

The direct and quadrature axis reactance of the polyphase reluctance, machine are obtained according to the method proposed by Honsinger [16]. The procedural steps for finding out the direct axis reactance (X_d) and quadrature axis reactance (X_q) are as follows:

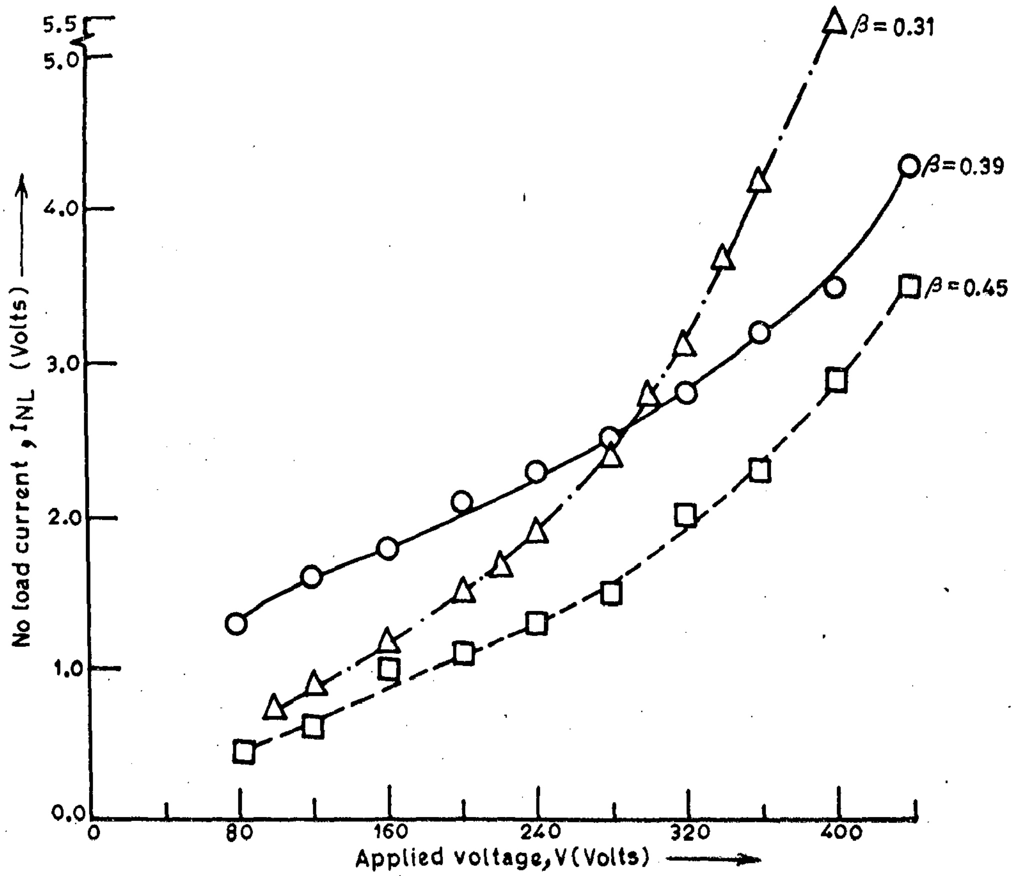

FIG.3.4: VARIATION OF NO LOAD CURRENT WITH APPLIED VOLTAGE FOR DIFFERENT POLE ARC TO POLE PITCH RATIO (β).

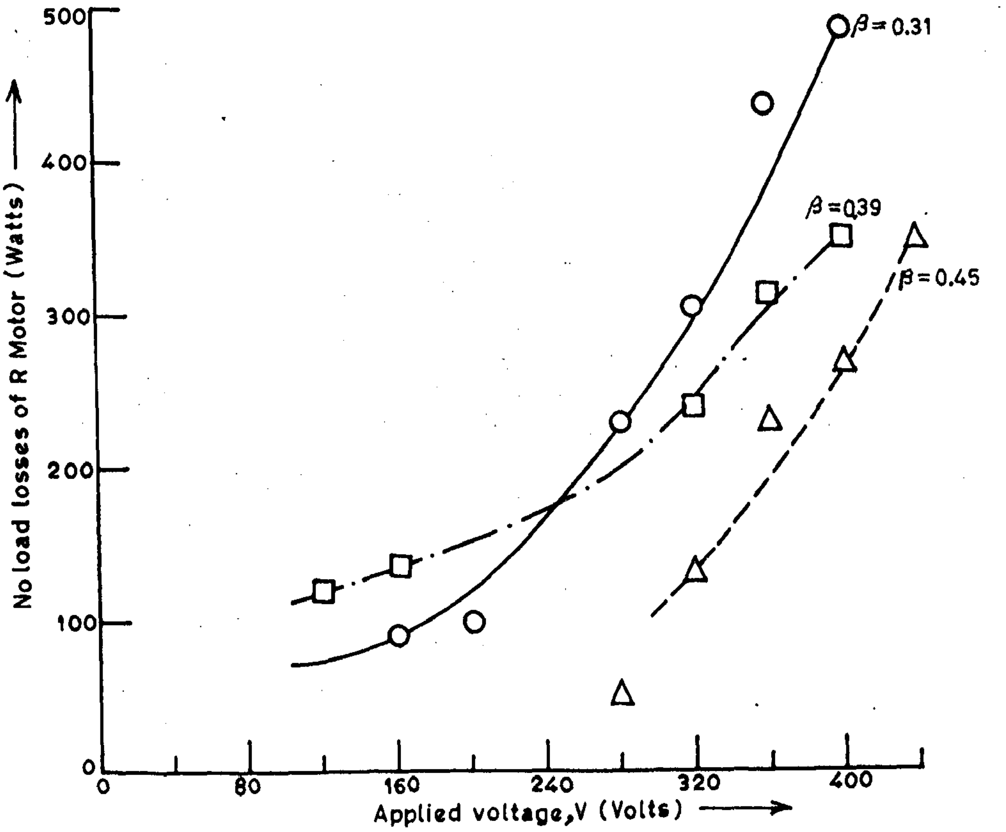

FIG.3.5: VARIATION OF NO LOAD LOSSES WITH APPLIED VOLTAGE FOR DIFFERENT POLE ARC TO POLE PITCH RATIO (β).

At no load $I_q = 0$

$$I_d = I_{nL} = \frac{V}{\sqrt{x_d^2 + r_a^2}}$$

and hence x_d may be found from no load test data according to

$$x_d = \sqrt{(V/I_{nL})^2 - r_a^2}$$

or $$x_d \simeq \frac{V}{I_{nL}} \qquad ...(3.1)$$

where the right hand approximation applies to measurements made around 50 Hz. Evidently, there is no way that x_q can be measured directly at no load since I_q is zero.

According to another test to measure x_q, the value of x_q will be based on a constant x_d whose value is given by equation (3.1).

In the another attempt by Honsinger [9], he has reported that the machine admittance components G and B can be written to be:

$$G = \frac{2\, r_a + (x_d - x_q)\sin 2\delta}{2(x_d \cdot x_q + r_a^2)} \qquad \text{and,}$$

$$B = \frac{x_d + x_q - (x_d - x_q)\cos 2\delta}{2(x_d \cdot x_q + r_a^2)}$$

These equations have the form

$$G = (r_a + E \sin 2\delta)/D$$

$$B = (F - E \cos 2\delta)/D$$

where,

$$E = (x_d - x_q)/2,$$
$$F = (x_d + x_q)/2,$$
$$D = x_d \cdot x_q + r_a^2$$

By rearranging

$$GD - r_a = +E \sin 2\delta$$
$$BD - F = -E \cos 2\delta \qquad \ldots(3.2)$$

Here, it is undesirable to measure torque angle, terms containing the torque angle are eliminated by squaring both sides of each equation and adding. This obtains

$$Y^2D^2 - 2\,(G\,r_a + BF)D + F^2 - E^2 + r_a^2 = 0$$

But,

$F^2 - E^2 + r_a^2 = D$, hence the equation reduces to

$$Y^2D - 2(Gr_a + BF) + 1 = 0$$

However, it is found that this equation simplifies when impedance components Z, R, and X are used. The relations between these types of components to admittance components Y, G, and F are

$$Y = \frac{1}{Z}\,, \quad G = \frac{R}{Z^2}\,, \text{ and } B = \frac{X}{Z^2}$$

Substituting these values and also substituting for D and F their equivalents obtains

$$x_d\,x_q + r_a^2 - 2\,Rr_a - X(x_d + x_q) + R^2 + X^2 = 0$$

or

or

$$(x_d-x).x_q + (R-r_a)^2 - X(x_d-x) = 0$$

Therefore,

$$x_q = x - (R-r_a)^2/(x_d-x) \qquad ...(3.3)$$

But, this value of x_q obtained in equation (3.3) does not include the effect of iron and rotational losses. Where as it should include both the losses.

Now, the correction for iron and rotational losses can be made as suggested by Hosinger.

It is reported by many investigators that the iron and rotational losses have negligible effect upon the measurement of X_d. In the other hand, these losses appreciably affect the measurement of X_q, which is a much smaller reactance than X_d.

When iron and rotational losses are included, the admittance components are called Y_1, G_1, and B_1. These are related to the just previously used components Y, G, and B by the relation.

$$G_1 = G + g_o, \qquad B_1 = B, \qquad Y = G_1 - jB_1$$

where,

$$g_o = (W_o/mV^2) \text{ and } W_o = W_{nl} - m\, I_{nl}^2 . r_a$$

It is only necessary to substitute $G = G_1 - g_o$ in equation (3.2) and then carry out the same procedure for finding X_q which gives

$$x_q = \frac{X(x_d-X)-(R-r_a)^2-g_o[(Z^2g_o-2R)r_a^2+2r_aZ)}{[1+go(g_o Z^2-2R)]x_d-X}$$

$$\therefore x_q \simeq \frac{X(x_d-X)-(R-r_a)^2}{[1+g_o(g_oZ^2-2R)]x_d-X} \qquad ...(3.4)$$

where,

$$Z = \frac{V}{I}, \quad R = Z\cos\phi, \text{ and } X = Z\sin\phi$$

This equation (3.4) gives exact value of quadrature axis reactance having considered iron and rotational losses.

Using equations (3.1) and (3.4) the values of direct axis reactance (x_d) and quadrature axis reactance (x_q) under saturated and unsaturated conditions of the machine are obtained for all the three rotors. The values obtained are tabulated in Table -3.1.

TABLE 3.1

DIRECT AND QUADRATURE AXIS REACTANCES (X_d and X_q) AT DIFFERENT EXCITATION LEVELS

S.No.	Applied voltage (V) volts	Pole arc to pole pitch ratio (β)	Direct axis reactance (X_d), ohm	Quadrature axis reactance (X_q) ohm	Rateo of X_d to X_q
1.	400	0.32	126.0	41.0	3.07
2.	400	0.39	197.9	50.4	3.93
3.	400	0.45	243.1	58.6	4.20
4.	280	0.32	202.1	41.4	4.90
5.	280	0.39	242.5	55.6	4.36
6.	280	0.45	293.9	57.2	5.14

3.4 DISCUSSION OF RESULTS

In the present investigation, three rotors of reluctance motor are fabricated having different values of pole arc to pole pitch ratios obtained from computer aided design results for optimum steady state synchronous performance. The following are the salient features observed on developed machine.

It is observed that the developed reluctance motor operates stably over the wide range of excitation levels with all the three rotors. After pull-in at higher excitation levels, the motor runs in synchronism upto quite low voltages. Fig. 3.4 shows the variation of no load current with applied voltage of the developed machine for all the three rotors. It may be observed from this Figure that in general the no load current increases with increasing the excitation levels. However, the no current also increases with the decrease in the value of pole arc to pole pitch ratio.

Figure 3.5 shows the variation of no load losses with applied voltage to reluctance motor for all the three rotors. It may be observed from this Figure that the no load losses increases with the increase of excitation in all the three cases. However there is not much appreciable effect of pole arc to pole pitch ratio on the no load losses as may be seen from Fig.3.5.

The direct and quadrature axis reactances (X_d and X_q) are measured by conducting different tests and are given in Table 3.1. From these results, it may be observed that direct axis and quadrature axis reactance increases with increase of pole arc to pole pitch ratio. However, in general, these reactances decreases with increases value of excitation levels due to saturation. The ratio of direct to quadrature axis reactance is observed tobe maximum for pole arc to pole pitch ratio (β)=0.45, at both the excitation levels i.e. 400 and 280 volts.

It is observed here, that the driving torque of the polyphase reluctance motor at asynchronous speeds is generally poor for all the three rotors compared to cage motor. As the driving torque, in case of reluctance motor, is produced by the eddy current on the pole body and it decreases rapidly as the motor speed approaches near to synchronous speed. Therefore, the asynchronous performance, in the present investigation, is improved by installing a short circuit winding around pole body. This short circuit winding provided over the pole improves the motor torque over the entire slip range, it also improves the pull out torque slightly but has very little effect on load characteristic. The different values for pull-in of motor at no load for different pole arc to pole pitch ratio are given in Table 3.2. It may be observed from these results that the pull-in performance deteriotes with decreases in pole arc to pole pitch ratio. The rotor of lower pole arc to pole pitch ratio draws large amount of current from supply.

However, the pull-in performance is improved by short circuit ring around the pole body for all the three rotors. The pull-in is possible at lower supply voltage and reduces the current drawn at pull in condition for all the three rotors.

TABLE 3.2

VARIATION OF PULL-IN FOR RELUCTANCE MOTOR AT NO LOAD

	$\beta = 0.31$	$\beta = 0.39$	$\beta = 0.45$
Pull-in without short circuit ring	440V,15.5A	440V,12.5A	400V,8A
Pull-in with short circuit ring provided.	320V,10.5A	354V,9.8A	300V,6A

3.5 CONCLUSIONS

The developed reluctance motor with different rotor dimensions runs stably over the wide range of excitation levels. It is observed that the no load current and no load losses are increased by decreasing the pole are to pole pitch ratio. The direct and quadrature axis reactances are also decreased by decreasing the pole arc to pole pitch ratio and increasing the excitation levels. It is observed experimentally that the pull-in performance deteriotes with the decrease of pole arc to pitch ratio and it is improved by providing short circuit conducting material rings at quadratureaxis channels of the rotor, for all the three rotors.

CHAPTER - 4

PERFORMANCE CHARACTERISTICS

4.1 GENERAL

This chapter deals with the experimental investigations which have been carried out on the synchronous performance characteristics of the developed polyphase reluctance motor, and the results obtained with change in construction and geometry of rotor have been reported. The performance of the developed polyphase reluctance motor is studied at normal frequency (50 Hertz) as well as at variable frequency.

4.2 EXPERIMENTATION

The performance of the polyphase reluctance motor is studied here experimentally by conducting various tests. The effect of pole arc pole pitch ratio (β) on the synchronous and asynchronous performance is also investigated. The effects of certain relatively important machine parameters like effect of excitation and frequency is also studied.

The experimental set up to conduct no load test and load test onfixed or variable frequency at different excitation levels is shown in Fig. 4.1.

In the no load test, conducted for different rotors, first applied voltage is increased gradually till the motor

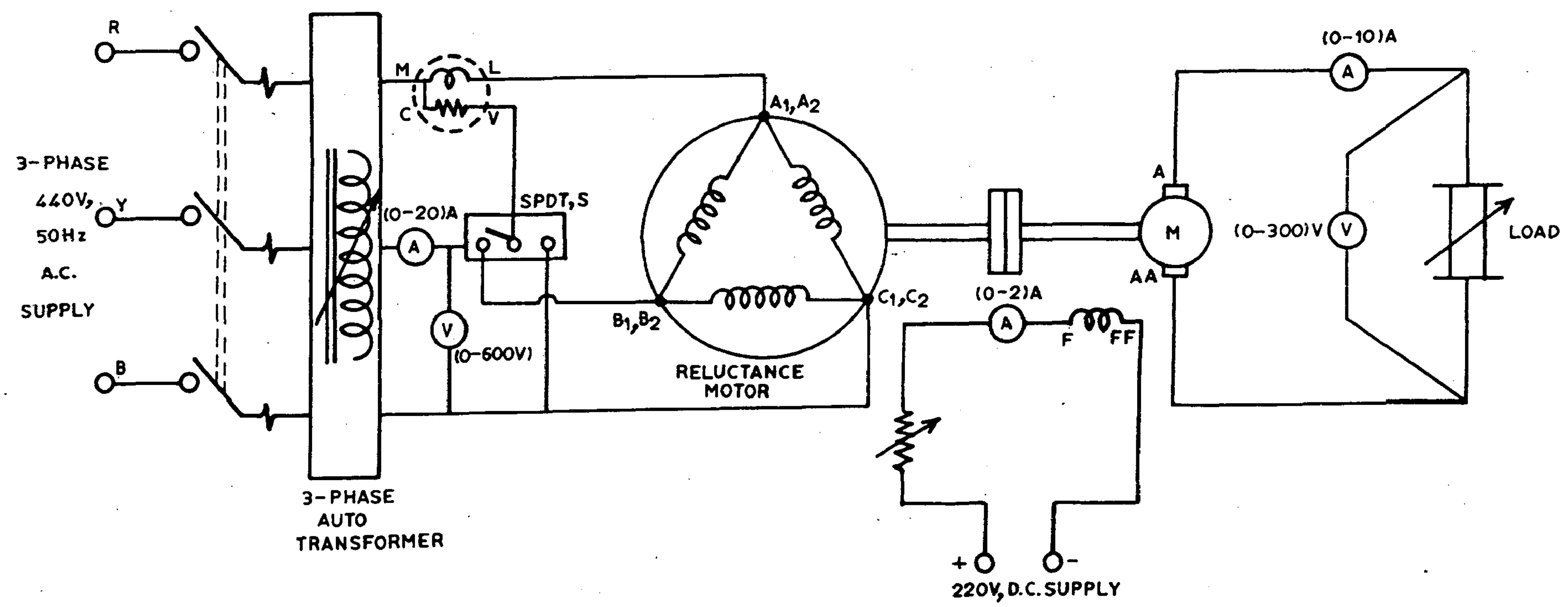

FIG.4.1: CIRCUIT DIAGRAM FOR LOAD TEST ON DEVELOPED RELUCTANCE MOTOR.

attains the pull-in condition. Once the motor achieves pull-in, it starts behaving as a reluctance motor. The starting procedure of reluctance motor is same as of induction motor. Now the input voltage can be varied in steps for a large range, upto its rated value and corresponding parameters are recorded.

In order to conduct the load test, to study the variation of power output with different parameters, the polyphase reluctance motor fitted with the reluctance rotor under test, is coupled with a same rating d.c. machine for loading. To study the performance, the input supply voltage is increased gradually till the reluctance motor comes to pull-in condition. Once the motor attains the pull-in the excitation level is fixed as per the requirement and d.c. machine is loaded in steps and corresponding parameters are recorded.

To obtain the safe maximum output power for the given stator current (2.59A), the applied voltage to the motor is varied over the wide range with all the three rotors.Further, for a given output power, the applied voltage is varied to achieve the minimum stator current and its corresponding optimum voltage for the rotor having pole arc to pole ratio of 0.39.

The various tests are performed over the wide range of frequency in which voltage to frequency ratio is maintained up to rated frequency and voltage is kept constant above rated frequency for all the three rotors.

4.3 PERFORMANCE CHARACTERISTICS AND DISCUSSIONS

A series of tests are conducted in order to investigate the performance of the developed polyphase reluctance motor at supply frequency (50Hz) and at variable frequency.

4.3.1 Performance at 50 Hz frequency

The performance of the developed polyphase reluctance motor with rotor of different pole arc to pole pitch ratio, at 50 Hz supply frequency is studied by conducting various tests and results are plotted in Fig. 4.2-4.6. Following salient features are observed.

Fig. 4.2, 4.3 and 4.4 show the load characteristic i.e the variation of efficiency, current and power factor with power output for the pole arc to pole pitch ratio 0.31, 0.39 and 0.45 respectively at 400V and 50 Hz supply frequency conditions. It is observed here that stator current, efficiency and power factor have the increasing tendency with increase in power output. For higher values of pole arc to pole pitch ratio, the performance is found inferior im terms of efficiency and power factor. The stator current at no load as well as at load is observed to be higher with decrease in the pole arc to pole pitch ratio. However, efficiency and power factor are found to be maximum at particular load and

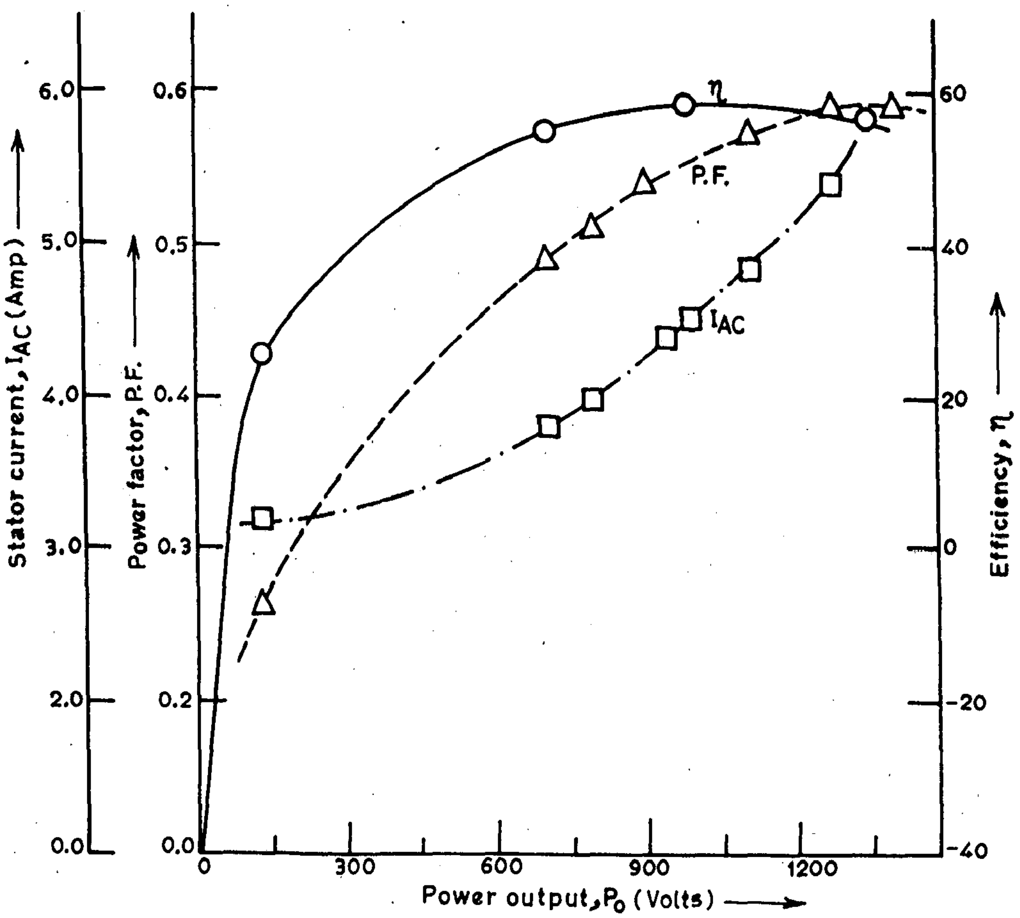

FIG.4.2: VARIATION OF EFFICIENCY, CURRENT AND POWER FACTOR WITH POWER OUTPUT FOR POLE ARC TO POLE PITCH RATIO (β = 0.31, V = 400 Volt, F = 50 Hz).

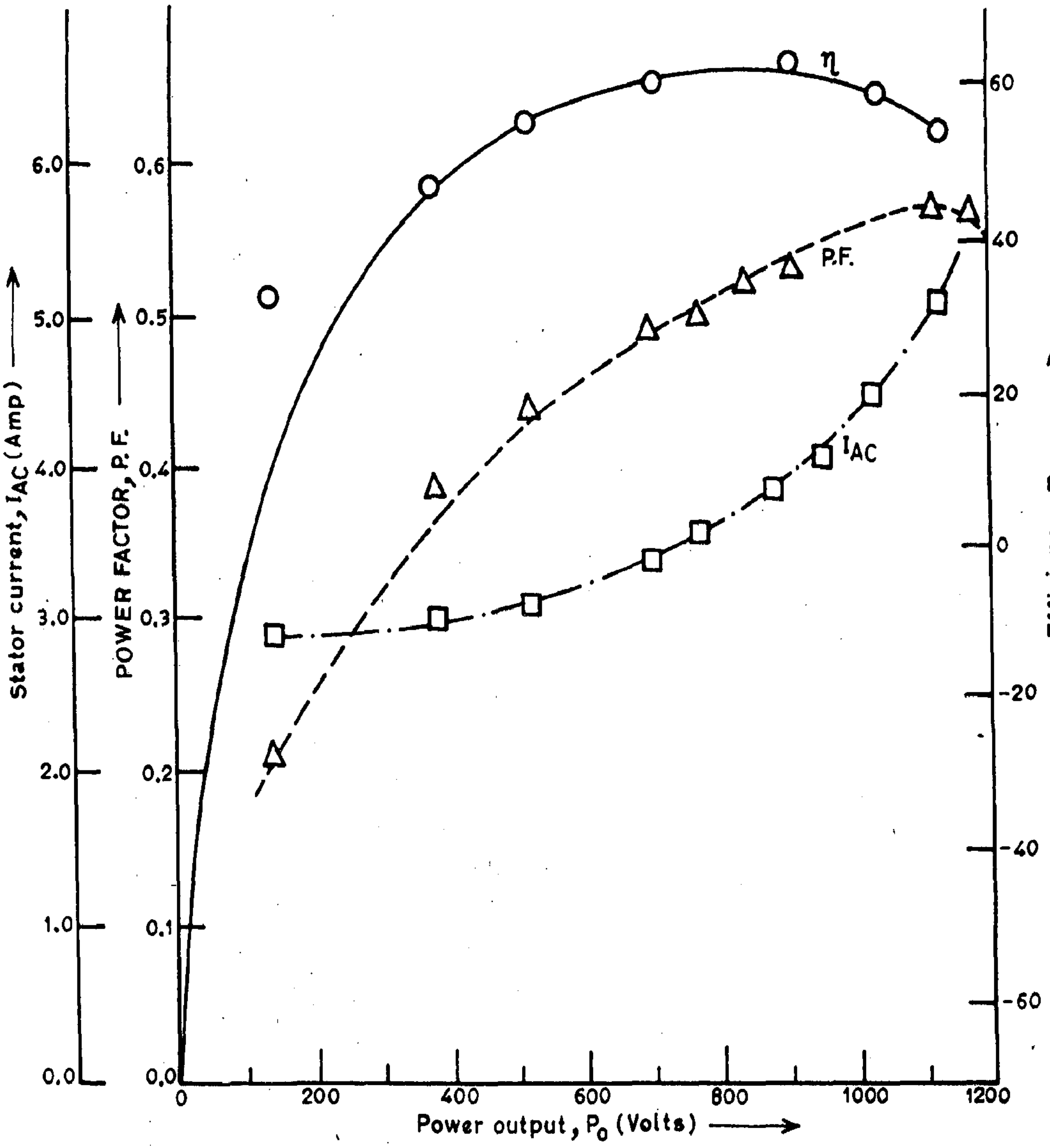

FIG.4.3: VARIATION OF EFFICIENCY, CURRENT AND POWER FACTOR WITH POWER OUTPUT FOR POLE ARC TO POLE PITCH RATIO (β=0.39, V=400 Volt, F=50 Hz).

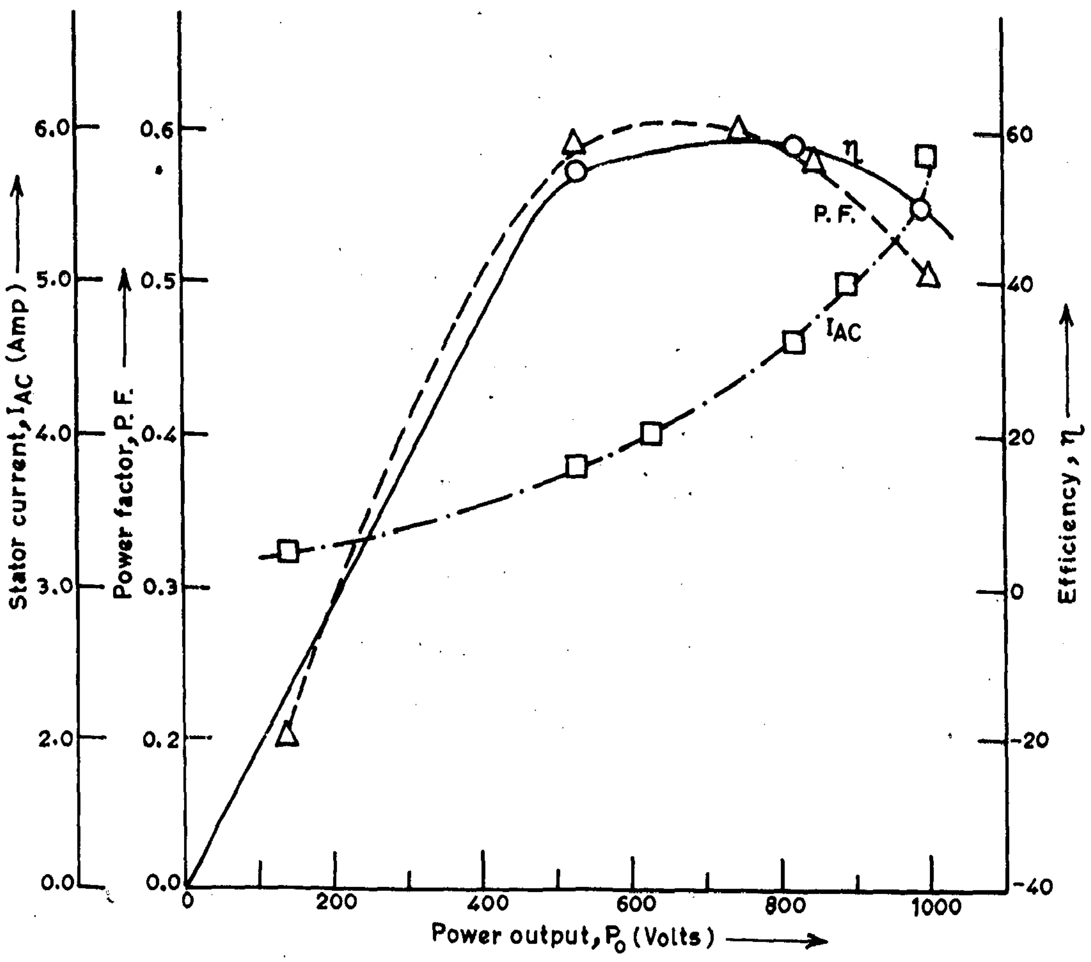

FIG.4.4: VARIATION OF EFFICIENCY, CURRENT AND POWER FACTOR WITH POWER OUTPUT FOR POLE ARC TO POLE PITCH RATIO (β = 0.45, V = 400 Volt, F = 50 Hz).

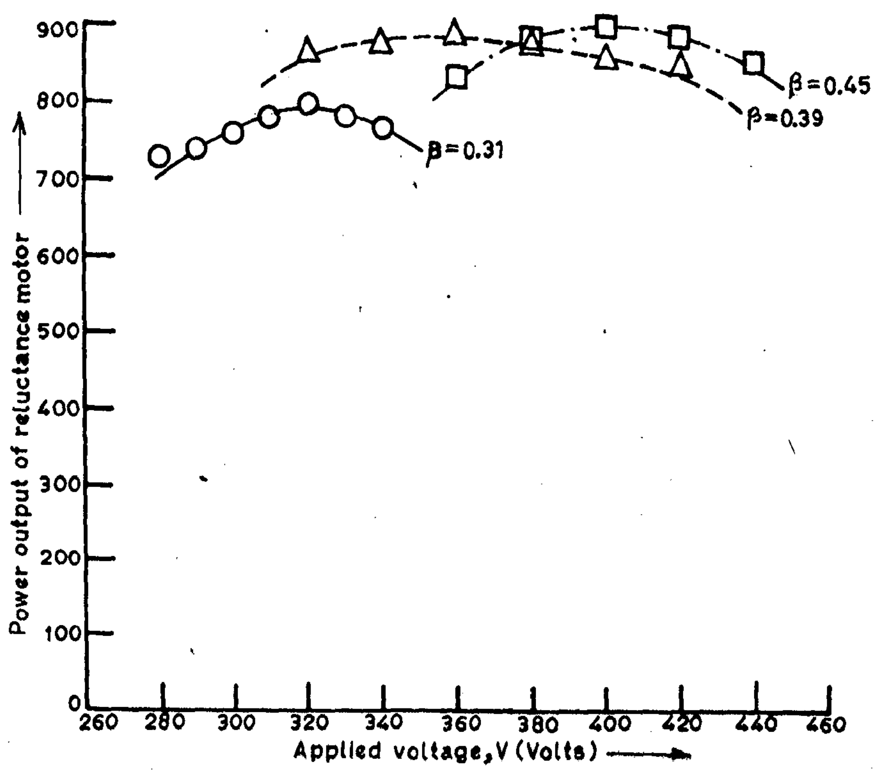

FIG.4.5: VARIATION OF POWER OUTPUT OF RELUCTANCE MOTOR (Stator current equal to rated current) WITH APPLIED VOLTAGE FOR DIFFERENT POLE ARC TO POLE PITCH RATIO.

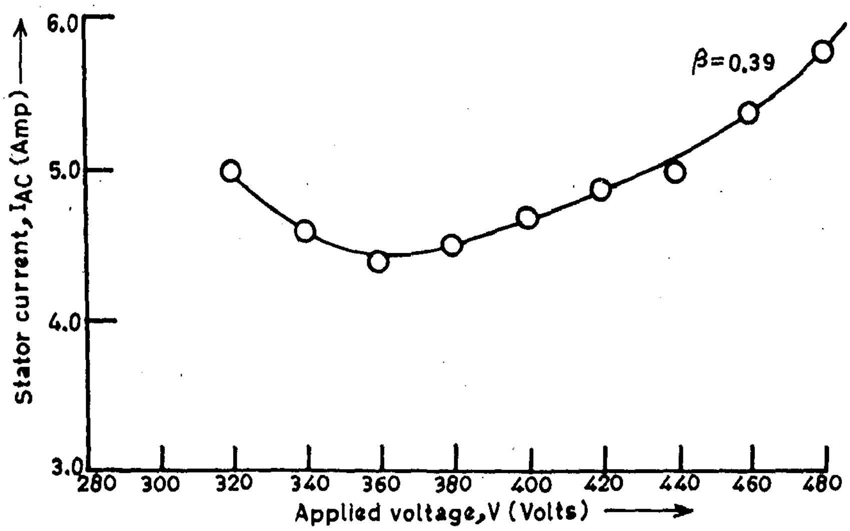

FIG.4.6: VARIATION OF STATOR CURRENT (Output power kept constant) WITH APPLIED VOLTAGE FOR POLE ARC TO POLE PITCH RATIO (β=0.39 at power output =1223 W).

corresponding output is found higher for the rotor having pole arc to pole pitch ratio value lower.

The variation of power output of reluctance motor with applied voltage while keeping the stator current equal to rated current (2.59A) is shown in Fig. 4.5. It may be observed from the figure that for the constant stator current more power output is obtained for larger values of pole arc to pole pitch ratio and this value decreases slightly as the applied voltage is increased. The maximum output power for rated stator current, are obtained of different amount for all the three rotors and at different supply voltages. However, the rotor with pole arc to pole pitch ratio (β=0.39) gives the comparable output power as in case of rotor with pole arc to pole pitch ratio (β=0.45).

Figure 4.6 shows the variation of stator current with applied voltage at constant output power for rotor of pole arc to pole pitch ratio (β)=0.39. From this figure, it may be observed that the stator current is maximum at a particular voltage which to be optimum (360V) for the given output power. However, it is observed that the optimum voltage increases with increase of load.

4.3.2 Performance at Variable Frequency

Based on various tests it is observed that the polyphase reluctance motor can run stably, even at wide range variation of frequencies except the case lower frequency (4 Hz). The performance of the developed poly-phase reluctance motor is studied for the frequency range 30 Hz to 70 Hz., and the following salient features are observed.

The power output variation with speed (by varying the frequency) for rated stator current is shown in Fig. 4.7. It may be observed from this figure that the maximum power output is obtained for the lower value of pole arc to pole pitch ratio. Figure 4.8 shows the variation of pull outpower with speed. It shows that maximum pull out power is obtained for the lower value of pole arc to pole pitch ratio, and an increase in pole arc to pole pitch ratio results in decrease of pull-out power.

Figures 4.9, 4.10 and 4.11 show the load characteristic i.e. the variation of efficiency, current and power factor with power output at 30 Hz for rotor having pole arc to pole pitch ratio (β) = 0.31, 0.39 and 0.45, respectively. It is observed from these figures that all these parameters increase with increase in power output similarly as at 50 Hz.

The torque speed characteristic of developed poly-phase reluctance motor having rotors of different pole arc to pole pitch ratio are shown in Figures 4.12, 4.13 and 4.14 respectively. The torque is observed to be maximum

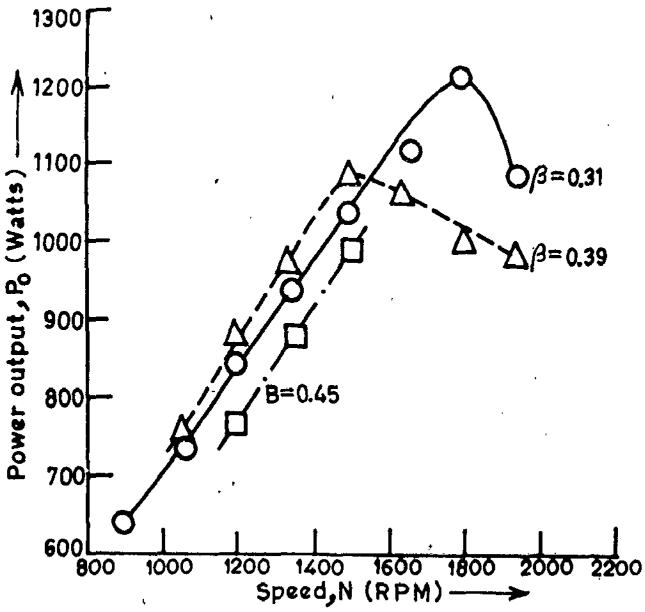

FIG. 4.7: VARIATION OF POWER OUTPUT WITH SPEED FOR DIFFERENT POLE ARC TO POLE PITCH RATIO, KEEPING STATOR CURRENT CONSTANT.

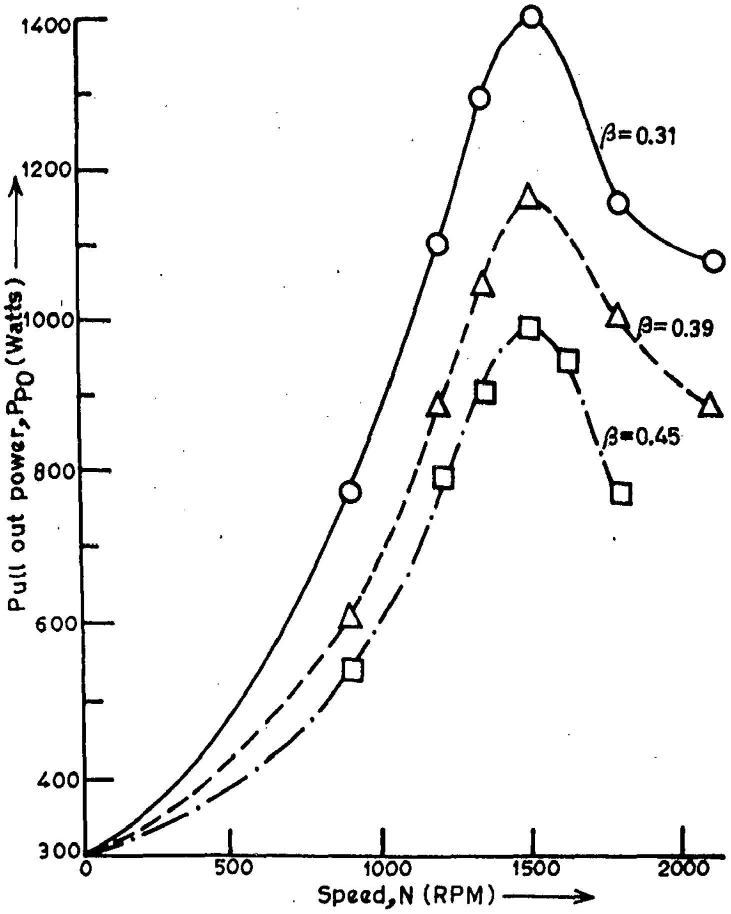

FIG. 4.8: VARIATION OF PULL OUT POWER WITH SPEED.

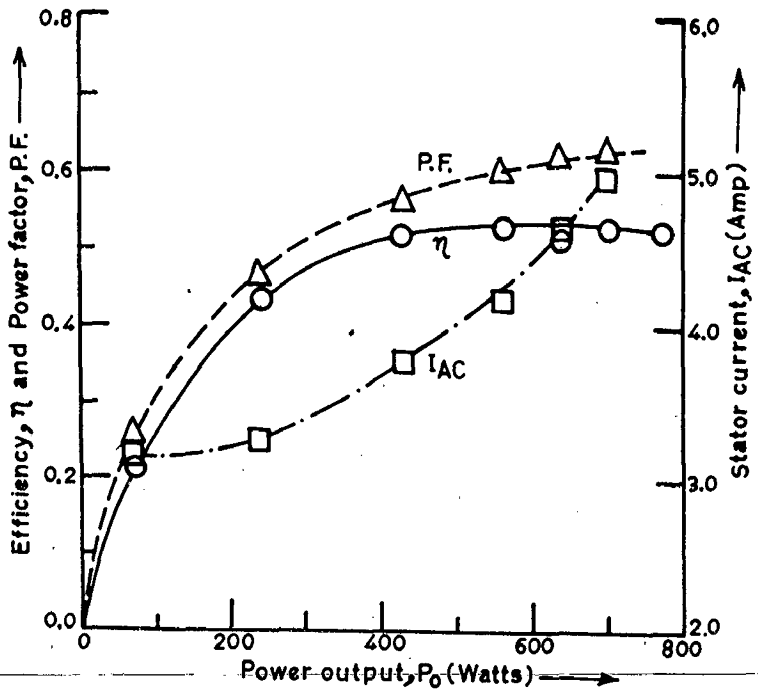

FIG.4.9: VARIATION OF EFFICIENCY, STATOR CURRENT AND POWER FACTOR WITH POWER OUTPUT FOR POLE ARC TO POLE PITCH RATIO (β=0.31, V=400 Volt and F=30Hz).

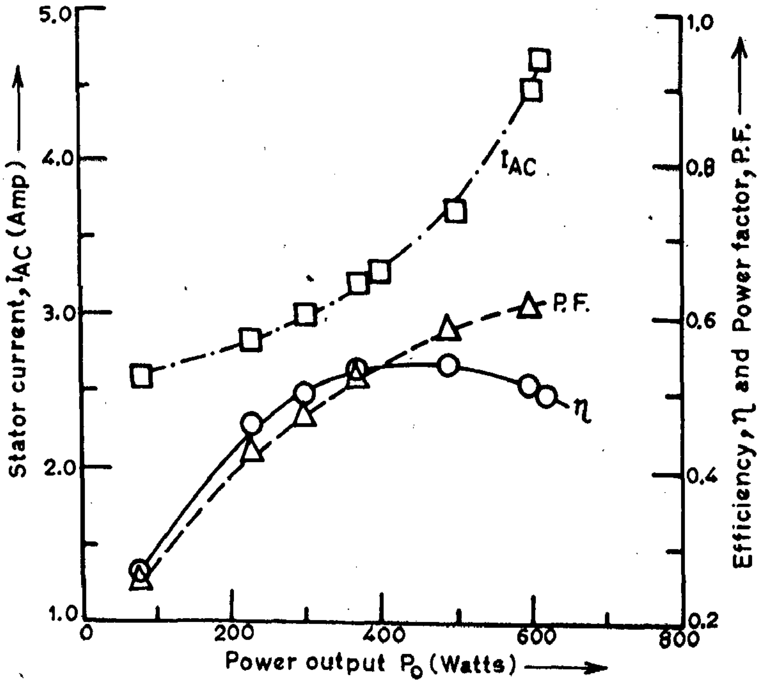

FIG.4.10: VARIATION OF EFFICIENCY, STATOR CURRENT AND POWER FACTOR WITH POWER OUTPUT FOR POLE ARC TO POLE PITCH RATIO (β=0.39, V=400 Volt and F=30Hz).

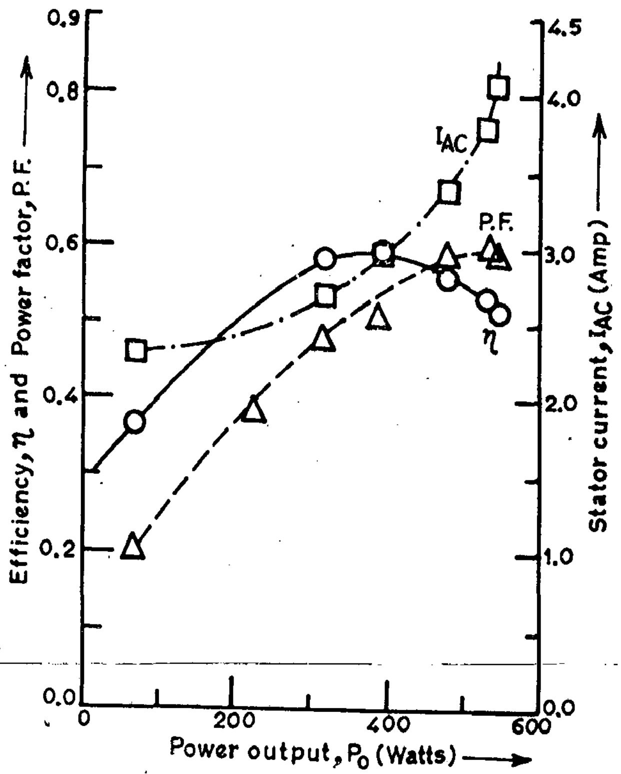

FIG.4.11: VARIATION OF EFFICIENCY STATOR CURRENT AND POWER FACTOR WITH POWER OUTPUT FOR POLE ARC TO POLE PITCH RATIO (β=0.45, V=400 Volt and F=30Hz).

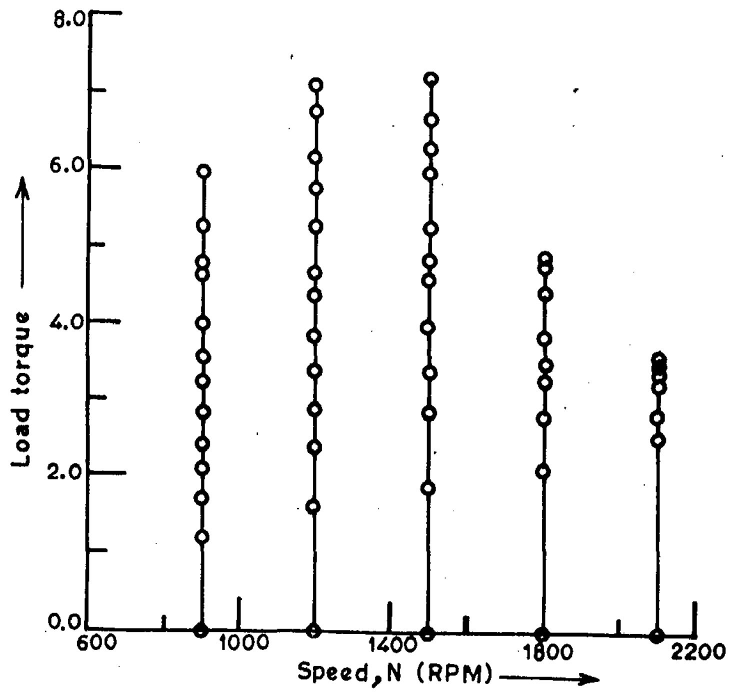

FIG.4.12: VARIATION OF LOAD TORQUE WITH SPEED FOR POLE ARC TO POLE PITCH RATIO (β=0.31).

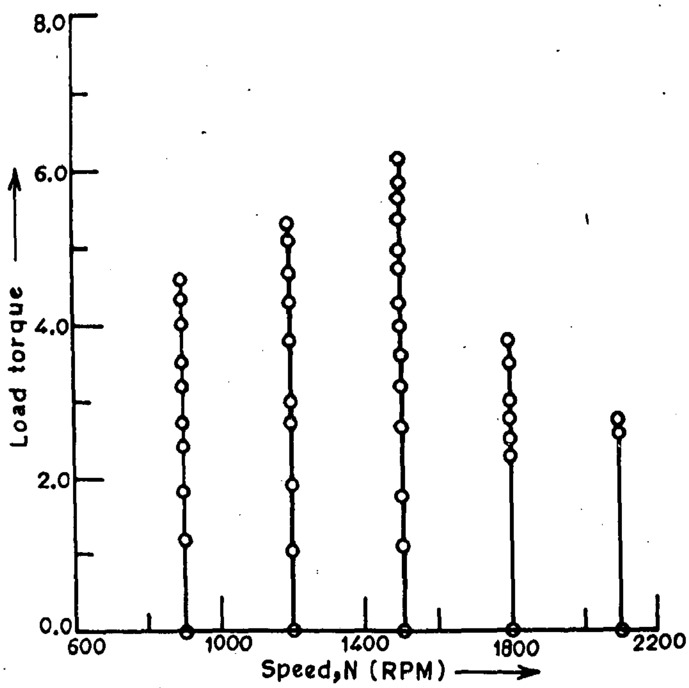

FIG.4.13: VARIATION OF LOAD TORQUE WITH SPEED FOR POLE ARC TO POLE PITCH RATIO ($\beta = 0.39$).

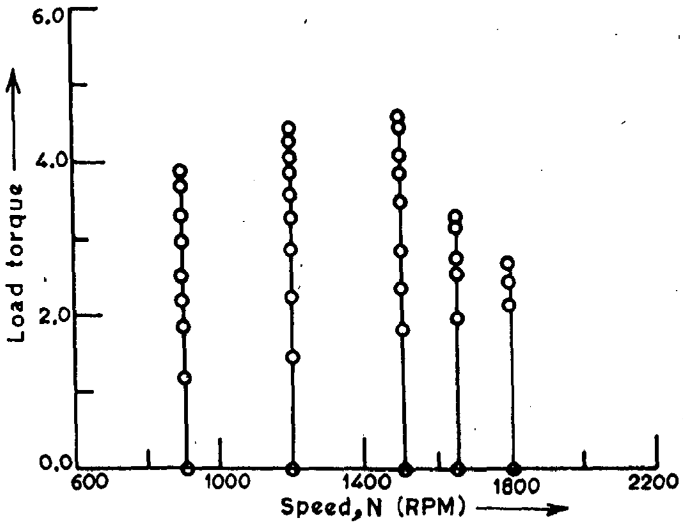

FIG.4.14: VARIATION OF LOAD TORQUE WITH SPEED FOR POLE ARC TO POLE PITCH RATIO ($\beta = 0.45$).

for 50 Hz supply frequency condition. For all the three rotors the torque capability decreases for lower as well as higher frequencies.

4.4 CONCLUSIONS

The various performance characteristics have been obtained experimentally on the developed reluctance motor having three rotors of different pole arc to pole pitch ratio at rated and variable frequency. From these characteristics it is concluded that the rotor of pole arc to pole pitch ratio (0.39) is found to be better on the over all performance basis. The stator current is found to be minimum at 360 V for a load (1223.3 W) with the rotor of pole arc to pole pitch ratio (β =0.39). It is observed that the motor show an unstable behaviour at lower value of frequencies (around 4 Hz) for all the three rotors. Where as the motor shows stable operation over the wide range of excitation level (voltage at 50 Hz), and upper range of frequency with all the three rotors.

CHAPTER - 5

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

5.1 MAIN CONCLUSIONS

The work reported in this dissertation covers the development and performance characteristics of improved reluctance motor. Three rotors of reluctance motor are fabricated here based on computer aided design results for its optimum steady state synchronous performance. The various performance characteristics have been obtained experimentally on the developed reluctance motor for all the three rotors. The scope and main conclusions of the present work are summarised as follows.

(i) An approach for computer aided design of polyphase reluctance motor has been developed based on three different criteria. The stator of reluctance motor is taken as of cage motor of standard rating and only rotor design parameters are considered as variables for improving its design. Out of all rotor dimensions, the pole arc to pole pitch ratio (β) is most effective and considered as independent variable in computer aided design. The optimum value of pole arc to pole pitch ratio for first criterion has been found to be 0.31 for minimum stator current (3.57A) at a given output power (2200W) and designs are not found feasible for the value of pole arc to pole pitch ratio greater than 0.38. In the second criterion, the maximum output power (1450W) for a given stator current (2.59A) has been obtained on pole arc to pole pitch ratio value (β =0.39 and designs are not feasible for the value of pole arc to pole pitch ratio (β) less than 0.21 and greater than 0.56. In the third criterion the maximum output power (2215W)for a given total losses (620W) is found on the pole arc to pole pitch ratio (β)=0.31 and designs are not feasible for pole arc to pole pitch value less than 0.13 and greater than 0.45.

(ii) From the computer aided design results, it is concluded that the designs for first and third criterion are very close to each other and have higher efficiency and reasonable power factor under normal condition. However the design results of second criterion provides the output power lower than the third criterion and at reasonable higher value of pole arc to pole pitch ratio. In general, it is observed from computer aided design results that the reluctance motor has larger stator current and lower value of power factor compared to cage induction motor of same rating.

(iii) It is concluded that the proposed computer aided design approach is simple and requires small computational efforts and may be used for the design of different rating motors.

(iv) The rotors of poly phase reluctance motor have been fabricated using the dimensions obtained from computer aided design. The various tests have been conducted on the developed motor with all the three rotors. It is concluded based on experimental investigations that no load current and no load losses are increased on the decrease of pole are to pole pitch ratio. Moreover, the direct axis and quadrature axis reactances are decreased on the decrease of pole arc to pole pitch ratio and also on increase of excitation levels. However the ratio of direct axis to quadrature axis reactances is increased with the increase of pole arc to pole pitch ratio.

(v) It is concluded that the pull in performance deteriotes on the decrease of pole arc to pole pitch ratio and it is improved by providing the short circuit ring of conducting material in quadrature axis channels around the pole body. The improvement in pull in performance is more for rotors of having lower value of pole arc to pole pitch ratio.

(vi) From the load performance characteristics, it is concluded that the stator current increases with load in all the three cases and it is increased with lower value of pole arc to pole pitch ratio for a particular value of load. However, power factor and efficiency increase initially with load and decrease after a certain value of load. These are found to be maximum at a particular value of load which are of different values for all the three rotors. The amount of load of having maximum efficiency and power factor increases with decrease in pole arc to pole pitch ratio.

(vii) From the test results, it is found that pull-out power and overload capacity increases with the lower value of pole arc to pole pitch ratio. However the possible safe output power for a given current (2.59A) is found to be maximum with rotor of higher value of pole arc to pole pitch ratio and corresponding applied voltage is also to be on higher side. But the rotor of pole arc to pole pitch ratio (β) = 0.39 also gives the results comparable to the rotor of higher value of it (0.45).

(viii) Having found the rotor of pole arc to pole pitch ratio (β) = 0.39, to be better on the over all performance basis. The effect of excitation level is also studied on this rotor. For a load of (1223W). The stator current is found to be minimum (2.57A) at the optimum voltage level of 360V. However, this optimum level of voltage also increases with load.

(ix) For the motor operation fed cfrom variable frequency source, it is found that the motor shows an unstable behaviour at low frequencies (around 4 Hz) but it gives quite stable operation over wide range of excitation level and on upper frequencies with all the three rotors.

(x) However, on variable frequency, maintaining V/F constant upto 50 Hz and constant voltage at greater than 50 Hz), the safe output for the rated stator current is found to be maximum for rotor having pole arc to pole pitch ratio of (0.31) in higher frequency range (peak at 60 Hz) and it is also found higher power output with rotor having pole arc to pole pitch ratio (β) = 0.39 for frequency less than 50 Hz.

Based on the investigations carried out it is concluded that the poly phase reluctance motor under test, gives the overall improved performance with rotor having pole arc to pole pitch ratio of 0.39. The motor with rotor of pole arc to pole pitch ratio (β) = 0.31 draws higher stator current at no load as well as on load and it results in inferior pull-in performance. However on the other hand the motor with rotor of pole arc to pole pitch ratio (β) = 0.45 is not capable of giving even the output power equal to cage motor and its pull-out power capability is also low.

5.2 SUGGESTIONS FOR FURTHER WORK

As every thing has got its own limitations this dissertation is also no exception. Although the main objectives of the present investigation have been successfully realised. However, this work can be extended on the following aspects.

(i) The proposed design approach may be employed for different rating reluctance motors in order to finally establish the computer aided design procedure.

(ii) The computer aided design package must also include the start up and pull in performance subroutines for successful design in all respects which are not considered at present in computer aided design package.

(iii) In the present investigation, the stator of reluctance motor is considered same as of standard cage motor, but in the design procedure the stator design variable may also be considered in seeking optimum design of reluctance motors.

(iv) In the proppsed work, standard conventional shape of rotor is used, however different shapes in computer aided design package as well as for fabrication may be considered for improving the design of reluctance motor.

(v) Here, the rotors are fabricated of mild steel, However rotors may be fabricated with improved magnetic material. Moreover the quadrature axis channels may also be filled in with conducting material for better starting and pull-in performance.

(vi) The analysis package may also be developed for stability studies for variable frequency operation and to be included in the design procedure.

(vii) The reluctance machine may be designed and fabricated for generator applications of high speed prime movers and with capacitor excitation due to its robustness.

(viii) The design approach may also include the aspects of converter-inverter fed reluctance motor for its variable frequency operation.

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APPENDIX - 1

Following are the different specified parameters, of the motor selected, used in computer programme in order to get its optimized steady state synchronous performance.

Rated power (PR)	= 2200 W
Rated Voltage (V), Volts	= 400
Rated Current	= 4.5A(L) = 2.59 A per/phase
Leakage reactance (X_L), ohms	= 25.6
No load losses (P_{LN}), Watts	= 226.41
Rated frequency (FR), Hertz	= 50
Number of poles (P)	= 4
Magnetizing reactance (X_c), ohm	= 305.99

Here no load losses (P_{LN}) and magnetising reactance (X_c) are obtained by conducting synchronous machine test and stator winding resistance test on the motor selected for the experimentation work.