# DESIGN IMPROVEMENT OF INDUCTION MOTORS FOR ADJUSTABLE SPEED DRIVES

A DISSERTATION

*Submitted in partial fulfillment of the*
*requirements for the award of the degree*
*of*
MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in Power Apparatus & Electric Drives)

By

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**MANTAJ KAUR**

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# CANDIDATE'S DECLARATION

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I hereby declare that the work that is being presented in this dissertation report entitled **"Design Improvement of Induction Motors for Adjustable Speed Drives"** submitted in partial fulfillment of the requirements for the award of the degree of **Master of Technology in Electrical Engineering** with specialization in **Power Apparatus and Electric Drives,** submitted in the **Department of Electrical Engineering, Indian Institute of Technology Roorkee,** Roorkee, is an authentic record of my own work carried out, under the guidance of **Prof. Pramod Aggarwal,** Professor, Department of Electrical Engineering, Indian Institute of Technology Roorkee, **Prof.S.P.Srivastava**, Professor, Department Of Electrical Engineering, Indian Institute Of Technology, Roorkee.

I have not submitted the matter embodied in this seminar report any other degree.

Date: 30/06/08
Place: Roorkee

30/06/08
**(MANTAJ KAUR)**

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## CERTIFICATE

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

**Prof. Pramod Aggarwal**
Professor,
Dept. of Electrical Engineering,
IIT Roorkee,
Roorkee – 247667.
India

**Prof. S.P.Srivastava**
Professor
Dept. of Electrical Engineering
IIT Roorkee
Roorkee – 247667.
India

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(MANTAJ KAUR)

Enrollment No:064107

# Abstract

The Induction motors are widely used in the industry, because of their simplicity, robustness & maintenance free operation. But to overcome the use of the DC motors they had to be supplied by the flexible three phase sinusoidal power supplies. This had been made possible with the advent of the solid state devices in the field of the ac drives. Nowadays, the advanced adjustable speed drives powered through power converters, are burning topic of discussion. They provide the desired flexibility in the speed torque characteristics of the Induction motors, as per the requirements.

This is obtained at the cost of the high harmonic contents in the input power supply of the motor, injection of harmonics in the power distribution line and greater chance of failure of the Induction motor due to high losses and heating.

A lot of modifications of the basic adjustable speed drives are available today, to overcome these problems in the adjustable speed drive, but less has been focused on the main part of the drive i.e. the motor itself. The design of the machine is the main factor which can compensate for the ill effects caused due to the harmonics present it the input of the motor.

Also the design and the optimization procedure had reached the new heights due the introduction of the new machine design softwares and the computer aided design technologies.

Here a new optimized design of the induction machine is presented with the help of the machine design software SPEED which is introduced by the University of Glasgow. The factors like temperature rise and maximum flux density are taken in consideration automatically in the SPEED software design, hence making the design optimization easier. The new machine is designed to give a suitable operation under adjustable speed drives with the harmonics present in the input power of the machine by reducing the losses in the machine and the wide range of the speed is available due to high breakdown torque.

In the present work, the main considerations of the high efficiency and high breakdown torque are taken into consideration for the adjustable speed drive, to make the machine suitable for operation under the harmonics in supply. Different rotor bars are studied and the best among them is searched out.

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# 1. INTRODUCTION

This chapter consists of the introduction of the work done in thesis. It gives the statement of the problem and a review of the previous stepwise growth of the work done in this field. The organization of dissertation is given in the end of the chapter.

## 1.1. Introduction

The development of the mankind and the high status of living of human being today are actually attributed to the development of the Electric motors in a big way. What is the field today where the electric motors are not used whether its ac or dc. But which one among them is better is still a matter of discussion.

The interesting history of competition between dc and ac might be considered as a battle. When Tesla had invented the induction motor in 1888, there was no polyphase ac system in operation. Although ac system, including induction motors was on winning side of battle, the dc motor survived the battle because of its superior controllability. The ac motor in itself can't match the dc motors in controllability. Railway trains are still driven by dc motors, most robots are operated by them, and small motors in computer accessories recorders and so on are dc motors.

For a century ac motors have suffered from problems regarding their controllability. Induction motors are awkward in their start and stop operations. They are inferior in speed control and torque control response is not as quick as that of dc motors.

The basis of these limitations does not lie in ac motors themselves but in ac power supplies. Voltage and frequency are fixed and difficult to change. The advent of thyristors has helped the dc motors more than ac motors by increasing the controllability of dc power supplies and reducing the cost.

Further development in power electronics is changing the scenario of ac power supplies. The PWM inverter has become practical, thus the inferiority of ac motor to dc motor is disappearing. But the use of these Power electronic power supplies had opened a new area of challenge for the non sinusoidal operating devices-Power supply pollution.

Till now the focus of the researchers and engineers had been more on the modification of the power supply side for not only fast and better controllability of the induction motors but also for the compensation of the pollution due to these power supplies. But there is a simpler and better way to compensate for the ill effects of the power supply pollution, which is also referred as the harmonics of the supply.

The variation in the design of the induction motors can suppress the harmonics and its ill effects and the better performing machines could be obtained which can give a high performance and also reduces the cost and constraints being imposed on the power supply design. Not only this, a better design of the machine can also reduce the operating cost of the machine to great extent, hence resulting in the better acceptance of the ac induction machines. Thus this dissertation is an attempt to look into the design aspects of the induction machine which can give a better performance even in the presence of the power supply pollution.

## 1.2. Statement of problem

The main aim of the dissertation is to design an induction machine which can compensate for the ill effects of the non sinusoidal supplies on the induction machine and take care of the requirements of the adjustable speed drives. This work is not a one step work but includes a lot of small jobs in it. The breakup of the dissertation work done could be given as follows.

- To look into the effects of the Non sinusoidal power supplies on the induction machine operation.
- To study the design of the sinusoidal supply induction machine and considerations taken while the design procedure.
- To design a sinusoidal induction motor and study the variable and constraints and effect on the objective function of the induction motor.
- Study of the difference of the design requirements of the induction machine for the adjustable speed drive, of the same rating as in sinusoidal supply operation.
- Select the variables and the constraints of Induction motor for the variable frequency supply operation.
- Design the Induction machine for the variable voltage variable frequency supply.
- To sum up the main differences between the design of the induction machine for sinusoidal supply and induction machine for the adjustable speed drive, and the factors affecting the design of Induction motor.

## 1.3. Background and literature review

*Induction motors are used extensively in homes and in industry. It is most popular electrical* motor and more are produced each year than any other motor. Induction motor in itself is a very superior motor being simple in structure, robust and easy to maintain, very reliable. But its performance depends on power supply and control methods used. The block diagram of the most generally used control strategy is given below

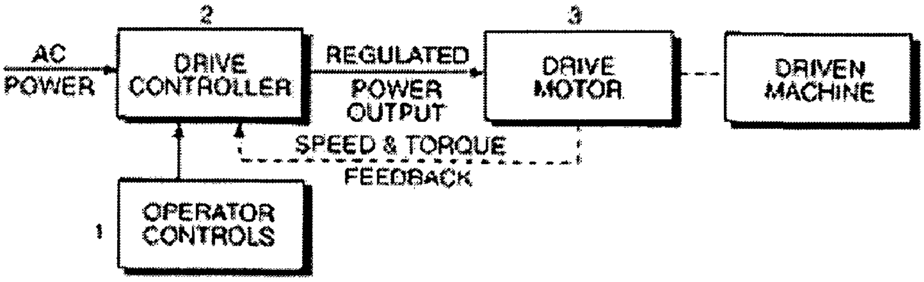


Fig.1.1. Block diagram of adjustable speed drives[2]

For making the controllability of the Induction motors superior, various kinds of adjustable speed drives are used. The semiconductor part of the drive comes in the block number 1 and 2 and in the feedback branch.

These power semiconductor controllers are the main sources of the harmonics. The harmonics present in the supply deviate the operation and performance of the motor from the normal sinusoidal supply operation. The effect is quite pronounced and the hence the need of the study of harmonics effect on the adjustable speed drive is necessary.

### 1.3.1. Impact of harmonics on Induction motors

Induction motors are the largest component of the load and they are widely used in industrial, commercial and residential applications. Therefore the study of impact of induction motors under harmonics voltage has drawn the attention of many researchers. The study of this issue has been found since 1960's. It has been studied that the major impact of the harmonics on the induction motor operation is to increase the losses of the induction motors. The earliest effect of harmonics on the losses was summed up in 1964 by G.C. Jain[3]. But the better analysis was provided thereafter recently by Klingshirn et. al. in 1968[4] and then in the same year Chalmers et. al. [5]had elaborated the effect of harmonics on the various kinds of losses of the induction machines i.e. primary copper losses, secondary copper losses, core losses, skew leakage losses, end leakage losses, space harmonic MMF losses.

A further detailed insight of the stray load losses due to harmonics was given by Novotny et. al. in 1991 [6]. These calculations had referred the previous studies done by Alger et. al. in 1959 [8] on stray load losses for sinusoidal supply induction motor. Till date also the detailed analysis of stray load losses is the major focus of the researchers and with the new advanced tools like FEM the researchers had given the insight of the stray load losses and core losses in induction motors which even include the spatial location of losses and their dependence on slotting, switching frequencies[8] etc.

Apart from the major impact on the efficiency of the induction motor, harmonics affect the other performance parameters of induction motors. The torque pulsations induced in the motor were first analyzed in 1971 by Robertson et. al [9]. Also the impact on the stability of the machine was studied by Lipo et. al.[10] in 1969 and it was found that the stability of the motor depends on the compatibility of the converter used in drive and the motor. Other effects like noise and bearing currents are also the burning topics in field of harmonics and drive systems and had been studied in detail.

To sum up it could be said that the impact of the semiconductor power supplies have a lot of dimensions but the major and most fatal of them are the enhanced losses and torque pulsations

### 1.3.2. Harmonic suppression techniques

There had been different standards which prescribe the permissible level of the harmonic content in the drive systems [12].

- EN61800-3 (IEC1800-3) Adjustable speed electrical power drive systems
- IEC1000-2-2, Electromagnetic compatibility (EMC)
- IEC1000-2-4, Electromagnetic compatibility (EMC)
- IEC1000-3-2, Electromagnetic compatibility (EMC)
- IEC1000-3-4, Electromagnetic compatibility (EMC)
- IEEE519, IEEE Recommended practices and requirements for harmonic control in electrical power systems

With the discovery of the high harmonic contents in the output of the mostly used voltage source inverters and with the analysis of the ill effects of these harmonics not only on the motors which are being fed by them but also on the whole distribution system, various attempts has been made to compensate for these harmonics. A lot of research work had been done and is going on regularly to modify the drive systems in every which way possible, so that the problem of harmonics could be get rid of.

The strengthening of the power supply and using the high pulse rectifier reduces the harmonics to some extent [12]. This was the fact which had given birth to PWM technique and its various modifications. Other than increasing the number of pulses, the ways which can change the harmonic contents by the changing the form of the supply waveform is injection of harmonics intentionally. The injection of 3rd harmonic currents was pioneered by B.Bird et.al. in 1969 [13]. Then the other refined ways were given in coming years [14]. The flux compensation technique was also given a thought [15].

The harmonic problem is so elaborate that for the suppression of these harmonics from the supply, not only the new converter topologies were introduced but also special devices were added in the drive systems. The most basic form of the devices being used are chokes, reactors and capacitor banks which give the reactive power compensation [17]. The latest trends have new and special type of chokes to account for the varying loads on ASD, eg. Swinging chokes[16].

The most effective of all the techniques are the filters. The passive filters of different kinds are available like tuned single arm filter, tuned multiple arm filter [12], but have the disadvantage of the specific harmonic elimination. So the active filters were coined for harmonic elimination. Thereafter many modifications and refinements have been made in the active filter systems to suit the different requirements (combination of passive and active filters, use of instantaneous power theory in active filters [18] etc). But these filters are very expensive and even increase the size of drive.

Many subsequent ways were thought of and even the harmonic solutions had involved the latest technologies like SVM and genetic algorithms [19] for fault detection due to harmonics, integrated harmonic compensation. But still the harmonic problem stands unsolved.

The thought of the compatibility between the drive and the motor have also been discussed elaborately at times, but the adaptations were made in the drive systems and not in the motor. The idea of the changes in the design modifications in Induction motors is of the same time as the harmonic injection but now with the advanced ways of manufacturing and new advanced materials the idea has came into focus in recent times.

### 1.3.3. Previous Work on design modification of induction motors

It is well known that performance of any machine, other than the working conditions and the quality of input applied, largely depends on its design parameters. The same idea was involved with the new design of the induction machine when the ill effects of the harmonics on the induction machine were analyzed. The need of such an induction machine was felt which can give satisfactory performance even in the presence of the supply harmonics.

The initiative was taken by McLean et. al. [20] in 1969 when he, for the first times, focused on design of induction machine for square wave excitation. He had suggested the use of the multiphase motors, i.e. using more than three phases for the square wave excitation. It was explained that the use of the more phases will result in the following advantages.

- The harmonic amplitudes will be greatly reduced. As a result, the heating and harmonic losses will be reduced.
- The torque pulsation frequency will be increased resulting in an onset of low frequency torque pulsations at a much lower speed.

- It is possible to obtain an increased drive rating with standard inverter power modules due to the use of more modules of lower rating.

But the idea was not much attended. In late 70's leakage reactance effect and some more design considerations which can improve the induction motor performance for ASD were suggested, with the explanation of the effects of the harmonics by DeBuck [21] and Douglas Scholey[22].

In 1984 E.Levi [23] had put up the expressions for ASD motors analogous to the DC motors and hence evaluated the performance and given the idea of the choice of number of poles for the adjustable speed drive induction motors. He deduced the following equation for the determination of bore dimension in terms of its surface area

$$\pi DL = 30\frac{e}{n_L r N_{eff} B}$$

$$K = \frac{m N_{eff}^2 n_L r B}{15e/I} L$$

Where D is stator bore diameter, L is stack length, $n_L$ is load speed, B is flux density in air gap, r is gear ratio, $N_{eff}$ is effective number of series connected turns, K is current loading, m is number of phases, and e is electromotive force.

Henceforth, especially towards the end of 80's and in the 90's the design considerations and trade offs in Induction motors for the ASD operation were vastly analyzed. The effect of varying the number of poles [24] and the rotor slot shape were the most discussed topics for the design improvements. The selection of the number of poles for an inverter driven induction motor cannot be based solely on selecting the pole structure for minimum volume or weight. Inverter limitations, frequency, and distribution of losses and power factor must be considered [26]. Number of poles in ASDs is decided by taking into consideration the effect on the different type of losses [25]. Not only this, the number of poles does affect the equivalent circuit parameters largely for non sinusoidal supply operation.

Also different shapes of the rotor bars were considered to look into the effect of the changed slot shape and dimensions. The different rotor slot shapes are graded on the basis of their performance under harmonics or high frequency.

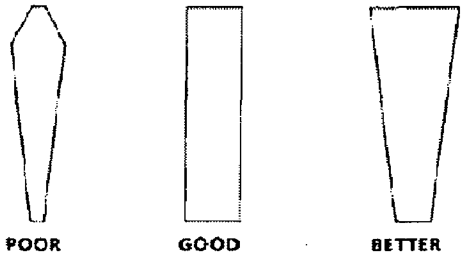


Fig.1.2. Rotor slot shapes for skin effect considerations [27]

The different slot shapes were introduced which can reduce the skin effect in the Induction machine rotor.

Other phenomenon like cross path resistance also affects the efficiency of the induction machine largely [28]. Also there is a need to carefully specify the rating of the ASD motors. The considerations for specifying the induction motors for ASD are quite different from the conventional induction motors [29].

The induction machines are required for different applications and the area of applications had even broadened with the advent of the semiconductor drives. Thus for different applications the focus should be given on different performance characteristics. There are specific design parameters in the induction motor design which if handled separately and carefully do give the required performance for specified operation of ASD. The cooling of the induction machine is one more factor which need proper care while induction machine operation under the non sinusoidal operation.

To seek out the parameters which specify the performance of the machine under harmonics different ways were introduced to get proper calculation of losses, torque pulsation etc., sometimes based on empirical formulas, sometimes based on the graphs of constants, and lately based on the FEM.

### 1.3.4. Optimization of Induction motors for ASD

With the various advances in the operation research and computer aided design methods the optimization had started playing an important role in the design of induction motors. Various optimization methods have been deduced which can give better convergence and proper result which had helped a lot in the better and better designs of the machine. Polyphase induction motor design optimization using a non linear programming approach was first carried out by Ramrathnam and Desai [30],[32]. Thereafter different non linear programming methods have contributed to obtain the induction machine design suitable for different applications. Further the latest techniques like fuzzy principles like genetic algorithm and simulated annealing are being used to get better performing induction motors design.

The optimization techniques are being used for the normal machine design since the 50's but the optimized design of induction machine supplied by the semiconductor supplies is recent. It requires the study of the constraints for the machine, and the variables are chosen in a different way as the requirement of the induction motors for the adjustable speed drives are quite different from the conventional induction motors.

In 1992 Bhim singh et. al. [31] had taken the torque pulsation as a constraint for the Inverter fed squirrel cage induction motor and minimized the cost of motor and the working cost of the motor. The method of optimization used was Rosebrock's method in conjunction with SUMT with interior penalty function.

Later the FEM was used for the optimization of the variable frequency driven three phase induction motors. Also the loss minimization was carried out in 2003 by K.S. Rama Rao et. al. [33] using unconstrained optimization methods with penalty function formulation.

## 1.4. Organization of dissertation

The dissertation mainly consists of a stepwise study of the design procedure of induction motor for variable frequency drives. Also while this design procedure the study of the design software SPEED is done and its features are studied. Mainly the dissertation is divided into six sections.

CHAPTER 1 is a review into the need of the adjustable speed drives and the previous work done to improve the overall performance of the Adjustable speed drives, and mainly the efforts done to design an induction motor suitable for the adjustable speed drives.

CHAPTER 2 helps in understanding the basic concepts of optimization and the various techniques of optimization. Also the factors which led to the selection of Rosenbrock's method for the design optimization of the induction motor are discussed.

CHAPTER 3 is a trial of gaining the knowledge of the SPEED software. Various features of the software are discussed. How the SPEED software is helpful in the design and analysis of the induction motors is described. Also the interface between MATLAB and SPEED are studied.

CHAPTER 4 is the complete problem formulation of the design optimization of induction motor. During this problem formulation the objective function, the constraints and the variables for the optimization are discussed. For selection of these parameters it is necessary to have clear knowledge of segregation between the design procedure and requirements for the direct on line operated induction motors and ASD operated motors, which is briefly described in the chapter.

CHAPTER 5 finally sums up the results obtained from all the study and design procedure. The factors affecting the design of induction motors for adjustable speed drives are mainly discussed.

And finally the dissertation work is concluded in the CHAPTER 6, with the knowledge gained during this dissertation work.

# 2. Harmonics generated and their effects

The source of harmonics and their effects are needed to be understood. The same is covered in the chapter. The pattern of the harmonics generated by main types of voltage source inverter is described. On basis of these order of harmonics the effect of on motor is studied.

## 2.1. Introduction

The harmonics generated in the adjustable speed drives depend mainly on the type of inverter being used. Many ways have been devised, which result in suppression of harmonics, but still the harmonic percentage in the input supply of motors is considerable. Once the harmonic rich supply is given at the motor terminals it affects the machines performance in an adverse way. It increases the losses and vibrations in the motor leading to an increased rate of failures of the motor. The final result is increased cost of maintenance and increased working cost. Although the flexibility of speed and torque control in the induction motors is revolutionary and advantageous, but the harmonics is the factor which is still limiting the wide acceptance of the induction motors in drive systems.

### 2.1.1. Adjustable Speed Drives

AC Adjustable Speed Drives (ASD) have become very popular variable speed control devices used in industrial, commercial and some residential applications. These devices have been available for about twenty years and have a wide range of applications ranging from single motor driven pumps, fans and compressors, to highly sophisticated multi-drive machines.

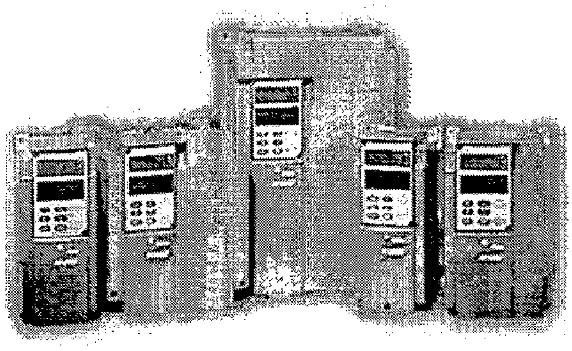


Fig. 2.1. The adjustable voltage and frequency power supplies

They operate by varying the frequency of the AC voltage supplied to the motor using solid state electronic devices. There are various kinds of adjustable speed drives. The most common among them is Variable Voltage Variable Frequency PWM Drives.

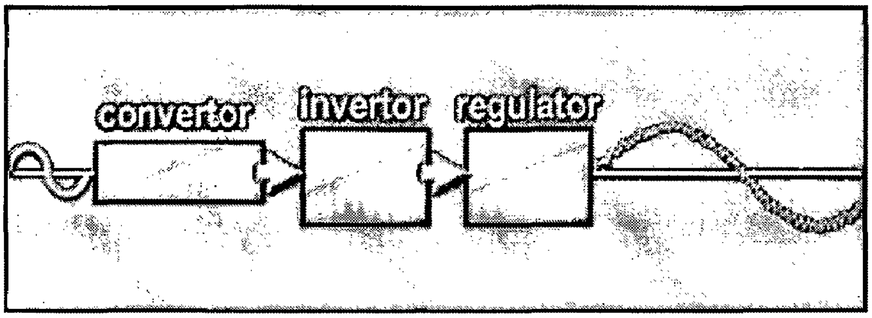


Fig.2.2. Block diagram of Adjustable Speed Drive power supply

Every ASD consists of a converter and an inverter. The converter works for the control of the magnitude of the output voltage by controlling the dc input to inverter and the inverter changes this dc into the ac and controls the frequency of the output with the help of the firing circuit.

## 2.1.2. Torque speed characteristics of Induction motor

In general the torque speed characteristics of the Induction motor follow the following equation

$$T_m = \frac{3R_rV_s{}^\wedge 2}{s\omega_s[\left(R_s + \frac{R_r}{s}\right)^2 + (X_s + X_r)^2]}$$

Where Rs, Rr are stator and rotor per phase resistances

Xs, Xr are stator and rotor per phase reactances

S is the operating slip

ωs is synchronous speed

Vs is the per phase stator voltage

For variable voltage and variable frequency drives as the option of varying the voltage and frequency is present the torque speed curve of same form but at different speeds could be generated.

The main base of the VVVF drives is actually to maintain the V/f (voltage and frequency) ratio constant so that the air gap flux in the Induction motor remains almost constant. In this way it performs the Torque speed control.

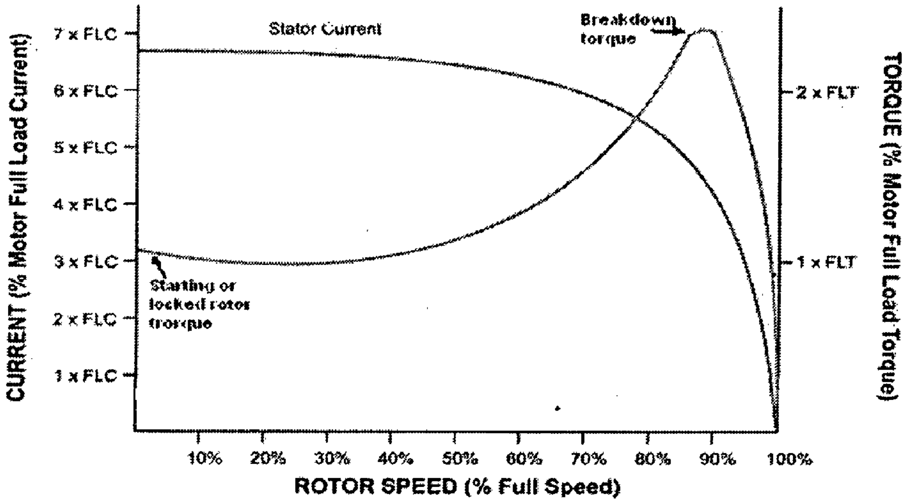


Fig.2.3. Speed torque characteristics for on line operating Induction motors

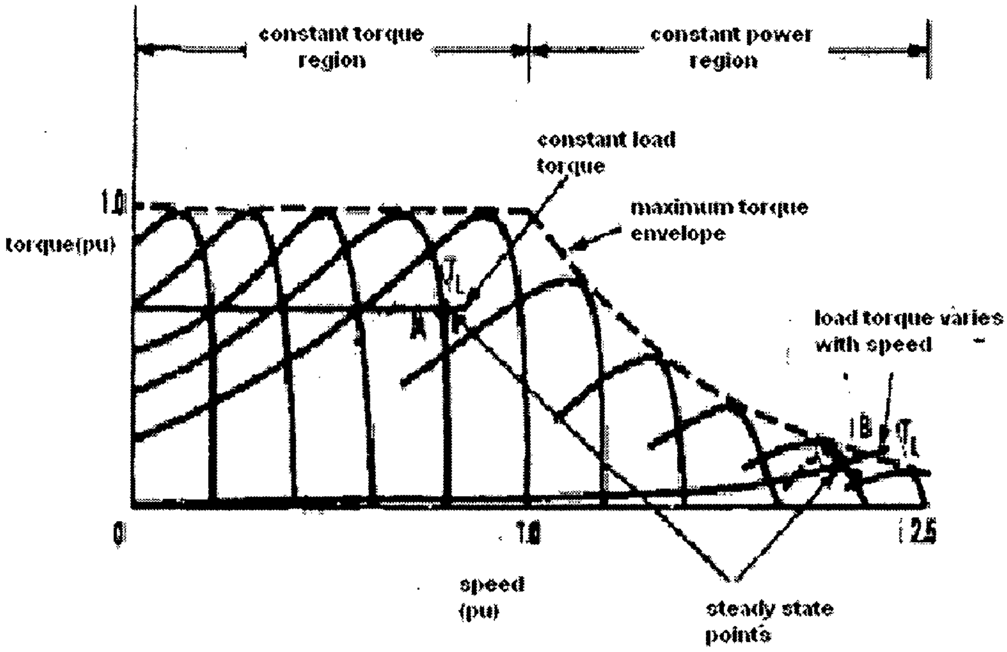


Fig.2.4. Speed torque characteristics for ASD Induction motors [34]

## 2.2. ASD Advantages & Disadvantages

Adjustable Speed Drives have a number of advantages and disadvantages compared to other types of variable speed controls including:

### 2.2.1. Advantages

- Energy Savings
- Improved Process Control
- Reduced Voltage Starting
- Lower System Maintenance

- Bypass Capability
- Multi-motor Control

### 2.2.2. Disadvantages

- Initial Cost
- Motor Heating at low Speeds
- Maintenance
- Output Harmonics
- Induced Power Line Harmonics

Here we will look into the main and foremost disadvantage of the Adjustable speed drives which is the harmonics produced in the output of the power supply of the adjustable speed drives. [12]

## 2.3. Harmonics produced in semiconductor power supply output

The harmonics produced in the semiconductor device power supplies depends mainly on the type of the circuit configuration used for the production of sinusoidal wave. The circuit configurations used are mainly of the voltage source type given below

- Square wave voltage source inverter
- Pulse width voltage source inverter

### 2.3.1. Square wave voltage source inverter

The line voltages produced at the output of the square wave voltage source inverter are of the following shape.

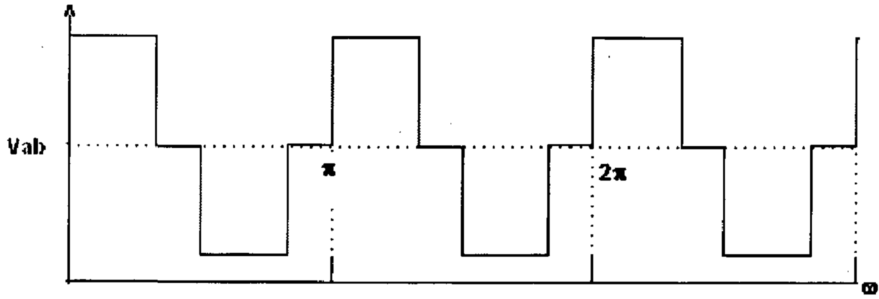
The line voltage expression of the output could be given as

$$v_{AB} = \frac{2\sqrt{3}\,V_d}{\pi}\left[\sin(\omega t) - \frac{1}{5}\sin(5\omega t) + \frac{1}{7}\sin(7\omega t) - \frac{1}{11}\sin(11\omega t) + \cdots\right]$$

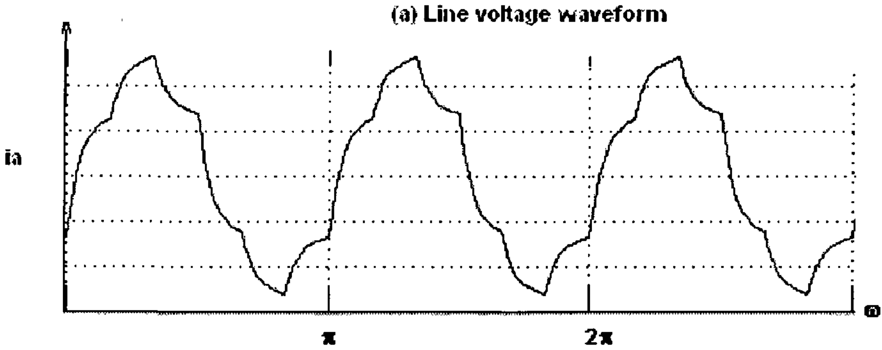
Hence it could be seen that mainly the harmonics present are of the order k=6n±1. The harmonic spectrum of the line voltage is given in fig.2.7.

### 2.3.2. PWM inverter

The PWM inverter output is rather close to the sinusoidal output but still it contains the harmonics. The output line voltage waveform is given below.



(a) Line voltage waveform



(b) Line current waveform

Fig.2.5. line voltage and current waveform at square wave inverter output

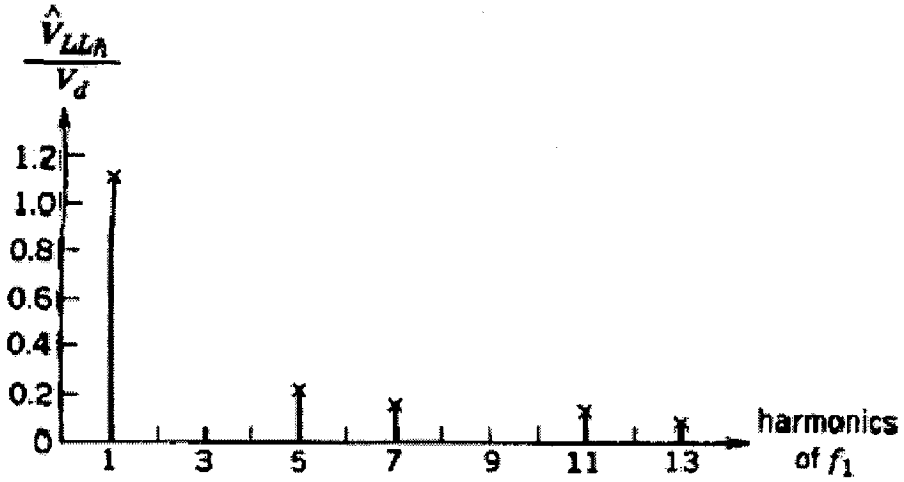
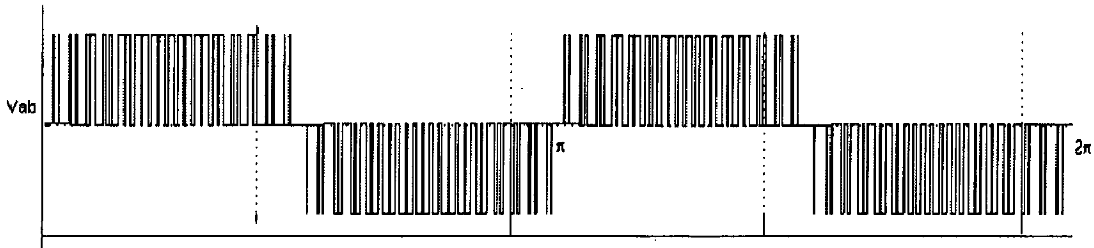
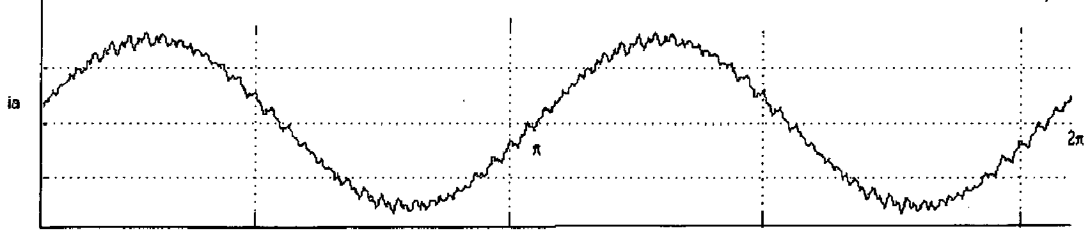


Fig.2.6. Harmonic spectrum for square wave inverter output voltage [34]



(a) Line voltage waveform



(b) line current waveform

Fig.2.7. line voltage and current voltage waveform of PWM inverter

The harmonics produced in the output voltage of the PWM inverter depends a lot on the frequency modulation ratio $m_f$

$$m_f = \frac{carrier\ frequency}{desired\ output\ frequency}$$

The carrier ratio $m_f$, determines the order of the predominant harmonics in the sinusoidally modulated pole voltage waveform. The analysis shows that the harmonics occur as sidebands of the carrier frequency and its multiples and, in general, the harmonic order is given by $k=nm_f\pm p$, the $p^{th}$ sideband of the $n^{th}$ carrier harmonic, such that n+p is always an odd integer.

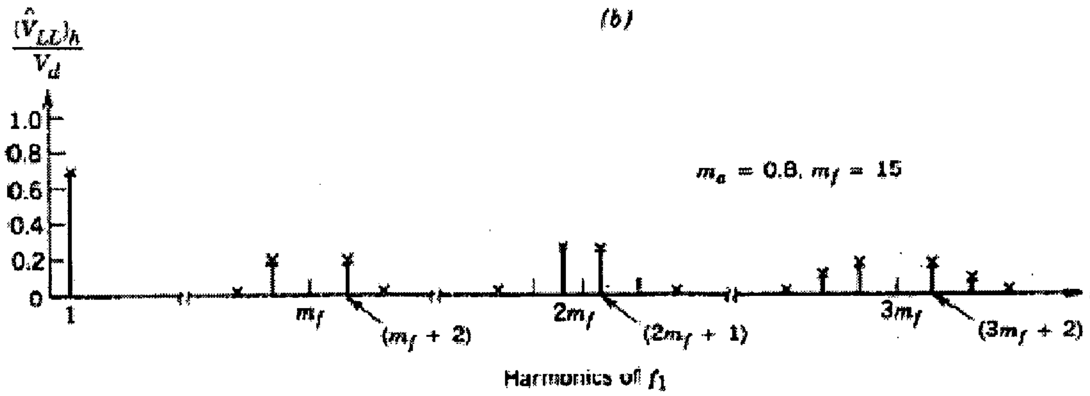


Fig.2.8. Harmonic spectrum of PWM inverter output voltage[34]

## 2.4. Effect of harmonics

The harmonics present in the airgap mmf could be divided into two categories depending upon its source.

- Space harmonics

- Time harmonics

The harmonics introduced in the machine due to the winding distribution and number of slots are known as space harmonics, whereas the harmonics inherently present in the input supply of the motor are known as time harmonics.

### 2.4.1. Time harmonics [1]

Time harmonics are produced by current harmonics in the phase windings. It is clearly known that the current harmonics of the order k=3n+1 produce forward rotating mmf waves, while the harmonics of the order k=3n-1 produce backward rotating mmf waves. The speed of the harmonic field is always k times the synchronous speed.

### 2.4.2. Harmonic equivalent circuit of induction motor [35]

The harmonic equivalent circuit is the most power tool for the analysis of the motor performance under different operating conditions. For the analysis of the motor under the non sinusoidal supply various harmonic equivalent circuits had been proposed. The one considering all the parameters is shown in the fig below.

In this figure, $V_k$ denotes the voltage harmonic of order, $R_{1k}$ the stator winding resistance, $R_{2k}$ the corresponding rotor resistance, $X_1$and $X_2$ the stator and rotor leakage reactances at fundamental frequency respectively, $X_m$ the magnetizing reactance at fundamental frequency and the $R_{mk}$ core loss resistance. $R_{l1k}$ and $R_{l2k}$ are resistors representing harmonic iron losses associated with stator and rotor leakage fluxes, respectively, placed in parallel with the corresponding leakage reactance terms.

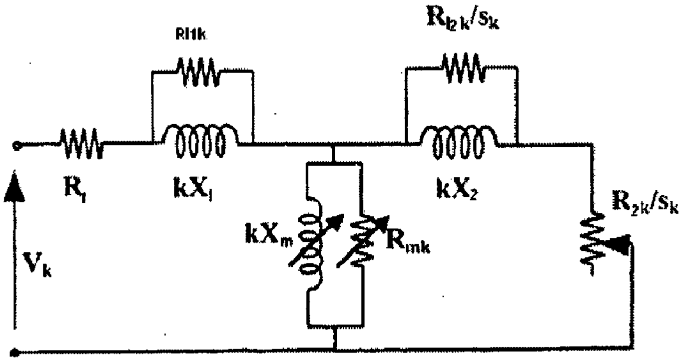


Fig.2.9. Harmonic equivalent circuit

#### 2.4.2.1. Equivalent circuit parameters

The actual frequency of the current in the stator is k f and in the rotor k f $s_k$, where f, is the fundamental frequency and $s_k$ is the slip for the $k^{th}$ harmonic. The synchronous speed corresponding to the applied frequency k f, is $kN_s$. Therefore, the slip $s_k$ at any speed N, of the rotor is given by

$$s_k = \frac{kN_s \pm N_r}{N_s}$$

The plus sign has been used to account for the fact that some harmonics result in rotating MMF's in the same direction as the motion of the rotor, while others result in rotating MMF's in the opposite direction of the motion of the rotor. In terms of the slip s (corresponding to the fundamental),

$$\mathbf{N_r = (1 - s)N_s}$$

And hence

$$s_k = \frac{(\mathbf{k \mp 1) \pm s}}{\mathbf{k}}$$

The stator and rotor resistances are also large due to skin effect at the harmonic frequency. Strictly speaking the rotor leakage inductance is also modified by the skin effect. The harmonic equivalent circuit can be modified by removing the parallel resistances with the stator and rotor reactance values. This is justified by the fact that inductive reactances increase linearly with frequency, while the increase in these resistances is nominal. Also the value of the magnetizing branch impedance becomes much greater than the rotor leakage reactances and hence may be omitted.

The resulting simplified harmonic equivalent circuit is given below.

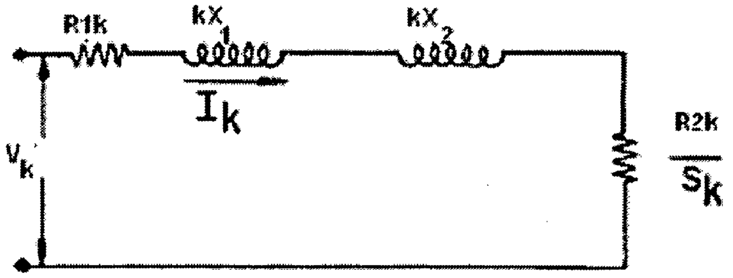


Fig.2.10. approximate harmonic equivalent circuit

For even more simplification sometimes the rotor and stator resistances are also eliminated, thus the resulting impedance will be $k(X_1+X_2)$ .

The effect of the harmonics on the motor performance characteristic will now be analyzed by using the equivalent circuit approach. The performance of the motor is discussed below

## 2.4.3. Harmonic currents [1]

Since $s_k$ is nearly unity at all speeds from standstill to synchronism, the harmonic equivalent circuit is practically independent of the motor speed. When the ac motor is fed by a voltage source inverter with a specific output waveform at a particular frequency, the harmonic currents remain constant at all operating conditions of the motor from no load to full load. The fundamental stator current is determined by the motor loading, and as a result the relative harmonic content is considerably greater at light load operations than for the full load condition. The approximate equivalent circuit is similar to the locked rotor induction motor circuit, when motor current is limited by the leakage reactance ($X_1$+$X_2$). Thus the standstill behavior of induction motor is a measure of its harmonic performance.

If $V_k$ denotes the $k^{th}$ harmonic component of supply voltage, the corresponding stator current harmonic is

$$i_k = \frac{V_k}{k}(X_1 + X_2)$$

As there are no zero sequence harmonics and no even harmonics hence total harmonic current is given by

$$\mathbf{I_{har}} = \sqrt[2]{\left(\mathbf{I_5}^2 + \mathbf{I_7}^2 + \mathbf{I_{11}}^2 + \cdots + \mathbf{I_k}^2 + \cdots\right)}$$

The rms value could be calculated as

$$\mathbf{I_{rms}} = \sqrt[2]{\left(\mathbf{I_1}^2 + \mathbf{I_{har}}^2\right)}$$

The $k^{th}$ harmonic current can be expressed in pu form as

$$\mathbf{I_k} = \frac{\mathbf{V_k}}{\mathbf{kX_{pu}}}$$

It is convenient to retain $X_{pu}$ as the per unit leakage reactance at rated frequency and to take account of frequency dependence of leakage reactance by means of a multiplying factor f1 which is per unit fundamental frequency. The kth harmonic per unit current at per unit fundamental frequency $f_1$is given by

$$\mathbf{I_k} = \frac{\mathbf{V_k}}{\mathbf{kf_1X_{pu}}}$$

Or

$$\mathbf{I_k} = \frac{\mathbf{V_1}}{\mathbf{k^2f_1X_{pu}}}$$

For variable frequency operation

$$\mathbf{I_k} = \frac{\mathbf{1}}{\mathbf{k^2X_{pu}}}$$

Hence it is clear that the harmonic current amplitudes are independent of supply frequency and motor load for voltz/hertz control.

The total rms pu harmonic current with six step voltage supply is evaluated a 0.046/$X_{pu}$

Thus the harmonic rms current is inversely proportional to the per unit reactance. The per unit leakage reactance of the induction motors is usually 0.1 to 0.2, and total rms current at full load on a six step voltage supply is 2 to 10 % greater than fundamental current. The harmonic distortion not only increases the rms value of the stator current but also produces large current peaks, which increase the required current rating of the inverter transistors or commutating duty imposed on the inverter thyristors.

## 2.4.4. Losses in motor

### 2.4.4.1. Stator copper loss [1]

The stator copper losses on a non sinusoidal supply are proportional to the square of total rms current. If $R_1$ is the stator resistance per phase, the total stator copper loss is

$$P_1 = 3{I_{rms}}^2 R_1$$

Or

$$P_1 = 3\left({I_1}^2 + {I_{har}}^2\right)R_1(\omega)$$

where, the second term represents the harmonic copper loss. It has been found that the harmonic current also increases the fundamental component, due to an increase in the magnetizing current. The magnetizing current increases because of the saturation of the leakage flux paths because of harmonic fluxes.

### 2.4.4.2 Rotor copper losses [1]

For large ac motors there is an increase in stator resistance with frequency which depends on the shape, size and disposition of the conductors in the stator slots. However the skin effect is much more pronounced in the cage rotor, which exhibits a significant increase in resistance at harmonic frequencies particularly in case of deep bar rotors.

In motors, the fifth harmonic mmf rotating backward and the seventh harmonic mmf rotating forward will induce rotor currents at 6 times fundamental frequency. Similarly rotor currents at 12 times fundamental frequency are induced because of eleventh and thirteenth harmonic mmf.

The rotor resistance is much greater than the dc value. The actual increase depends on the geometrical shape of conductor cross section and of rotor slot in which it is placed.

In general, for $k^{th}$ harmonic the rotor copper loss is

$$P_{2k} = 3{I_{2k}}^2 R_{2k}$$

$I_{2k}$ is the $k^{th}$ harmonic rotor current. Rotor leakage reactance reduces considerably due to skin effect thus a lower value of per unit reactance should be taken, which should be approximately 80 to 90 % of rated value.

The additional rotor copper losses are the primary cause of the reduced efficiency of the motors at non sinusoidal supply.

### 2.4.4.3. Harmonic core loss

The time harmonic waves by each harmonic current have same number of poles as fundamental field but rotate forward or backward at a multiple of fundamental speed.

However the resultant fluxes are small. Since the harmonic frequency is five times fundamental frequency, the fifth harmonic flux is only 0.02pu. Similarly 7th harmonic flux is 0.01 pu. These small time harmonic main fluxes cause negligible increase in core loss of the motor.

### 2.4.4.4. The end leakage loss [36]

The end leakage loss is the eddy current loss in core lamination due to the end winding leakage flux which enters the lamination axially. The end leakage flux is given by following expression [4]

$$W_{SE} = 0.3C_1 m \sum_{k=1}^{n} (I_k^{s})^2 k f_1.$$

$C_1$ is the machine constant and 0.3 is empirical power factor applied to leakage flux.

### 2.4.4.5. Skew leakage losses [2],[36]

There is a skew leakage effect in cage rotor in which rotor slots are skewed with respect to the stator slots. This construction results in an angular phase difference along core length between the peak values of stator and rotor mmf. If the airgap mmf of stator and rotor conductors balance one another midway along the core length there is a resultant radial airgap mmf as one moves axially in either direction. The skew mmf which is greater at core ends establishes skew leakage flux in the airgap that produces a core loss in stator and rotor lamination. For harmonics this flux changes at harmonic frequency in both stator and rotor thus these losses could be substantial at harmonic frequencies.

### 2.4.4.6. Rotor Zig-Zag Loss [36]

This loss is due to pulsating flux in the rotor teeth due to slot permeances and slot MMF harmonics. This flux induces currents in the rotor bars, with an $I^2R$ loss resulting. The analysis leads to an approximate equation:

$$W_{zz} = mC_{db}R_{2k}\left[C_o I_o{}^2 + C_l I^2\right]$$

The authors give curves to find machine constants $C_o$ and $C_L$ in their paper. -The parameter $C_{db}$ is a constant to account for the deep-bar effect at the slot harmonic frequency. $I_0$ is fundamental no load current.

### 2.4.4.7. Friction and windage losses

These losses are not affected by the harmonic introduction.

The increase in core loss is less predictable because it is influenced by the machine construction and magnetic material. The load on the machine has a significant influence on the loss, particularly at lower frequencies. The increase in loss with load can be attributed to the reduction in rotor leakage inductance (due to local saturation) which provides less effective filtering of the harmonics and leads to increased copper loss. At low harmonic frequencies the copper loss predominates.

## 2.4.5. Harmonic torques

### 2.4.5.1 Steady state harmonic torques[1]

The steady state harmonic torques, which are a very small fraction of rated torque, have negligible effect on motor operation. The $k^{th}$ harmonic torque $T_k$ can be calculated by the expression

$$T_k = \pm \frac{pm_1}{2\pi f_1}(I_{2k})^2\frac{R_{2k}}{s_k}$$

And the kth harmonic torque expressed as a fraction of fundamental torque is therefore

$$\frac{T_k}{T_1} = \pm\left(\frac{I_{2k}}{I_2}\right)^2\left(\frac{R_{2k}}{R_2}\right)\left(\frac{s_1}{k\mp 1}\right)$$

Or

$$\frac{T_k}{T_1} = \pm\left(\frac{\varphi_1}{k^2X_{pu}}\right)^2\left(\frac{R_{2k}}{R_2}\right)\left(\frac{s_1}{k\mp 1}\right)$$

Now considering the fifth harmonic torque in case of induction machine operating at six step voltage $\phi_1$ is kept unity. A threefold increase in rotor resistance due to skin effect is assumed that is $R_{2k}/R_2 = 3$, and the fundamental full load slip is 0.03. Thus the $T_5/T_1$=-0.24*10^-4/$X_{pu}^2$.This small counter torque due to negative sequence fifth harmonic is somewhat opposed to small positive torque due to forward moving seventh harmonic torque. The combined effect produces a very small value of the negative torque which opposes the fundamental torque. The overall effect is about 1 % reduction in steady state torque

### 2.4.5.2 Pulsating harmonic torques

Pulsating harmonic torque components are produced by reaction of harmonic rotor mmf with harmonic rotating fluxes of different order. Dominant pulsating torques arises from interaction between harmonic rotating currents and fundamental rotating flux.

The rotor currents induced by the fifth time harmonic field react with fundamental rotating field to produce a pulsating torque at six times fundamental frequency.

The seventh harmonic stator current also produces pulsating torque at six times the fundamental frequency. Similarly the eleventh and thirteenth harmonic produce a fundamental torque rotating at a speed 12 times the fundamental frequency

The pulsating torques has zero average value but their presence causes the angular velocity of rotor to vary during a revolution. At very low speeds motor rotation takes place in series of jerks or steps, and this irregular cogging motion sets a lower limit to the useful speed range of the motor. In certain applications, the speed fluctuation is intolerable. Abnormal wearing of gear teeth can also occur, particularly is torque pulsation coincide with the shaft mechanical resonance.

As the load torque angle increases at a rate of 6 times the fundamental frequency the torque due to fifth harmonic after time t could be given as

$$\mathbf{T = \varphi_1 I_5 \sin(\delta_5 - 6\omega t)}$$

Also for seventh harmonic

$$\mathbf{T = \varphi_1 I_7 \sin(\delta_7 + 6\omega t)}$$

Hence the net pulsating sixth harmonic torque is obtained as

$$\mathbf{T_6 = \varphi_1 \sqrt[2]{\left[I_5{}^2 + I_7{}^2 - 2I_5 I_7 \cos(\delta_5 + \delta_7)\right]} \cos(6\omega t + \beta)}$$

Where

$$\beta = \frac{\mathbf{I_5 \cos\delta_5 - I_7 \cos\delta_7}}{\mathbf{I_5 \sin\delta_5 + I_7 \sin\delta_7}}$$

In general the harmonic currents of order k=6n-1 and 6n+1, develop a pulsating totqueof order 6n with a per unit amplitude given by

$$\mathbf{T_{6n} = \varphi_1 \left[I_{6n-1}{}^2 + I_{6n+1}{}^2 - 2I_{6n-1} I_{6n+1} \cos(\delta_{6n-1} + \delta_{6n+1})\right]^{1/2}}$$

In general $\delta_{6n-1}$ and $\delta_{6n+1}$ are zero. Also with voltage supply, the kth harmonic current is given as

$$\mathbf{I_k = \frac{\varphi_1^2}{k^2 X_{pu}}}$$

Thus substituting this in the eqn above gives

$$\mathbf{T_{6n} = \varphi_1 [I_{6n-1} + I_{6n+1}]}$$

The dominant sixth harmonic pulsating torque is obtained when n=1. Thus

$$\mathbf{T_6 = \frac{\varphi_1{}^2}{X_{pu}} * 0.02}$$

From the above equation the sixth harmonic pulsating torque amplitude is in the range 20 to 10 % of base torque-with lower reactance machines obviously developing large torque pulsations. The field weakening could also be employed to reduce the pulsating torque. The harmonic currents produced by the inverter produce a sixth harmonic voltage ripple on the dc link capacitor, which amplifies the harmonic components in inverter output voltage. As a result harmonic current flow to the motor increases and sixth harmonic pulsating torque is amplified. It has been found that the low speed torque pulsations may be twice or three times the theoretical value predicted by analysis.

Low order torque pulsation can be avoided by supplying the motor with an improved voltage or current waveform, such as pwm waveform with sinusoidal modulation. However, it is characteristic of pwm technique that large amplitude torque pulsations are produced at higher switching frequency.

In pwm for a carrier ratio of 12 and a fundamental flux of 1 pu the dominant pulsating torque is therefore of order 24 and has an amplitude of 0.513 pu. There are additional ninth and fifteenth harmonic torques of amplitude 0.065 pu and 0.047 pu.

## 2.5. Conclusion

The harmonics in the input supply of the motor are big reason for the increase in the faults occurring in the induction motors. The increased losses and hence increased temperature rise result in the deterioration of the quality of the insulation and the grease provided in the motor and bearing structure. The wear and tear is high. Also due to the harmonics there are other problems. Torque pulsations result in vibrations in the motor, causing noise problems. Also the problem is severe because the vibrations could be maximized due to resonance.

Hence it could be summarized that the main problems in the induction motors supplied with harmonics which leads to all other problems are increased losses and torque pulsations.

# 3. Optimization techniques

This chapter deals with the mathematical programming techniques associated with the optimization problems. The terminology used in the optimization theory is introduced. The classification of optimization problems is given and various techniques available for the solution of these problems are discussed.

## 3.1. Introduction

In any engineering system while designing, fabricating or maintaining the system, engineers are required to take many technological and managerial decisions at several stages. It is expected that the decisions taken should lead to either minimize the efforts or maximize the gain. In any practical situation the ultimate goal can be defined as a function of certain decision variables. Thus the optimization can be defined as the process of investigating the conditions that give the maximum or minimum value of a function under given circumstances. There is no unique method available for solving all optimization problems with the same efficacy, and hence several optimization methods have been propounded to handle specific type of problems. The optimum seeking methods are commonly known as mathematical programming techniques. These techniques provide a means for finding the minimum or maximum of a function of several variables under a prescribed set of constraints.

## 3.2. General optimization problem and terminology

A general mathematical programming problem can be stated as

$$Find\ X(x_1, x_2, \dots\dots\dots\dots\dots\dots, x_n)$$

$$to\ optimize\ \ F(X)$$

$$subject\ to\ g_j(X)\ [< or >]\ 0, \qquad j = 1,2,3, \dots\dots\dots\dots, m$$

$$and \qquad l_j(X) = 0, \qquad\qquad j = m+1, \dots . p$$

Where X is an N-dimensional vector termed as the design vector, F(X) is called the objective function and $g_j(X)$ and $l_j(X)$ are respectively the inequality and equality constraints. The problem can be said to be unconstrained when p=0, and when p is greater than m the problem is said to have both equality and inequality constraints. In some problems only inequality or equality constraints may be present. The terminology used may be explained as follows.

### 3.2.1. Design vector

In any engineering system the design is controlled by several parameters and they are termed ads design variables or decision variables. In some of the problems the number of variables I too large and it is unwieldy to deal with such a large number of variables. Fortunately, in most of the designs certain quantities can be fixed at the outset and such parameters are called as assigned or preassigned parameters.

### 3.2.2. Design constraints

In order to produce an acceptable design certain restrictions are to be satisfied. The restrictions put on the design are collectively called as design constraints. They can further be classified into two types, i.e. functional constraints and side constraints, depending upon whether the restrictions refers to performance or some other physical limitations.

### 3.2.3. Objective function

In any design procedure under given circumstances several acceptable designs can be produced for different sets of design variables. The optimization process enables to select the best design on the basis of certain criterion with respect to which the design is to be optimized. This criterion, when expressed in terms of design variables is termed as objective function. In most of the cases the optimized design in case of one criterion may not necessarily be optimized design for some other criterion and hence selection of suitable objective function is one of the most important decisions in whole of the optimum design process.

## 3.3. Classification of optimization techniques

The optimization problem can be classified on the basis of the following

### 3.3.1. Existence of constraints

The problem may be typified as constrained or unconstrained depending upon whether the constraints are imposed or otherwise.

### 3.3.2. Nature of design variables

If a design vector for optimizing a function satisfying the restrictions put on the design is to be investigated, the problem is termed as a static problem. The problems in which the optimization depends not only on the set of variables but also on their trajectories through space are called dynamic problems.

### 3.3.3. Physical structure of the problem

In optimal control problems two types of variables, control (design) and the state variables, exist. The control variables govern the evolution of the system from one stage to another, whereas the functional behavior of system in a stage is described by the state variables. The other classification is that of non-optimal control problems.

### 3.3.4. Nature of equations involved

The nature of the expressions for objective functions and constraints decides the different categories of the problems, e.g. Linear, nonlinear, geometric and quadratic programming problems. In order to obtain an efficient optimized design, several methods have been developed considering a particular class of problems.

A problem can be said to be nonlinear (NLP) when any of the function amongst the objective or constraints function happens to be nonlinear. Problems in which these equations are linear may be classified as linear programming (LP) problems. A geometric programming problem (GMP) is one in which the objective function and constraints are expressed as polynomials in X, the design vector. A quadratic programming problem is a nonlinear programming problem with a quadratic objective function and linear constraints.

In short, the nonlinear programming problem can be considered to be a most general case and other problems as special cases of it.

### 3.3.5. Permissible value of design variables

There are certain optimization problems in which design variables are restricted to take only integer or discrete values. Such a problem is called an integer programming (IP) problem. If the variables are of continuous type and are permitted to take any real value, the problem is termed as a real value programming problem. The most practical cases consider both the integer (discrete) and continuous types of variables. Such problems are classified as mixed integer programming problems and are termed as MILP or MNLP depending whether they belong to the classification of linear or nonlinear problems.

### 3.3.6. Deterministic nature of variables

If the optimization problem contains probabilistic parameters the problem can be classified as stochastic programming problem and one with deterministic parameters is termed as deterministic programming problem.

The classification discussed above helps in deciding the nature of the problem and thereby an appropriate optimization technique can be selected for solution.

## 3.4. Methods of optimization

Various methods are used for solving optimization problems of different nature have been given by several authors.

The classical methods of differential calculus can be used to find the maxima or minima of a function of several variables and without any constraint. Another requirement with such methods is the demand for continuous differentiable functions with respect to design variables. In most of the engineering problems the analytical differentiation of functions is a difficult task and hence such methods have limited scope in the applications.

Dantzig put forth simplex method for linear programming in 1947. Kuhn and Tucker in 1951 *established the necessary and sufficient conditions for the optimal solution of programming* problems. For non-linear optimization of function works presented by Hooke and Jeeves [37] and Davidon [38] in 1959, Rosenbrock [39] in 1960, are worth noting, however the work presented by Fiacco and McCormick [40] has developed the subject to such an extent that any non linear optimization problem can be solved with ease.

As is very much evident that the motor design is a non linear programming problem hence for the optimization one method among the various available non linear programming problems have to be used. The various types of the non linear optimization methods are tabulated below in fig.3.1. to fig.3.3.

## 3.4.1. One dimensional minimization methods

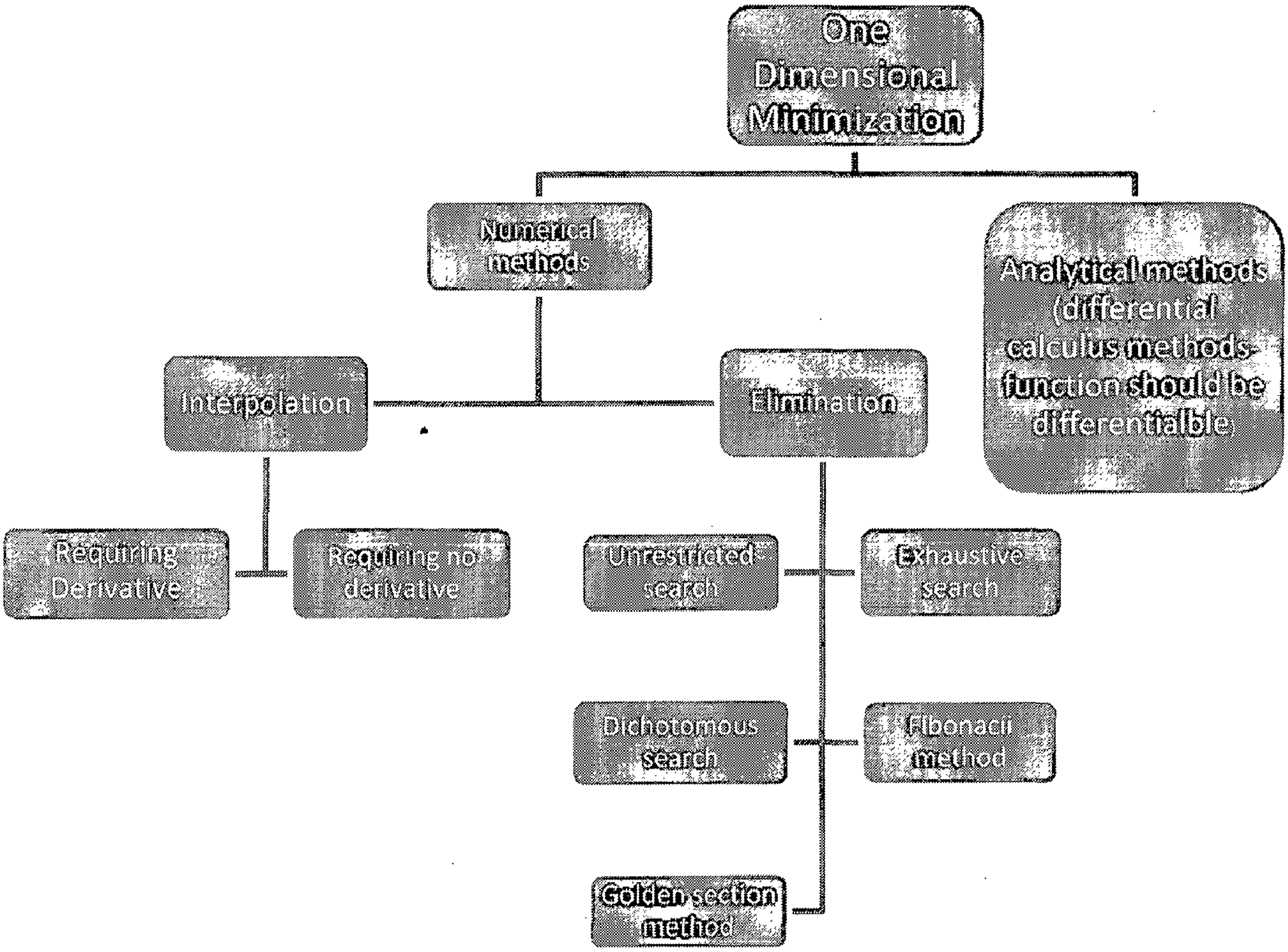


Fig3.1. various one dimensional minimization techniques

### 3.4.2. Constrained minimization method

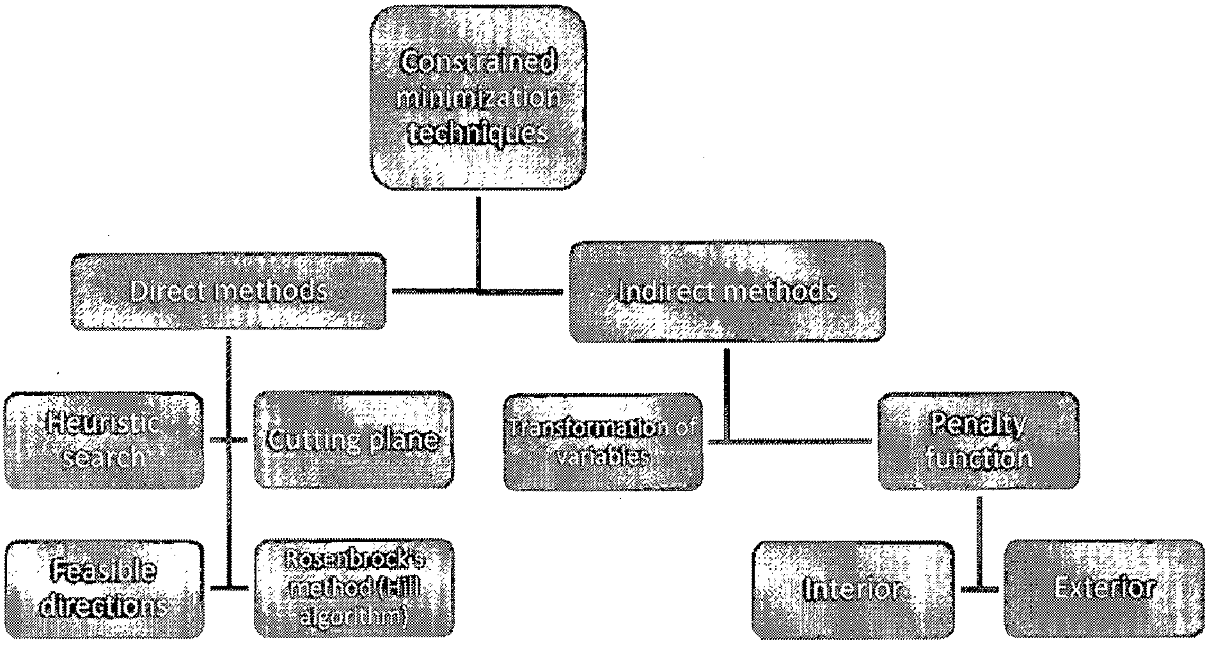


Fig.3.2. various constrained minimization methods

### 3.4.3. Unconstrained minimization method

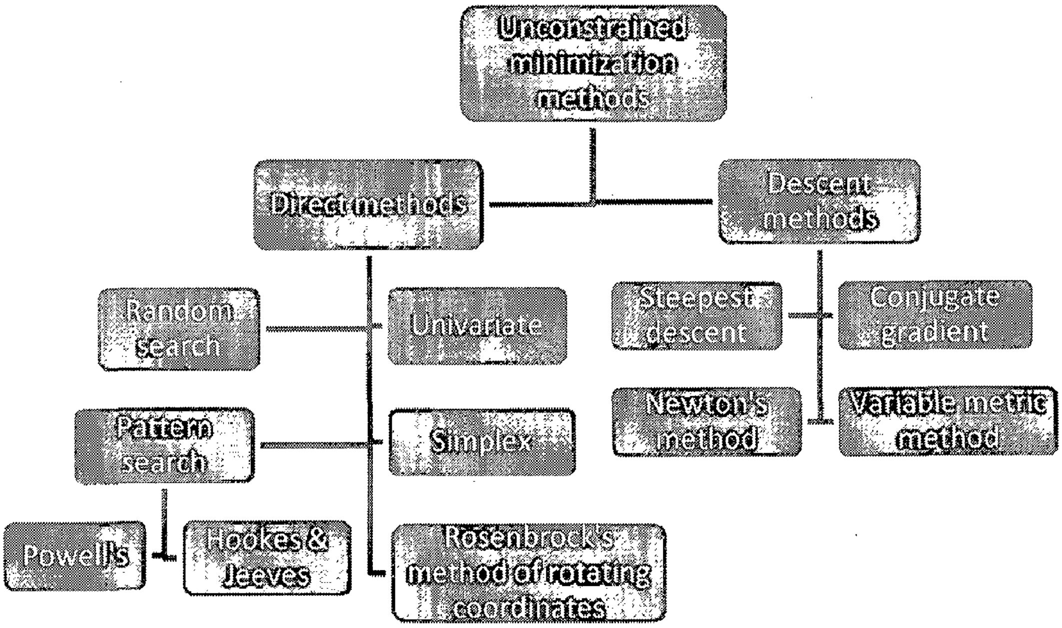


Fig.3.3. various unconstrained minimization methods

## 3.5. Choice of minimization technique

The theory of non linear programming is still in development, and computational experience with specific algorithms is limited.

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

- Nature of problem to be solved and required accuracy.
- The time necessary for preparation of the program. Available programs, if any for direct use and improvement
- The generality of program, necessity of derivatives, previous knowledge of the methods and their efficiency etc.
- The ease with which the program can be used and its output interpreted
- Computation facilities- Time taken for convergence

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

The constrained minimization techniques for nonlinear function and constraints are more justified to select. In this category amongst the direct methods, cutting plane method requires convex programming problem with objective function and constraints as nearly linear functions and hence cannot be used. Feasible directions methods are more effective for the problem using linear constraints or for linear programming problems. Heuristic search method (Box method) and Rosenbrock's method (Hill algorithm) can conveniently be applied for the induction machine optimization problem.

Hence the optimization technique selected for the optimization of machine design is the Rosenbrock's method.

## 3.6. Rosenbrock's method

The method is an iterative procedure that bears some correspondence to the exploratory search of Hooke & Jeeve, in which small steps are taken during the search in orthogonal coordinates. Instead of continually searching the coordinates corresponding to the directions of independent variables, the improvement can be made after one cycle of coordinate search by lining the search directions up into an orthogonal system, with the overall step on the previous stage as the first building block for the new search coordinates. This procedure is followed by Rosenbrock for optimizing nonlinear unconstrained problems with several variables. Constrained Rosenbrock method (Hill algorithm) developed is quite general and effective in solving the problem, however it requires starting feasible point satisfying constraints which are well within boundary zone. The program developed here is the improvement of Rosenbrock's method and does not necessarily requires a starting feasible point. If the starting point is not feasible, it searches for the feasible point and if no feasible point exists an error message is printed. This is actuated by incorporating an iterative search program in the method.

### 3.6.1. Algorithm

The algorithm for the method used proceeds as follows-

***Step 1)***- Read n, m (explicit plus implicit constraints) and number of stages (nn)

- Select starting point $X_i$ and initial step size $\lambda_i$, i=1,2 ,..............., n.

***Step 2)***- Calculate objective function and constraints

***Step 3)***- Check constraints. If satisfied, go to step 4, otherwise select another starting point using the iterative method and go to step 2. Continue the procedure till feasible point is obtained and then go to step 4.

If in a preselected range no feasible design exists, then print the error message and terminate the program.

***Step 4)***- Set i=1

***Step 5)***- Increment the variable $X_i$ with a discrete $\lambda_i$ parallel to the axis and evaluate the function.

***Step 6)***- Check the feasibility of the point. This is done as follows-

Define $F_0$, the current best objective function value for a point where the constraints are satisfied, and $F^*$, the current best objective function value for a point where the constraints are satisfied and in addition the boundary zones are not violated. Initially set $F_0=F^*=$ feasible starting point objective function. If the current point objective function, F, is worse than $F_0$ or if constraints are violated the trial is a failure, go to step 7.

If there is an improvement in the objective function and in addition the constraints and boundary zones are violated, set $F^*=F_0$ and go to step 8.

***Step 7)***- Record the failure and set $\lambda_i$(new)= $-\beta$ $\lambda_i$(old), The recommended value of $\beta$ by Rosenbrock is 0.5.

***Step 15)***- Stop

The flow chart for general Rosenbrock's algorithm is given on the next page.

overall step on the previous stage as the first building block for the new search coordinates. This procedure is followed by Rosenbrock for optimizing nonlinear unconstrained problems with several variables. Constrained Rosenbrock method (Hill algorithm) developed is quite general and effective in solving the problem, however it requires starting feasible point satisfying constraints which are well within boundary zone. The program developed here is the improvement of Rosenbrock's method and does not necessarily requires a starting feasible point. If the starting point is not feasible, it searches for the feasible point and if no feasible point exists an error message is printed. This is actuated by incorporating an iterative search program in the method.

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If there is an improvement in the objective function and in addition the constraints and boundary zones are violated, set $F^*=F_0$ and go to step 8.

***Step 7)***- Record the failure and set $\lambda_i(\text{new}) = -\beta\ \lambda_i(\text{old})$, The recommended value of $\beta$ by Rosenbrock is 0.5.

***Step 8)***- Record the success and set $\lambda_i$(new)=$\alpha$ $\lambda_i$(old), The recommended value of $\alpha$ by Rosenbrock is 3.0

***Step 9)***- Check whether all the variables are considered. If not set i= i+1 and go to step 5

***Step 10)***- Check convergence. If the number of stages prescribed exceeds the prescribed limit or if the change in the objective function or the vector components is smaller than the preselected value, go to step 15

***Step 11)***- Check for the success and failure.

If atleast one success and failure have been encountered in all directions, the stage ends. If so, go to next step. If success and failure are not encountered in each direction, go to step 4.

***Step 12)***- Rotate the axes. Each rotation of axes is termed a stage. The axes are rotated by the following procedure.

$$S_{i,j}^{(k+1)} = \frac{D_{i,j}^{(k)}}{\sqrt{\sum_{m=1}^{n}(D_{m.j}^{k})^2}}$$

$$where\ D_{i,1}^{(k)} = A_{i,1}^{(k)}$$

$$D_{i,j}^{(k)} = A_{i,j}^{(k)} - \sum_{e=1}^{j-1}\left[\left(\sum_{n=1}^{j} M_{n,e}^{(k+1)}.A_{n,j}^{(k)}\right).M_{i,e}^{(k+1)}\right] \qquad j = 1,2,\dots\dots\dots\dots,n$$

$$A_{i,j}^{(k)} = \sum_{e=j}^{n} d_e^{(k)}.M_{i,e}^{(k)}$$

Where *i= variable index=1,2,……………..n*

*j=direction index=1,2,………………..n*

*k=stage index*

*$d_i$= sum of distances moved in the I direction since last rotation of axes*

*$M_{i,j}$= normalized direction vector component*

***Step 13)***- Make a search in all the directions using the new coordinate axes.

$$X_i^{(k)}(new) = X_i^{(k)}(old) + \lambda_j^{(k)} M_{i,j}^{(k)}$$

Go to step 4

***Step 14)***- Print results of optimum design

***Step 15)***- Stop

The flow chart for general Rosenbrock's algorithm is given on the next page.

### 3.6.2. Flow chart

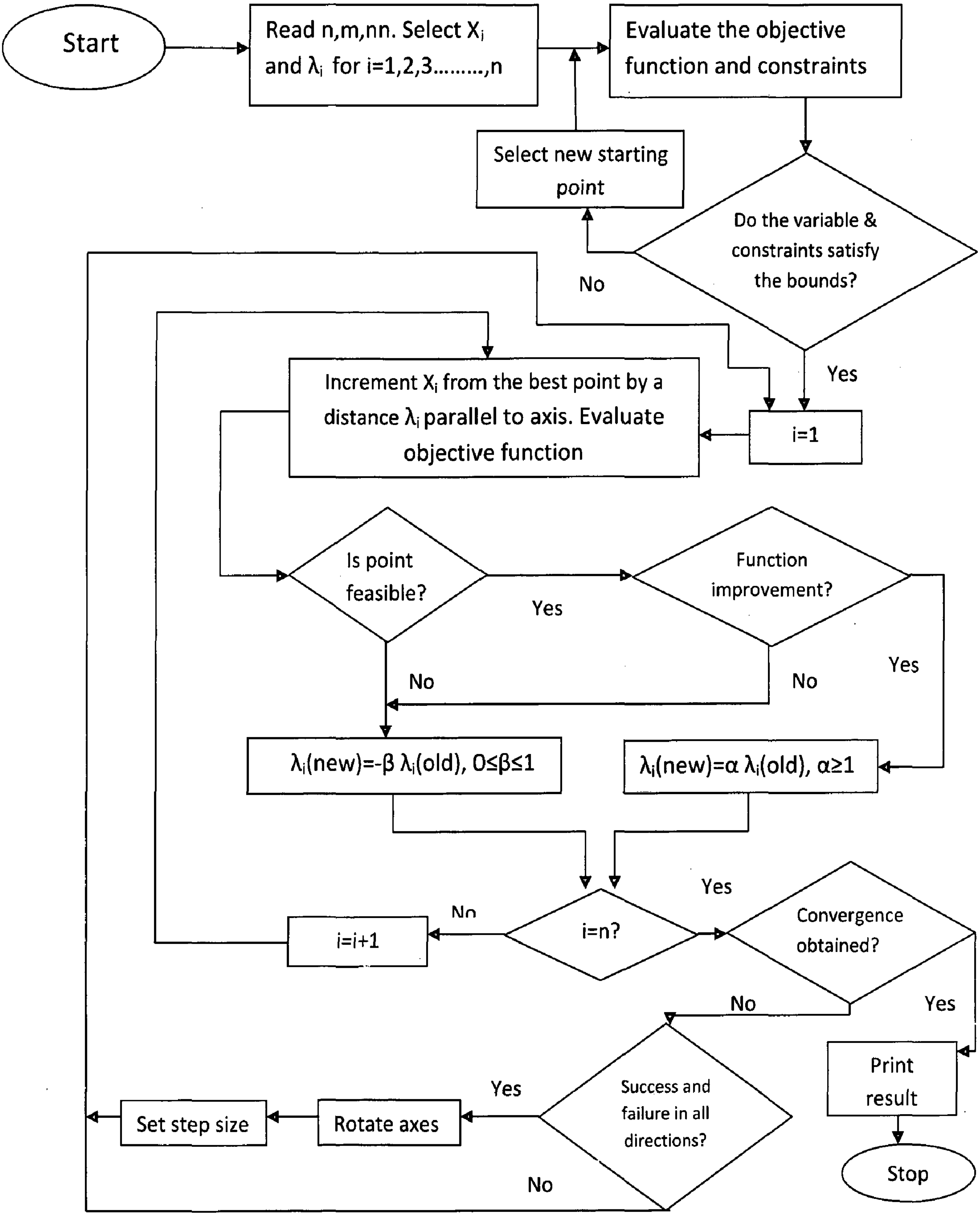


Fig.3.4. Flow chart of Rosenbrock's method

## 3.7. Conclusion

In this chapter the general optimization problem is stated and various terminologies are introduced. The optimization technique basics are described. The basis of classifying a problem and its classification is discussed in detail. The various types of nonlinear programming techniques used for optimization are given and among them a suitable method of optimization for Induction motor design is chosen. Also the algorithm and the flow chart of the Rosenbrock's method are explained to make the optimization procedure clear.

# 4. SPEED Software and machine design

The Induction machine is made simple by some of the principles developed on the basis of experience gained by machine designers. Also these principles are giving good results for a long time now. But the fact is true that the principles are not accurate for all situations and supplies. Also the need has been felt when the performance of Induction machine has to be evaluated for the unconventional working conditions. As all the electric machines involve the magnetic circuits and the shape of the machines is complex to study, hence to make the design and the analysis of the electric machines simple and effective, special softwares are being evolved. This chapter gives the insight of one such software used for machine design and analysis.

## 4.1. Introduction

Scottish Power Electronics and Electrical Drives (SPEED) is a software consortium with common interest in power and motor drive. SPEED was formed in 1987 by Professor T.J.E. Miller in the Department of Electronics and Electrical Engineering of University of Glasgow. SPEED software is designed for modern motors. It is available Induction motors (polyphase/single-phase), brushless permanent magnet motors (square wave/sinusoidal wave), switched reluctance motors, synchronous reluctance motors, and commutator machines. It run on the IBM PC platform, so it is easy to equip to multiple users in one company, including laptop users, It is easy to learn and use, and is provided with full documentation that include extensive information on the motor theory and design.

## 4.2. Features of SPEED programs

### 4.2.1. The outline editor

The user can modify the lamination geometry and quickly understand the relationship between design features and particular performance characteristics, an almost lost art, which used to take years to learn.

### 4.2.2. The graphical winding editor

It lets the user understand winding configurations, modify the winding, or build custom windings. It also displays the airgap MMF distribution and its entire harmonics graphically and in tabular form.

### 4.2.3. The template editor

It is for editing non-geometric parameters including those of the drive. It includes wire tables and database for steels, permanent magnet materials, carbon brushes, and power semiconductors. These databases can be customized and extended by the user.

### 4.2.4. The design calculator

Evaluates the design and performance data, including the thermal model, at a given speed and load. In most cases this takes only one or two seconds, computing as many as 500 output parameters. Speed is the key feature, with no waiting time; the user maintains concentration and progress quickly. SPEED software doesn't do the engineer's job. It eliminates calculation time and adds information that can hardly be calculated by hand.

### 4.2.5. Design sheets

Output is available in the form of design sheets listing the calculated parameters.

### 4.2.6. Graphical output

It includes waveforms of current, torque, speed, flux densities, and plots of radial forces and other specialized parameters.

## 4.3. Induction machine design in SPEED

PC-IMD is intended for designing and calculating induction motors. It is based on the classical theory of the induction motor, with several extensions to this theory developed by the SPEED Laboratory and its associates. The theory behind PC-IMD can be found in SPEED's Electric Motors manual.

### 4.3.1. PC-IMD's function

The main menu bar is of SPEED PC-IMD is shown in the figure. The Data, Analysis and Window menu items are added to the menu bar only when some data file is open. Also when the analysis is run the Result menu item gets activated. Also if there are some warnings or errors in design, the Warning item is highlighted in green color, whereas Errors item is highlighted in red. Other operations are shown in fig.4.1.

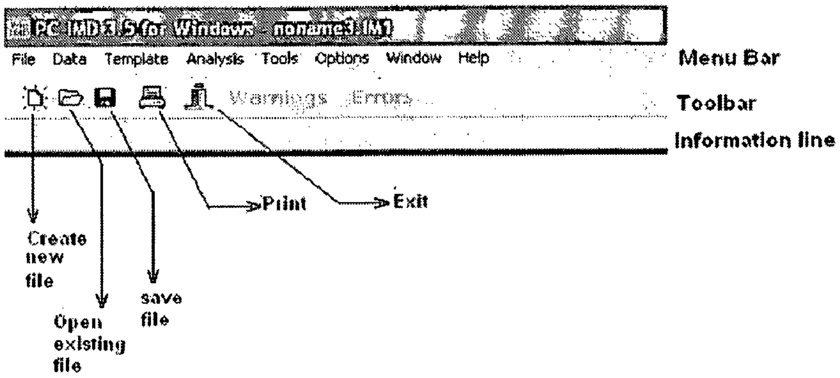


Fig.4.1. Main menu of SPEED

### 4.3.2. Creation of new file

For creating a new machine the Create new file icon is clicked. This opens the following box

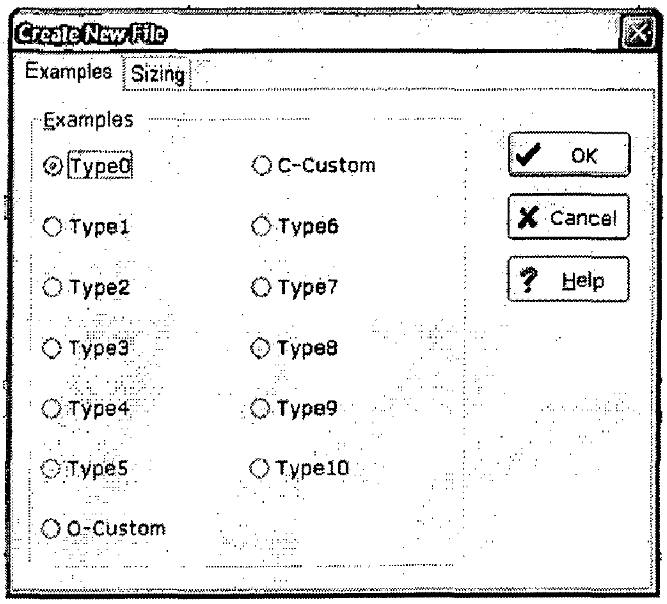


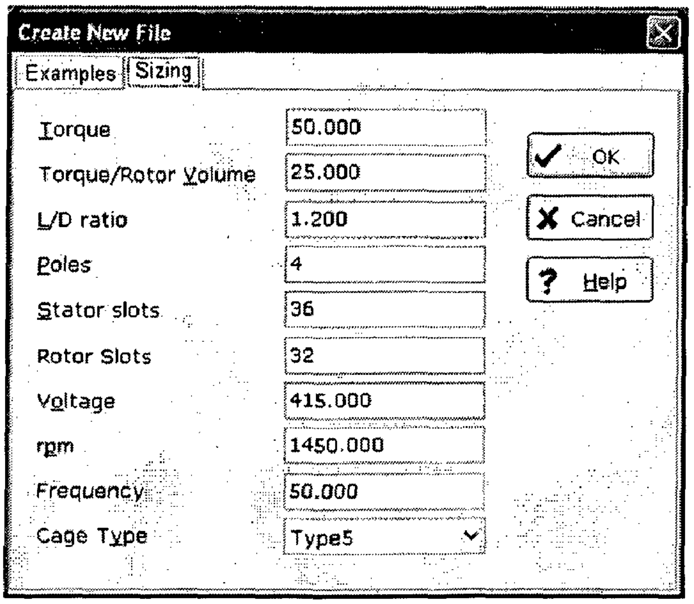
Fig.4.2. Menu of standard rotor bar types

Hence the new design could be started just by specifying type of rotor bar. The various types of rotor bars available are given below.

| | |
|---|---|
| Type 0 | Closed slot with pent top and round bottom |
| Type 1 | Open slot with round bar |
| Type 2 | Open slot with plain rectangular bar |
| Type 3 | Open slot with "coffin" bar and parallel-sided teeth |
| Type 4 | Open slot with round top bar and rectangular bottom bar |
| Type 5 | Open slot with round top bar and round bottom bar and parallel-sided teeth |
| Type 6 | Open slot with rectangular top and round bottom |
| Type 7 | Open slot with oblong top bar defined by 2 drill holes and bottom bar defined by 3 drill holes |
| Type 8 | Open slot with trapezoidal top bar and rectangular bottom bar |
| Type 9 | Oblong open slot |
| Type 10 | Open slot with round bars separated by a neck |
| Open custom | User-defined open slot |
| Closed custom | User-defined closed slot |
| Double cage | Double cage with any combination of the above slot types |

Table.4.1. Type of rotor slots provided by SPEED

The new file could also be created by selecting the Sizing in Create New File



Torque 50.000
Torque/Rotor Volume 25.000
L/D ratio 1.200
Poles 4
Stator slots 36
Rotor Slots 32
Voltage 415.000
rpm 1450.000
Frequency 50.000
Cage Type Type5

Fig.4.3. Sizing menu for new design specification

In this menu the motor specifications are given which gives a new design suitable according to the given specifications. However, it is not necessary that the given design is optimized or not. SPEED doesn't give the optimized design by itself. But the optimized design could be obtained by using the Scripting with SPEED or by interrelating SPEED with other softwares.

Create new file menu just opens an initial design window. This design could be modified later by the various functions, which are there in SPEED for the design and analysis of Induction motor.

| **Function** | **Hotkey** | **Purpose** |
|---|---|---|
| **Data** | | |
| OUTLINE EDITOR | Ctrl+1 | Display and edit the cross section geometry |
| TEMPLATE EDITOR | Ctrl+3 | Edit non geometric parameters |
| WINDING EDITOR | Ctrl+W | Display and edit the stator winding |
| MATERIAL | Ctrl+M | Select the material (steel) |
| **Analysis** | | |
| STEADY STATE ANALYSIS | Ctrl+2 | Calculating a single operating point at fixed speed and load |
| TORQUE/SPEED | | Calculate complete torque/speed curves |

| | | |
|---|---|---|
| NO LOAD CALCULATION | | Calculate operation at no load |
| **Results** | | |
| DESIGN SHEETS | Ctrl+4 | Complete listing of input and output parameters |
| PHASOR DIAGRAM | Ctrl+A | Display and analyze the phasor diagram |
| GRAPHS | | Torque- speed characteristics, line start transients etc. |
| **Tools** | | |
| EQUIVALENT CIRCUIT DIAGRAM | Ctrl+E | Display, edit and recalculate the equivalent circuit |
| CALCULATOR | F4 | Simple arithmetic operations on PC-IMD |

Table.4.2. Menu of the various functions of PC-IMD

### 4.3.3. Outline editor

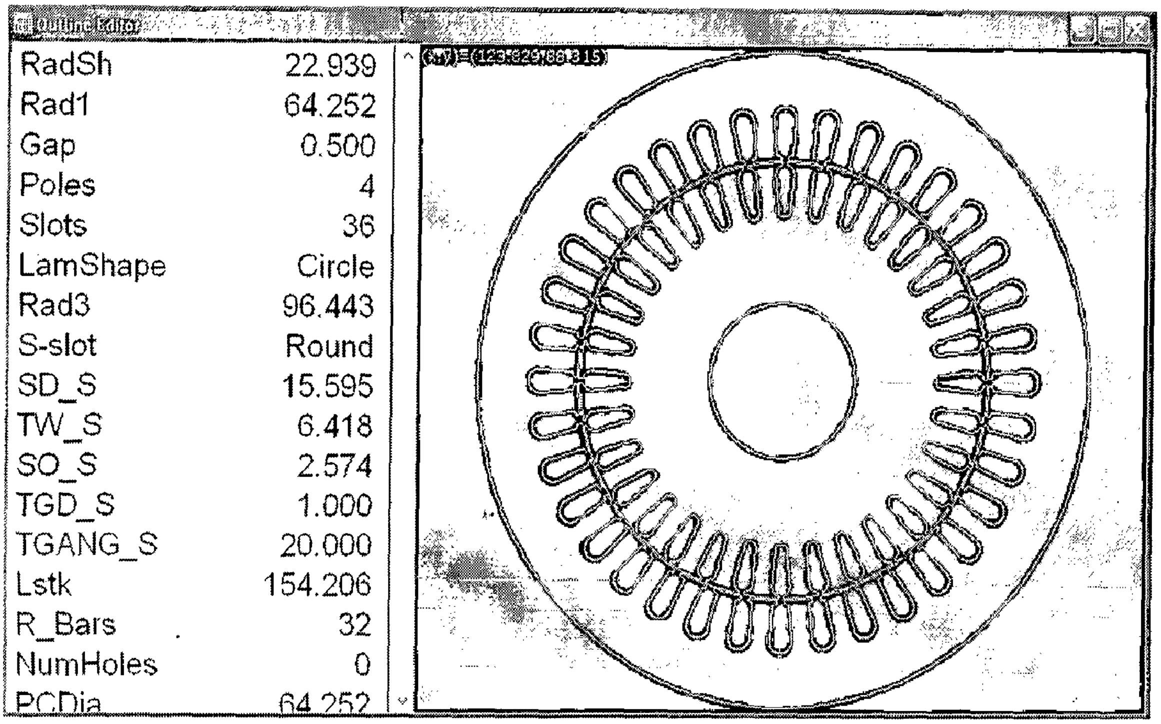
The outline editor is for editing the motor geometry, particularly the cross section and the axial dimensions. When we change a parameter, PC-IMD checks the validity of the new value. If the date is invalid, an error message appears and the drawing disappears. The rotor bar shape and the stator slot shape could also be changed here. A sample outline editor is shown in fig.4.4.

### 4.3.4. Template Editor, $T_{ED}$

Template editor contains all the input parameters of the motor and control, including the dimensional parameters that appear in the outline editor. It consists of sub templates which are

- Dimensions- Gives the stator input dimensions and related parameters of the machine.
- Sim. Options- Sets the factors required for analysis of machine
- Can loss- Sets the thermal parameters of machine
- Rotor bar- Gives the rotor dimensions and related parameters.

$T_{ED}$ does no error checking, so errors or inconsistencies will not show up until an Analysis. A sample template editor is shown in fig.4.5.

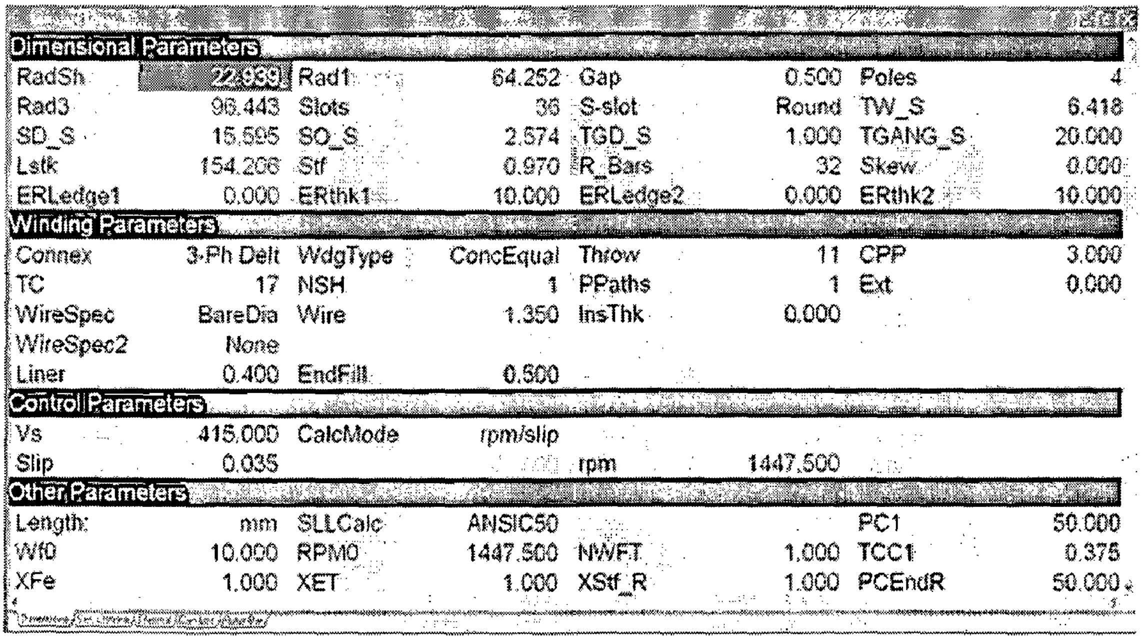


| | |
|---|---|
| RadSh | 22.939 |
| Rad1 | 64.252 |
| Gap | 0.500 |
| Poles | 4 |
| Slots | 36 |
| LamShape | Circle |
| Rad3 | 96.443 |
| S-slot | Round |
| SD_S | 15.595 |
| TW_S | 6.418 |
| SO_S | 2.574 |
| TGD_S | 1.000 |
| TGANG_S | 20.000 |
| Lstk | 154.206 |
| R_Bars | 32 |
| NumHoles | 0 |
| PCDia | 64.252 |

Fig.4.4. Outline editor

- Rotor bar- Gives the rotor dimensions and related parameters.

Design of induction motor in the SPEED PC-IMD is also possible for single phase induction motors, for which the auxiliary winding parameters are also provided in the Sim. Options template of the template editor. The different modes of motor operation are also decided on $T_{ed.}$. In short, $T_{ed}$ is the link between the user and all the input parameters to PC-IMD.



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Dimensional Parameters** | | | | | | | |
| RadSh | 22.939 | Rad1 | 64.252 | Gap | 0.500 | Poles | 4 |
| Rad3 | 96.443 | Slots | 36 | S-slot | Round | TW_S | 6.418 |
| SD_S | 15.595 | SO_S | 2.574 | TGD_S | 1.000 | TGANG_S | 20.000 |
| Lstk | 154.206 | Stf | 0.970 | R_Bars | 32 | Skew | 0.000 |
| ERLedge1 | 0.000 | ERthk1 | 10.000 | ERLedge2 | 0.000 | ERthk2 | 10.000 |
| **Winding Parameters** | | | | | | | |
| Connex | 3-Ph Delt | WdgType | ConcEqual | Throw | 11 | CPP | 3.000 |
| TC | 17 | NSH | 1 | PPaths | 1 | Ext | 0.000 |
| WireSpec | BareDia | Wire | 1.350 | InsThk | 0.000 | | |
| WireSpec2 | None | | | | | | |
| Liner | 0.400 | EndFill | 0.500 | | | | |
| **Control Parameters** | | | | | | | |
| Vs | 415.000 | CalcMode | rpm/slip | | | | |
| Slip | 0.035 | | | rpm | 1447.500 | | |
| **Other Parameters** | | | | | | | |
| Length: | mm | SLLCalc | ANSIC50 | | | PC1 | 50.000 |
| Wf0 | 10.000 | RPM0 | 1447.500 | NWFT | 1.000 | TCC1 | 0.375 |
| XFe | 1.000 | XET | 1.000 | XStf_R | 1.000 | PCEndR | 50.000 |

Fig.4.5. Template editor

### 4.3.5. Winding editor

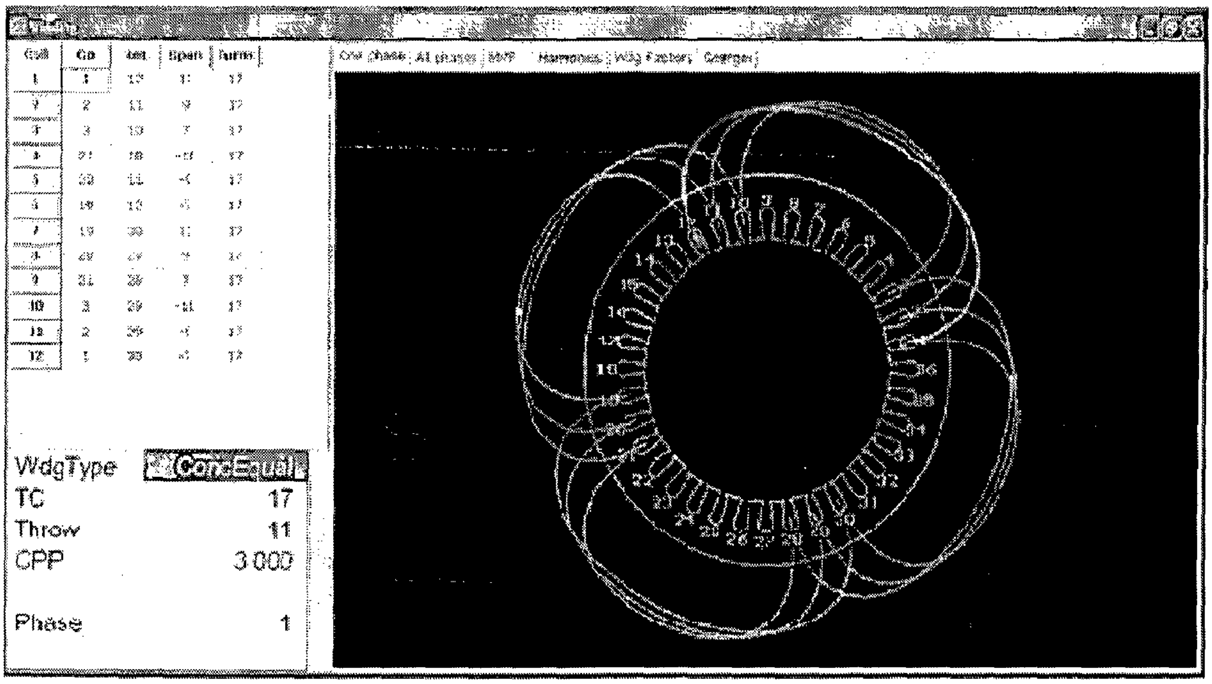
The winding editor can be used for visualizing the effect of the changes in the throw, coils/pole and other parameters. It can also be used for creating new, custom winding distribution scratch. When the winding is modified, PC-IMD keeps account of the coil side location and the number of turns in each coil, and displays this data in the coil list table. The coil list used to calculate resistance, inductances, winding factors etc. It also gives the MMF waveforms and the space harmonics, if MMF or harmonic sub editor is selected, respectively.

PC-IMD supports five types of windings

| | |
|---|---|
| ConcEqual | Concentric winding with equal turns/coil |
| ConcSine | Concentric with sine-distributed turns/coil |
| Lap | Intregal-slot lap winding |
| FracSlot | Fractional-slot winding |
| Custom | Fully editable winding layout |

Table.4.3. Type of winding

The first four type of windings could be selected from the template editor also but the custom winding may be specified only via winding editor. Custom winding may be assembled with any coil layout. A sample winding editor is shown in the fig below.



WdgType ConcEqual
TC 17
Throw 11
CPP 3 000
Phase 1

Fig.4.6. winding editor

### 4.3.6. Thermal editor

Heat transfer calculations are important in the electric machines because the temperature affects the life of insulation and bearing, the efficiency, and the magnetization of magnets.

The temperature of a machine rises when it is run under steady state load conditions from cold conditions. As the temperature rises, the active parts of the machine dissipate heat partly by conduction, partly by radiation and in most cases, largely by means of airgap cooling.

The various nodes in thermal editor are

| | |
|---|---|
| c | conductor |
| h | shaft and bearing |
| f | frame |
| g | airgap |
| s | stator core |
| r | rotor core |
| e | end winding |
| y | stator yoke |
| t | stator tooth |
| b | bearing temperature |

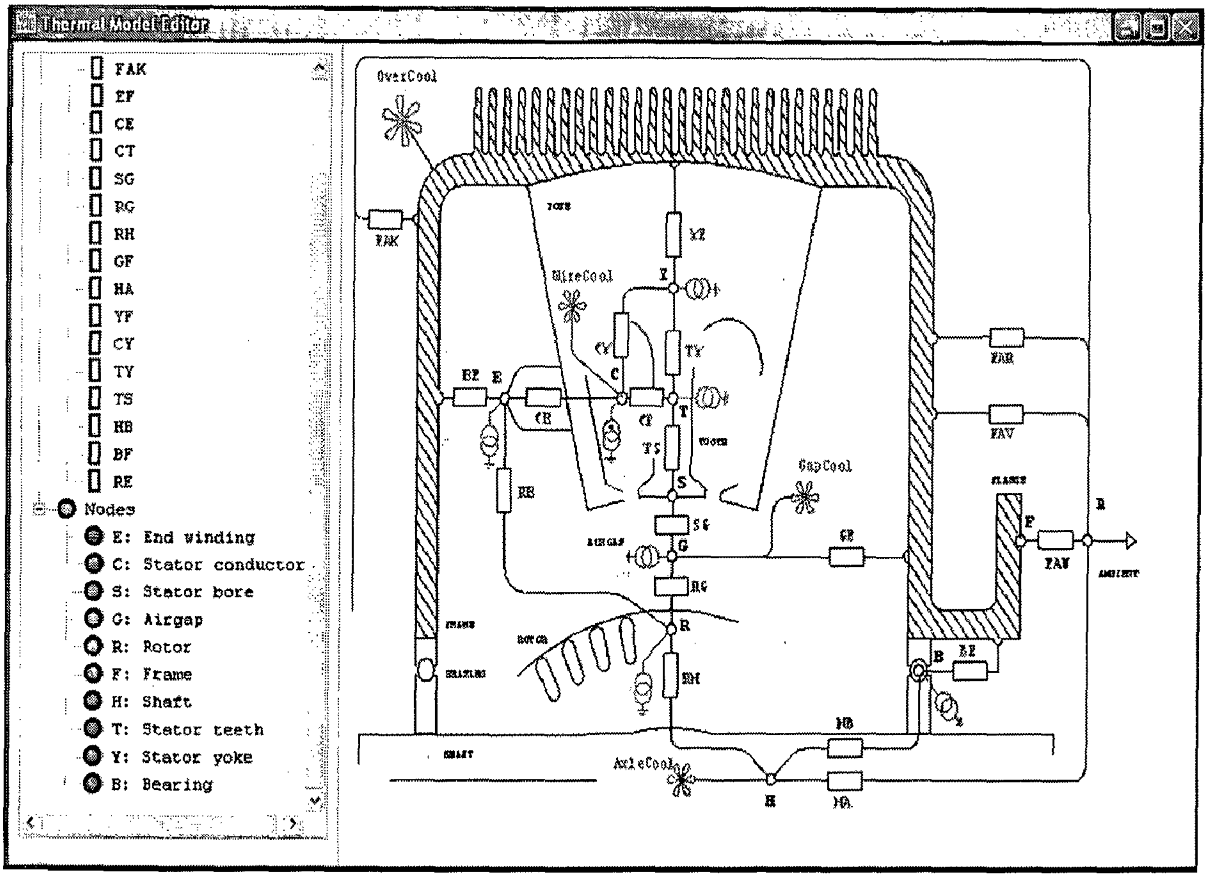


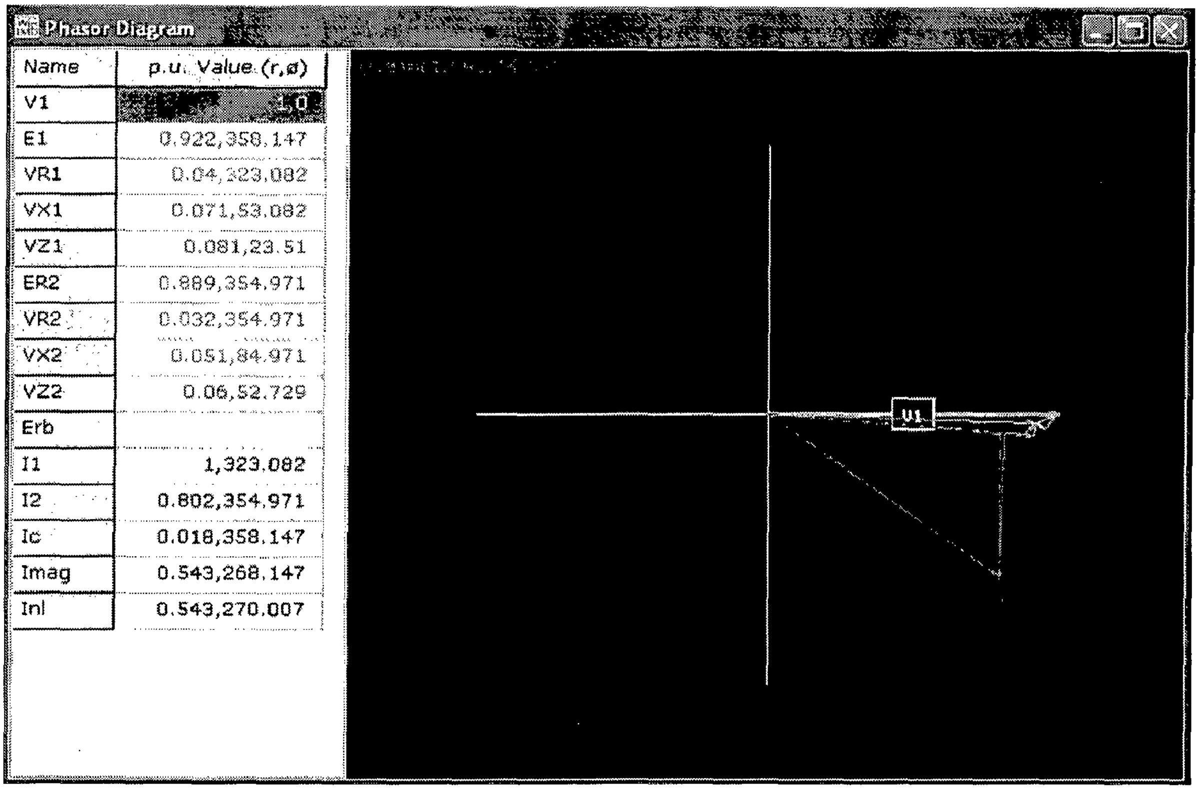
Fig.4.7. thermal editor

Electrical machines are not homogenous bodies. Their parts are made up of different materials like copper, iron and insulation. These materials have different thermal resistivities and due to this is rather difficult to calculate the temperature of a part of machine.

### 4.3.7. Steady state analysis

Steady state analysis is the calculation of the equivalent circuit parameters and the performance of the motor under the conditions defined in $T_{ed}$, i.e. at constant speed with a particular value of supply voltage, torque, etc.

### 4.3.8. Phasor diagram



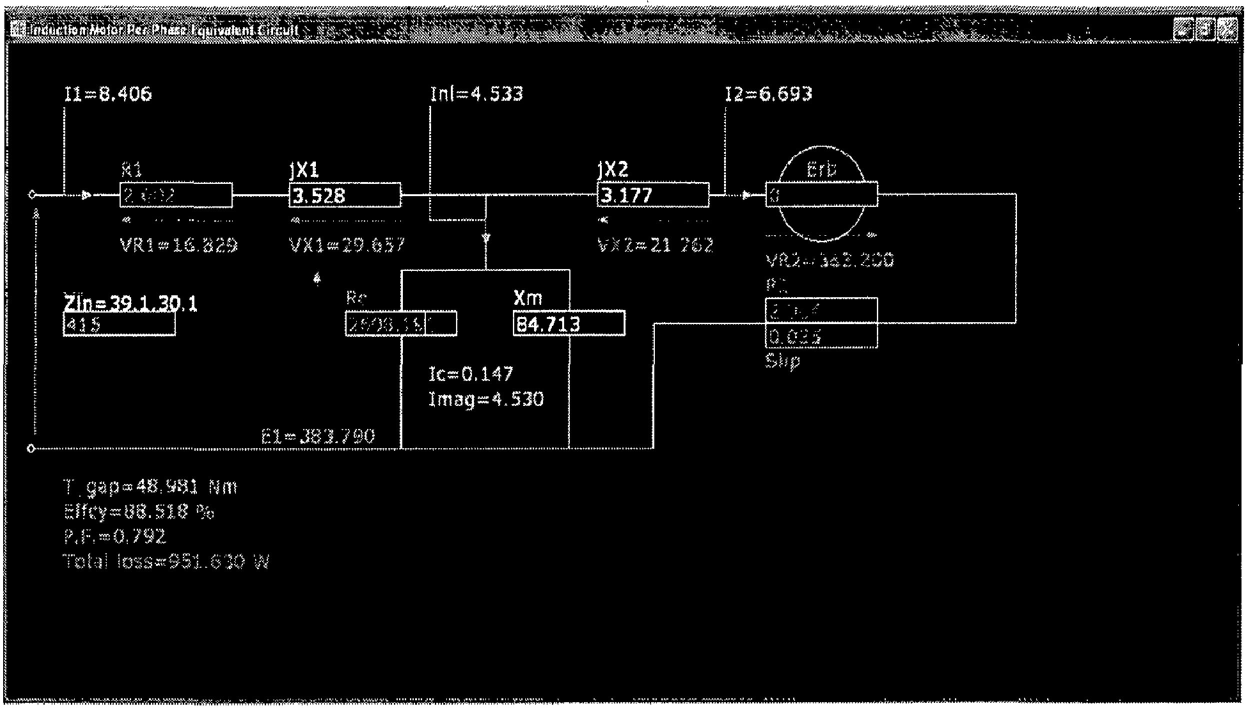
| Name | p.u. Value (r,ø) |
|---|---|
| V1 | 1,0 |
| E1 | 0.922,358.147 |
| VR1 | 0.04,323.082 |
| VX1 | 0.071,53.082 |
| VZ1 | 0.081,23.51 |
| ER2 | 0.889,354.971 |
| VR2 | 0.032,354.971 |
| VX2 | 0.051,84.971 |
| VZ2 | 0.06,52.729 |
| Erb | |
| I1 | 1,323.082 |
| I2 | 0.802,354.971 |
| Ic | 0.018,358.147 |
| Imag | 0.543,268.147 |
| Inl | 0.543,270.007 |

Fig.4.8. phasor diagram

The phasor diagram displays phase current and voltage in per-unit. The cursor keys select one phasor at a time, highlighting it and activating a label on the phasor itself for the identification, at the same time the name of the selected phasor is highlighted in the left hand panel, alongside its current value. Fig. 4.8 shows a sample phasor diagram.

### 4.3.9. Equivalent circuit

The equivalent circuit editor displays the impedances in the equivalent circuit of one phase, together with the voltages and the currents in all the branches. The impedance value can be edited by selecting them with the cursor keys and entering the new values. When we enter a new value for any editable parameter, PC-IMD automatically recalculates the performance and then displays the results.



```
T_gap=48.981 Nm
Effcy=88.518 %
P.F.=0.792
Total loss=951.630 W
```

Fig.4.9. Equivalent circuit

The equivalent circuit diagram shown above is given as a sample diagram.

## 4.3.10. Torque/speed characteristics

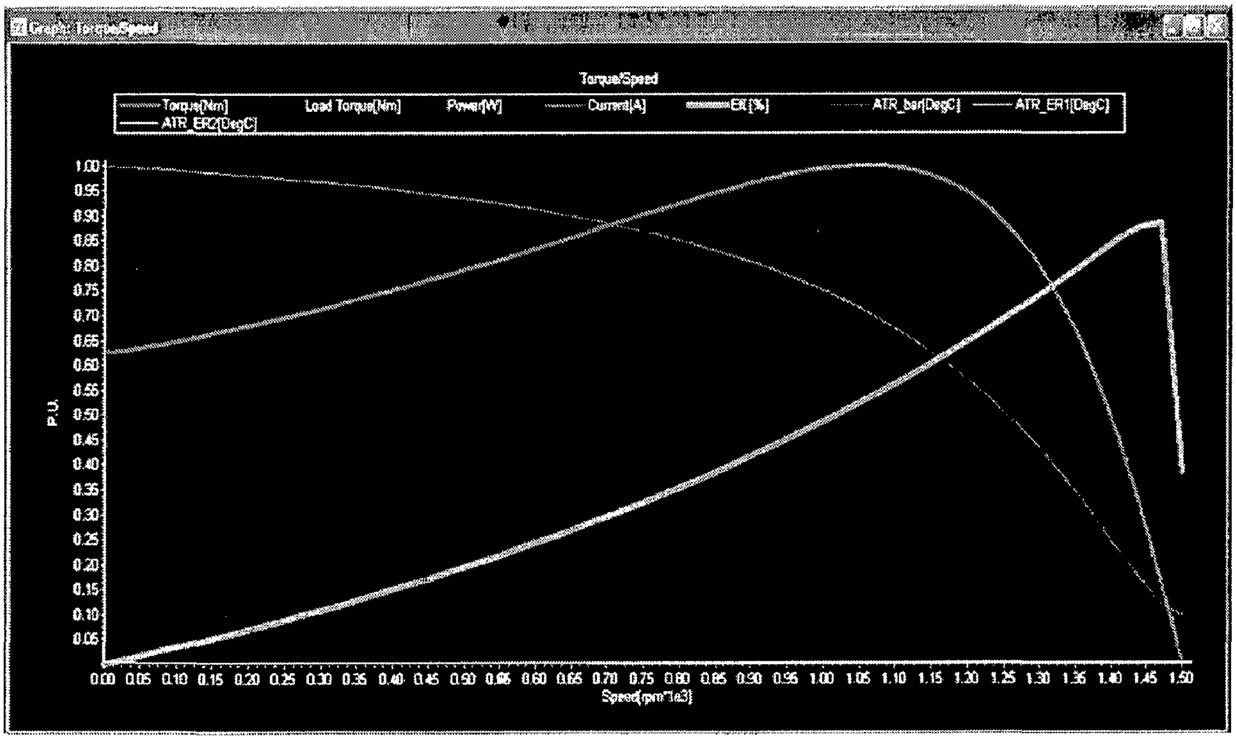


Fig.4.10. Torque/speed characteristics

The speed/torque curve can be plotted together with other graphs such as power or current efficiency vs speed or load. It is plotted over a range of slip from Smin to Smax.

## 4.3.11. Design sheet

The design sheet shows all the input and calculated output parameters, and their relevant units. On the screen the input parameters have red, while calculated output parameters have green color. The sample diagram of design sheet is shown in fig.4.11.

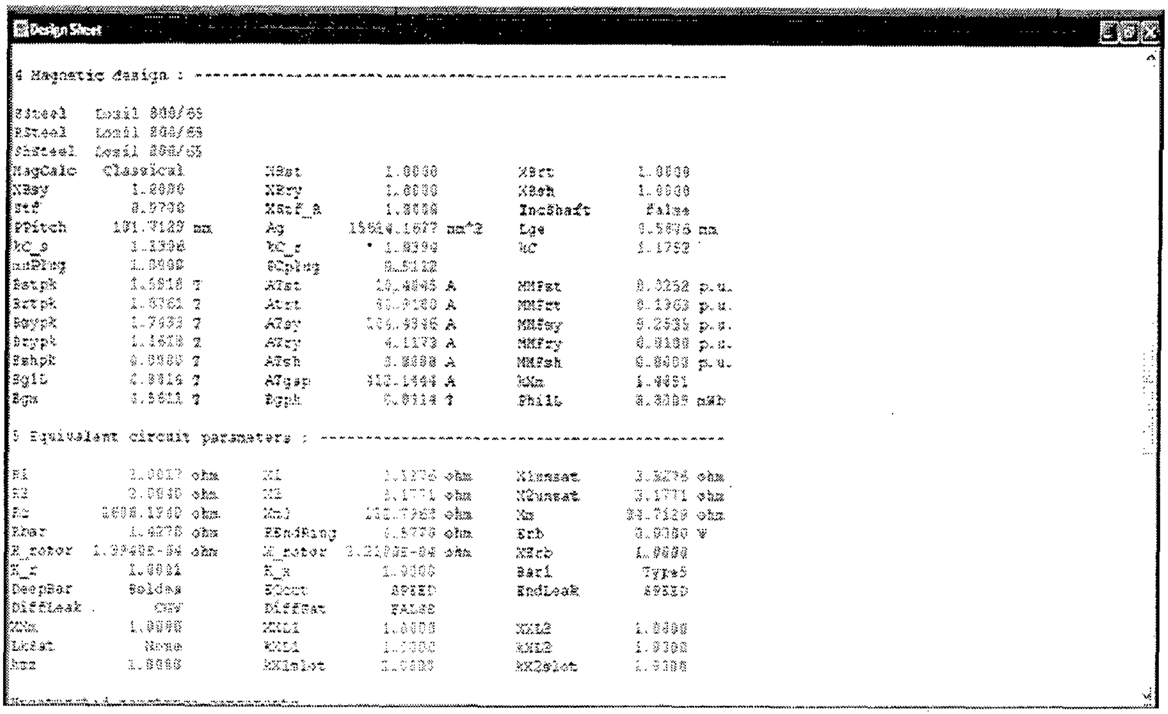


Fig.4.11. section of design sheet

## 4.4. Operation of PC-IMD

Operation of the PC-IMD can be performed with the input parameters, and after steady state analysis we get the output results in the form of design sheets, equivalent circuit, phasor diagrams, and torque speed curves.

### 4.4.1. Input parameters

This section gives the input parameters in the SPEED PC-IMD in tabulated form.

#### 4.4.1.1. Outline editor

| | |
|---|---|
| RadSh | Shaft radius |
| Rad1 | Rotor surface radius |
| Gap | Airgap length |
| Poles | Number of stator poles |
| Rad3 | Stator outer radius |
| Slots | Number of stator slots |

| | |
|---|---|
| S-slot | Shape of stator slot bottom |
| TW_S | Stator tooth width |
| SD_S | Stator slot depth |
| SO_S | Stator slots opening |
| Lstk | Stack length |
| NumHoles | Number of ventilation through-holes |
| Holedia | Diameter of ventilation through holes |
| R_Bars | Number of rotor bars or slots |
| Dblcage | Selects double cage rotor |
| Bar1 | The type of slot in the rotor cage |
| Bar2 | [only if Dblcage=true] |
| EditView | View: full motor, rotor only, stator only, stator slots, rotor slots, or axial view |

Table. 4.3. input parameters available in outline editor

The parameters change if the view is changed.

#### 4.4.1.2. Template editor

The parameters which are already discussed in outline editor are not discussed

***Dimensional parameters***

| | |
|---|---|
| Stf | Lamination stacking factor |
| Skew | Skew of rotor bars, measured in stator |

***Control parameters***

| | | |
|---|---|---|
| Vs | The RMS ac line voltage at fundamental frequency | |
| CalcMode | Select the method for specifying the machine operating point | |
| | f/rpm | Actual frequency in Hz and actual speed in rpm |
| | f/slip | Actual frequency and slip |
| | rpm/slip | Actual speed and slip |
| | rpmS/rpm | Synchronous speed and actual speed |
| | rpmS/slip | Synchronous speed and slip |

|  |  |  |
|---|---|---|
|  | f/PowerSh | Actual frequency and required shaft power |
|  | f/TorqSh | Actual frequency and required shaft torque |
| PowerSh | [only if CalcMode=f/PowerSh]. The required shaft power |  |
| TorqSh | [only if CalcMode=f/TorqSh]. The required shaft torque |  |
| Slip | [only if CalcMode=f/slip, rpm/slip, rpmS/slip]. Per unit rotor slip with respect to suchronous speed |  |
| Freq | [only if CalcMode=f/rpm, f/slip, f/PowerSh, f/TorqSh]. Fundamental line frequency |  |
| rpm | [only if CalcMode=f/rpm, rpm/slip, rpmS/slip]. Actual shaft speed |  |
| rpmS | [only if CalcMode=rpmS/slip]. Synchronous speed. |  |

Table.4.4. Input parameters available in template editor

These are some of the important input parameters. Knowledge of the other input parameters could be obtained from the speed manuals.

## 4.4.2. Output parameters

The dimensions and the control data is already discussed in the input parameters. The next block of design sheet starts with magnetic calculations.

### 4.4.2.1. Magnetic design

The parameters are tabulated below

|  |  |
|---|---|
| SSteel, RSteel, ShSteel | Name of selected steels for stator rotor and shaft respectively |
| Magnetic circuit flux densities |  |
| Bstpk | Peak stator tooth flux density |
| Brtpk | Peak rotor tooth flux density |
| Bsypk | Peak stator yoke flux density |
| Brypk | Peak rotor yoke flux density |
| Bshpk | Peak shaft flux density |
| MMFs expressed as fractions of the airgap MMF |  |
| MMFst | Stator tooth MMF |

| | |
|---|---|
| MMFrt | Rotor tooth MMF |
| MMFsy | Stator yoke MMF |
| MMFry | Rotor yoke MMF |
| MMFsh | Shaft MMF |

Table 4.5. Magnetic parameters from design sheet

#### 4.4.2.2. Equivalent circuit parameters

| | |
|---|---|
| R1 | Primary stator resistance per phase |
| R2 | Rotor resistance referred to primary |
| R_rotor | Actual resistance of rotor cage, un-referred to stator |
| Rc | Core loss resistance per phase |
| Xm | Saturated magnetizing reactance per phase |
| X1 | Primary reactance per phase |
| X2 | Secondary reactance per phase referred to primary |

Table 4.6. Equivalent circuit parameters from design sheet

#### 4.4.2.3. Performance

The parameters already discussed are not tabulated

| | |
|---|---|
| PElec | Electrical power at the motor terminals |
| EMtorque | Electromagnetic torque |
| Pgap | Air gap power |
| Effcy | Efficiency |
| P.F. | Power factor |
| Iph | RMS phase current |
| IL1 | RMs line current |
| I2 | RMS secondary amps/phase |
| INL | No-load RMS amps/phase |
| IMag | Magnetizing RMS amps/phase |
| Ic | Core loss current in core loss resistance |

| | |
|---|---|
| Jrms | RMS current density in stator copper |
| JRotor | RMS current density in rotor cage |
| WCuS | Stator $I^2R$ loss |
| WIron | Iron loss |
| WSLL | Stray load loss |

Table.4.7. Performance parameters from design sheet

#### 4.4.2.4. Core loss, space harmonic and stray load losses

| | |
|---|---|
| WstWkg | Specific rotor teeth core losses |
| WsyWkgWst | Specific stator yoke sore losses |
| Wry | Total stator teeth core losses |
| Wsy | Total stator yoke core losses |
| WFeS | Stator iron loss |
| WFeR | Rotor iron loss |

Table.4.8. Various losses from design sheet

These were some of the important parameters for the induction machine analysis provided in the SPEED PC-IMD

## 4.5. SPEED automation

Till now whatever operation of SPEED was discussed has to be initiated completely manually. But SPEED has the provision of automation. SPEED has its own internal scripting privilege in VBscript, with help of which the various operations like, generation of graphs, and tabulation of results, could be automated. Other than this SPEED have provision to be linked up with various already existing softwares for automation. SPEED PC-IMD in itself cannot account for the time harmonic affects on the motor neither it has any provision of supply other than single frequency sinusoidal supply. Thus these interfaces help SPEED PC-IMD to cope up with the issues of flexibility in the programming and complex calculations.

### 4.5.1. MATLAB and SPEED

MATLAB is a language for technical computing. It is a compact language especially suited for work with matrices and is increasingly being used for optimization studies. It has been used extensively for various engineering related problems.

#### 4.5.1.1. Parameter definition in scripting

Every input and output parameter is available via automation. The approach taken in SPEED software is to assign a particular index value to every input and output parameter. For automation purposes this is taken to be an integer (4 byte) although internally it is defined as an enumerated type and future versions of the automation interface may implement this directly. Each index value should be assigned to an integer variable with a name starting with .pi. for Parameter Index.

For example, the shaft radius should be accessed using the constant piRadSh with a value of 3. These are called as piXXXX variable names

The piXXXX values are divided into two sections representing input and output parameters. For convenience, four functions are provided to identify the starting and ending parameter of each section. These are particularly useful when you need to iterate over all the parameters say when writing all output values to a file

The numerical values for the piXXXX constants for output parameters follow on directly from the input parameter values so any changes the SPEED Laboratory makes to the input file format (adding parameters in particular) changes all the values for the output parameters. For this reason it is better to use the piXXXX variable name rather than the value directly.

The complete information of all the parameters with their data type, units and piXXXX names is given in PC-IMD –Help-Parameter information.

#### 4.5.1.2. Using ActiveX in MATLAB

As MATLAB is a cross-platform application, available on SUN, HP, IBM and SGI workstations (amongst others) as well as on MS-Windows based PCs it cannot be too closely tailored for one specific platform feature. In MATLAB basic ActiveX support can be performed by just four new commands.

- Actxserver- To create an instances of active object
- Invoke- To call an object method
- Get- To access the property
- Set- To access the property

#### 4.5.1.3. Adding piXXXX parameters to MATLAB

In order for a MATLAB program to access the internal parameters of a SPEED motor design program it must have an up-to-date version of the piXXXX constants used in the particular SPEED program.

On the SPEED CD the code is provided, which encapsulates the create or update capability into a MATLAB function. This function, updatepiXXXX, takes three parameters, an object containing the actxserver of the SPEED program, a path to store the piXXXX file and the MATLAB function name of the piXXXX file (i.e. the filename without the .m extension). For using the updatepiXXXX the list of pi variables should be provided in the m file format, which is automatically taken care of while installation of SPEED, as it copies the wimd32params.m in hard disk of computer.

So at starting of every MATLAB program the updatepiXXXX function is to be called.

The internal transfer of the variables is done with the help of Getvariable and Setvariable commands.

### 4.5.2. Simulink and PC-IMD

Simulink is the system simulator add-in for MATLAB. With Simulink it is possible to simulate electronics and control systems in a much more flexible manner than is possible with SPEED software (although with a large increase in execution time). Simulink uses a block modeling approach where control elements are represented by editable blocks on a diagram and signals represented by lines linking the blocks.

The link between the SPEED and SIMULINK is done through a "Initialize and plot" block. This block represents the MATLAB script (IMD_3.m) which is copied into hard disk while installation of the software.

### 4.5.3. Requirements

Before starting the automation or optimization procedures in MATLAB there should exist a SPEED PC-IMD data file, with all the input parameters and material database defined. With the data file provided the MATLAB can run the Steady state analysis and the resulting waveforms could be generated.

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## 4.6. Conclusion

SPEED software is second to none in training electric designers, and in serving experienced designers with the large variety of coordinated calculations they must do, including electric, magnetic, drive circuit simulation, control, thermal, mechanical aspects, and many features important for cost analysis, automation, user-customization, documentation and optimization. SPEED is fast, stable, intuitive, and consistent. Motor design with SPEED is interactive and fast.

Further the interface between the SPEED and other software, like MATLAB, enhances the performance of the software bestows SPEED with additional attractive features like easy programming. Interface between the SPEED and MATLAB makes the automated control of optimization of design procedure possible. The effects of harmonics in the induction motor could also be taken into account with the help of MATLAB and SPEED interfacing very easily.

# 5. Design optimization of induction motors

This chapter consists of the optimization of the Induction motor running on sinusoidal supply and on the non sinusoidal supply. The difference in design and prerequisites of optimization procedure will be discussed.

## 5.1. Introduction

The design of the induction motors means to determine the geometry and all data required for manufacturing so as to satisfy a vector of performance variables together with a set of constraints. Optimization design refers to ways of doing efficiently synthesis by repeated analysis such that some single (multiple) objective function is maximized (minimized) while all constraints are fulfilled. There are a lot of design parameters involved in the design of the induction machine. The proper optimization requires an intelligent selection of objective function, and constraints according to the drive's requirement, and further selection of variables which affect the objective function and the constraints.

## 5.2. Prerequisites of design optimization

The design optimization consists of some proper optimization technique. There are various optimization techniques available and as is already discussed in chapter 2, their stepwise procedures are provided. But machine design optimization is not only running of a mathematical optimization iterative procedure. There are some other important steps which are required to be followed before the implementation of the optimization technique. The steps are explained as follows.

### 5.2.1. Selection of objective function

First of all for the design of the induction motor, some aim is to be set. The objective function to be maximized (minimized) should be chosen. The objective function is mostly chosen keeping in mind the customers demand and the profit of manufacturer.

### 5.2.2. Selection of constraints

The performance of the induction machine is multidimensional. There are so many parameters which decide the good or bad performance of the motor. Just by optimizing one of the performance characteristic does not mean that the design of the motor was good. Also it is not possible to obtain best performance in terms of all the performance parameters. Thus, it is necessary to check that the factors which affect the motor's performance are well within the limits, so that the motor could give a satisfactory and reliable performance. These constraints play the most important role in the machine design.

Hence the selection of constraints is an important issue. The constraint which gets most effected with the variation in the objective function should be considered with special care.

### 5.2.3. Selection of variables

After the selection of the objective function and the constraints the next important step is to select the variables. There are a number of variables available which affect the machine design. But the optimization procedure demands the minimum possible number of variables. Hence it is required that the objective function and the constraints should be studied thoroughly and then the variables which affect them most should be chosen.

## 5.3. SPEED and Design optimization

After the study of the machine design software SPEED some points had been noticed which affect the design procedure of the Induction machine. These points are summed up as follows

- ➢ In previous machine design optimization it has been seen that the variables were chosen well with freedom. The parameters like magnetic loading and electric loading has been taken as the variables by many of the designers.
  In SPEED PC-IMD it is worth noting that only the input parameters of the induction machine could be chosen as the design variables. But in any case it doesn't hampers the effectiveness of design procedure as the machine dimensions in themselves are enough for design optimization of any kind of machine.
- ➢ As the SPEED PC-IMD calculates the performance of the machine and give the performance parameters, there is no need of any type of formulation for design procedure. But this is the case for the conventional working condition. For looking into the effects of harmonics on machine operation there is need of separate formulation.
- ➢ The selection of variables could be done by seeing the direct effect of the variable on the performance parameter in PC-IMD. This becomes very easy because of the easy variation of variables and by high speed performance of PC-IMD.

After summing up the main prerequisites of optimization now it is the time of problem formulation.

As the main of this dissertation is to obtain an induction motor suitable for working under the adjustable speed drive so for choosing a suitable objective function it is necessary to look into the various effects of the harmonics on the induction motor and to look into the main differences which these harmonics and adjustable speed supplies bring about.

The harmonics generated in the adjustable speed drives are studied in the previous chapter. These harmonics affect the performance of the drive to a great extent and hence with the increase of the use of the power converter circuitry in the adjustable speed drive it had become essential to study the induction motor's performance under the non sinusoidal input supply. This chapter aims at studying the effects of the harmonic generated by the rectifier-converter system on the performance characteristics of the induction motors.

## 5.4. Harmonics and their effects

The harmonics present in the supply change the nature of the MMF wave present in the airgap, which inturn produces the harmonic currents in the machine and these currents and their interaction with the air gap harmonic MMF are the main reasons for the change in induction motor's performance.

### 5.4.1. Stator copper loss [33]

The stator copper losses on a non sinusoidal supply is proportional to the square of total rms current. The value of the rms current increases from sinusoidal due to presence of harmonic currents and hence the stator copper loss also increase. The skin effect factor for stator resistance is given by $K_{rsn}$, and leakage reactance skin effect factor is given by $K_{xsn}$

$$K_{rsm} = \varphi(\varsigma_m) + \frac{N^2_{md} - 1}{3}\psi(\varsigma_m)$$

$$\varphi(\varsigma_m) = \varsigma_m \frac{(\sinh 2\varsigma_m + \sin 2\varsigma_m)}{(\cosh 2\varsigma_m - \cos 2\varsigma_m)}$$

$$\psi(\varsigma_m) = 2\varsigma_m \frac{(\sinh \varsigma_m - \sin \varsigma_m)}{(\cosh \varsigma_m + \cos \varsigma_m)}$$

$$\varsigma_m = AO_s \left[\frac{\pi m f_{op} \mu_0 BO_s N_{mw}}{x_s 10^3 \rho}\right]^{1/2}$$

$AO_s, BO_s$ = conductor dimensions, mm

$N_{md}, N_{mw}$ = number of conductors depth-wise and width-wise respectively.

$m$ = order of the harmonic

$f_{op}$ = operating frequency

$\mu_0$ = magnetic space constant, $4\pi \times 10^{-7}$ H/m

$\rho$ = specific resistance of copper, 0.021 ohm- m/mm$^2$

$$K_{xsm} = \frac{3}{2\varsigma_m} \frac{(\sinh 2\varsigma_m - \sin 2\varsigma_m)}{(\cosh 2\varsigma_m - \cos 2\varsigma_m)}$$

The additional loss could be calculated from equivalent circuit calculations and the following expression.

$$P_1 = 3\left(I_1^{\,2} + I_{har}^{\,2}\right)R_1(\omega)$$

### 5.4.2. Rotor copper losses

Under the non sinusoidal supplies, the skin effect is much more pronounced in the cage rotor as compared to sinusoidal supplies, which exhibits a significant increase in resistance at harmonic frequencies particularly in case of deep bar rotors. The rotor resistance is much greater than the dc value, which causes more losses.

$$P_{2k} = 3I_{2k}^{\,2}R_{2k}$$

Due to complex shapes of available rotor bars the skin effect factor is calculated by an iterative procedure by taking the smaller divisions of rotor slot area.

The additional rotor copper losses are the primary cause of the reduced efficiency of the motors at non sinusoidal supply.

### 5.4.3. Harmonic core loss [6]

The time harmonic main fluxes cause negligible increase in core loss of the motor.

$$W_{fes.r}(\omega) = \left[\sigma_e\left(\frac{f_\vartheta}{100}\right)^2 k_{sk}^{\,2}k_{er} + \sigma_h\left(\frac{f_\vartheta}{100}\right)^2 k_{sk}^{\,2}\right]B_{m\vartheta}^{\,2} \quad W/kg$$

$$k_{sk} = \frac{\sqrt{2}}{\zeta}\sqrt{\frac{cosh(\zeta) - cos\ \zeta}{cosh(\zeta) + cos\ \zeta}}$$

$$k_{er} = \frac{3}{\zeta}\sqrt{\frac{sinh(\zeta) - sin\ \zeta}{cosh(\zeta) - cos\ \zeta}}$$

Using same expression the rotor core losses can be calculated.

### 5.4.4. The end leakage loss

The end leakage loss is the eddy current loss in core lamination due to the end winding leakage flux which enters the lamination axially. These losses increase considerably due to increase in eddy currents

### 5.4.5. Skew leakage losses

There is a skew leakage effect in cage rotor in which rotor slots are skewed with respect to the stator slots. For harmonics the skew flux changes at harmonic frequency in both stator and rotor thus these losses could be substantial at harmonic frequencies.

### 5.4.6. Rotor Zig-Zag Loss [6]

This loss is due to pulsating flux in the rotor teeth due to slot permeances and slot MMF harmonics. This flux induces currents in the rotor bars, with an $I^2R$ loss resulting.

$$W_{z\vartheta} = 2(\pi D\delta)\frac{1}{8}\frac{\pi^2}{16}\left(\frac{\beta}{2-\beta}\right)^2 B_{\vartheta g}{}^2 L^2 \frac{\lambda^3 \rho}{\mu^2} C_{\vartheta r} k_{er}\left(\frac{\sinh(2\lambda d) - \sin(2\lambda d)}{\cosh(2\lambda d) - \cos(2\lambda d)}\right)$$

Value $C_{\vartheta r}$ is given in the work [6] ,λ is inverse of skin depth ς

### 5.4.7. Pulsating harmonic torques

Pulsating harmonic torque components are produced by reaction of harmonic rotor mmf with harmonic rotating fluxes of different order. Dominant pulsating torques arises from interaction between harmonic rotating currents and fundamental rotating flux.

The rotor currents induced by the fifth time harmonic field react with fundamental rotating field to produce a pulsating torque at six times fundamental frequency. The sixth harmonic pulsating torque amplitude is in the range 20 to 10 % of base torque-with lower reactance machines obviously developing large torque pulsations. It has been found that the low speed torque pulsations may be twice or three times the theoretical value predicted by analysis.

### 5.4.8. Bearing currents and shaft voltages

30 % of all motor failures operated with 60 Hz sinusoidal wave voltage are due to bearing current damage. PWM inverter modulation causes high frequency step-like voltage source waveforms and high dv/dt's to be impressed across the stator neutral to frame ground, which is one reason of bearing faults. Other reasons are the temperature rise which deteriorates the quality of bearing in induction machines, and torque pulsations, hence increasing the wear tear.

## 5.5. Selection of objective function

From the above analysis, it could be seen that the major effect of the harmonics on the induction motor operation is the increase of losses. The total harmonic copper losses are found to be significant compared to the fundamental copper losses and are about 22% of fundamental copper losses. Also the increase of the losses in the motor leads to the temperature rise which if not taken care of could result in the overheating of the machine, making the effect cumulative. Also the overheating of the machine leads to the damage of stator winding insulation, wedges and bearings thus shortens the life span of the induction motor. Thus the extra harmonic losses not only increase the operating cost of the machine but also are fatal for the machine.

It is very clear that the extra losses in the induction motor are necessary to be taken care of. If the motor is designed to reduce these harmonic losses, not only the reliability of the machine will be improved but also the operating and maintenance cost of the machine will be saved. Hence the objective function chosen for the machine is Maximization of the efficiency or minimization of the losses.

## 5.6. Selection of constraints

The operating conditions for the adjustable speed drives and the online supply drives are quite different. Adjustable speed drives provide flexibility to the system and hence the main concerns in the adjustable speed drive induction motors have to be different from the online supply drive motors. Thus the constraints for sinusoidal and nonsinusoidal supply motor will be chosen separately.

### 5.6.1. Constraints for sinusoidal supply induction motors

The constraints for sinusoidal supply motors are given below:-

| | |
|---|---|
| ➢ Maximum stator tooth flux density | $B_{tmax}<2.0$ wb/m$^2$ |
| ➢ Maximimum stator yoke flux density | $B_{symax}<1.8$ wb/m$^2$ |
| ➢ No load to full load current ratio | CR<0.8 |
| ➢ Full load slip | $S_{FL}<0.05$ |
| ➢ Starting to full load torque ratio | TRT1>1.5 |
| ➢ Maximum to full load torque | TRT2>2.0 |
| ➢ Full load power factor | Pf>0.8 |

### 5.6.2. Constraints for non sinusoidal supply induction motors

Some of the constraints for the non sinusoidal supply motors will remain same but some of the constraints require some considerations.

In an inverter drive, the induction motor is accelerated from rest by gradual increase in frequency, and hence the motor design can ignore the direct on-line starting conditions or pull in performance, which greatly influence the design of general purpose machine. Thus there is no need of any kind of starting torque or current constraints.

Next important thing to consider is the requirement of the wide constant power speed range in the induction motors. The induction motors which are being used in adjustable speed drives should operate satisfactorily in wide range of speeds. This could be sufficed by keeping a high value of breakdown torque. Mostly there is a requirement of **breakdown torque greater than 2.7 p.u. at base speed.**

Other than these, monitoring of the temperature rise is very important in the adjustable speed drive induction motors. Although it is clear that reduction in losses will automatically result in the temperature control, but still there is a requirement of constraint to be put.

Thus considering all these points the constraints for the adjustable speed drive induction motor are summed up as follows

| | |
|---|---|
| ➢ Maximum stator tooth flux density | $B_{tmax}<2.0$ wb/m$^2$ |

| | |
|---|---|
| ➢ Maximum stator yoke flux density | $B_{symax}<1.8\ wb/m^2$ |
| ➢ No load to full load current ratio | $CR<0.8$ |
| ➢ Full load slip | $S_{FL}<0.05$ |
| ➢ Maximum to full load torque | $TRT2>2.7$ |
| ➢ Full load power factor | $Pf>0.8$ |

## 5.7. Selection of variables

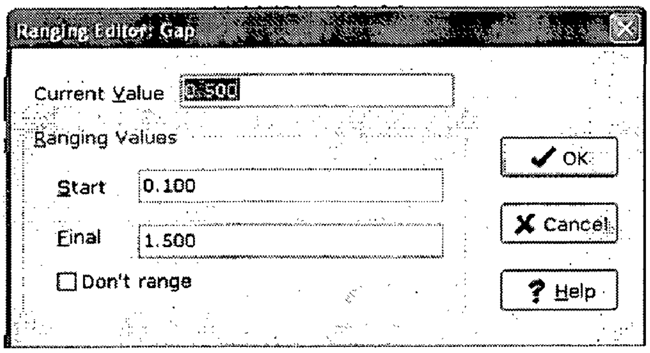
As is discussed already, that for selecting the variables, the effect of variables on the constraints and the objective function should be known. Normally the objective function and constraints equations are formulated. Then a program has to generated for detecting the effect of variables on the constraints and objective function.

But with the availability of SPEED the work has been made quite easy. SPEED contains an inbuilt function called "ranging", which is helpful in knowing the effect of variation of design parameters on the performance characteristics.

### 5.7.1. Ranging

Ranging is the repetition of the performance calculation to determine the effect of variation in one or more parameters. The input parameters to be varied should be assigned a range of variation, using Outline | edit ranging or template | edit ranging [Ctrl+R] (alternatively, right-click on the parameter in $T_{ed}$ or the outline editor: see §4.5). These parameters are called ranging parameters. They are identified by an asterisk when options *General | Show Ranging is checked, and the parameter ranges are saved with the datafile.

Ranging produces a stack of design sheets, one for each step in the ranging calculation. These can be viewed via Results|Design sheet [Ctrl+4]. A chart is provided, on which any two parameters can be plotted on two separate y-axes versus any other parameter on the x-axis. Use the drop-down lists x, y1 and y2 to select parameters.



Current Value 0.500

Start 0.100

Final 1.500

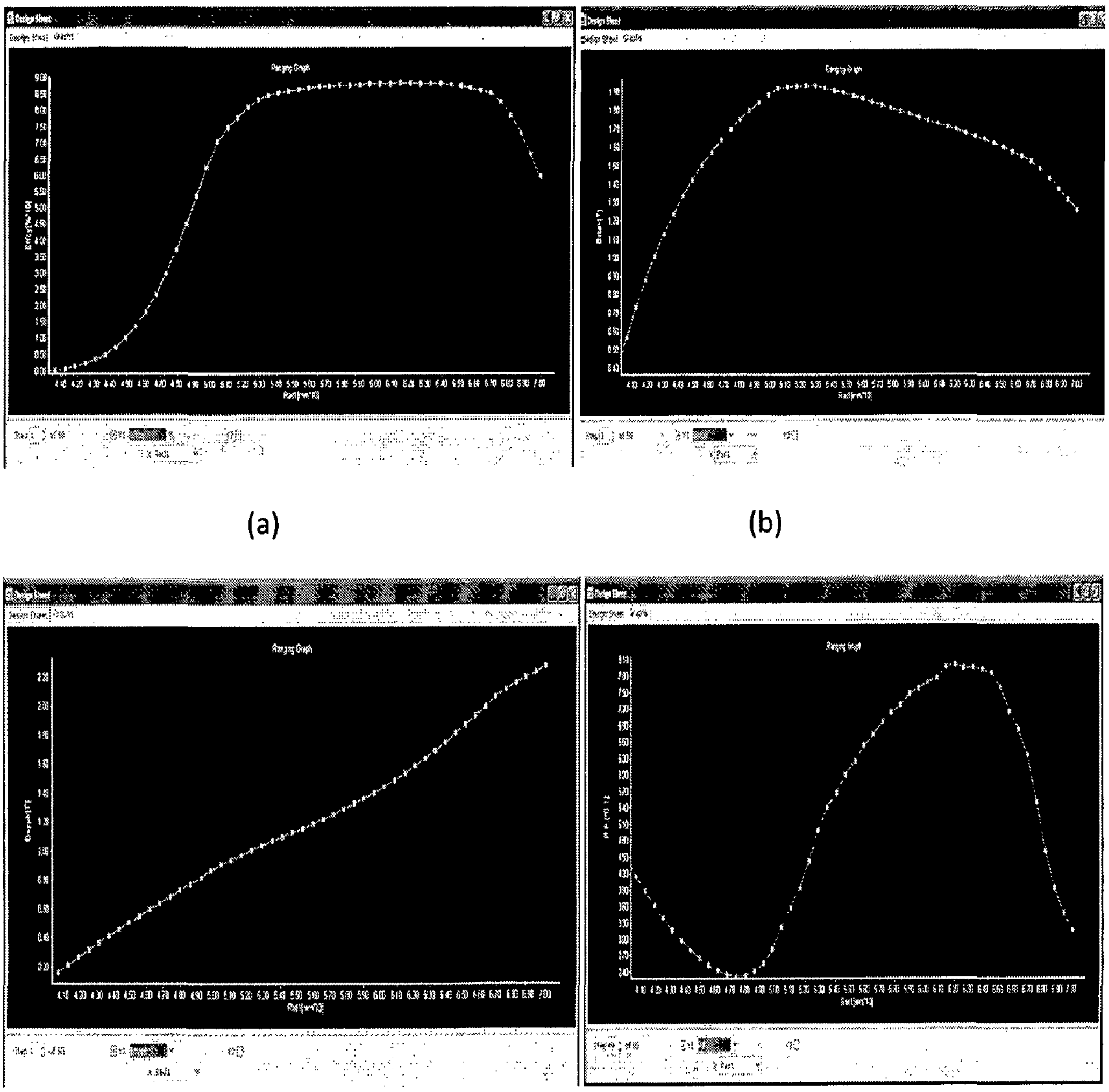
☐ Don't range

Fig.5.1. ranging editor

By using the ranging function effect of various design parameters are plotted against the objective function and some of the constraints. The constraints which are plotted are maximum stator tooth flux density, maximum stator core flux density, power factor. The other constraints are interrelated to these constraints hence these plots give sufficient information about the choice of the variables.

Following are given some plots showing the variation of various performance parameters with change in variables. According to these plots the subsequent discussions are given.

## 5.7.2. Rotor radius



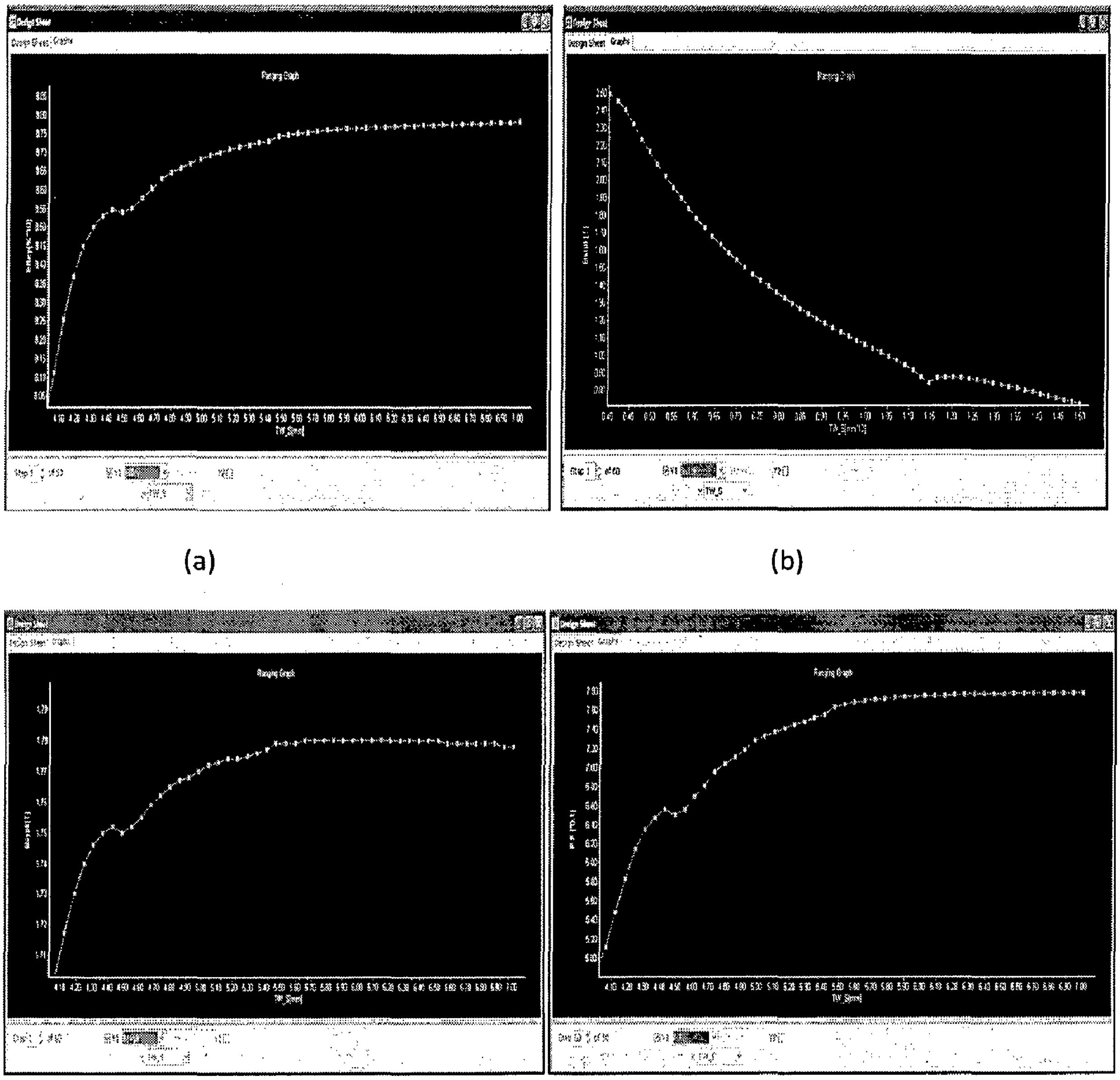
(a) (b)

© (d)

Fig.5.2. rotor radius \....... (a) Efficiency (b)$B_{tmax}$ (c)$B_{symax}$ (d) PF

From the above graphs it could be seen that the increase of rotor radius affects the efficiency only for starting range and later becomes constant. But the other constraints are affected during the whole range of variation. Hence the selection of rotor radius if quite important for constraints to be decided. Also from the plot of efficiency vs rotor radius it is clear that the optimized value of rotor radius should be somewhere in the 50 mm to 65 mm, but may vary on account of other constraints imposed.

### 5.7.3. Stator tooth width



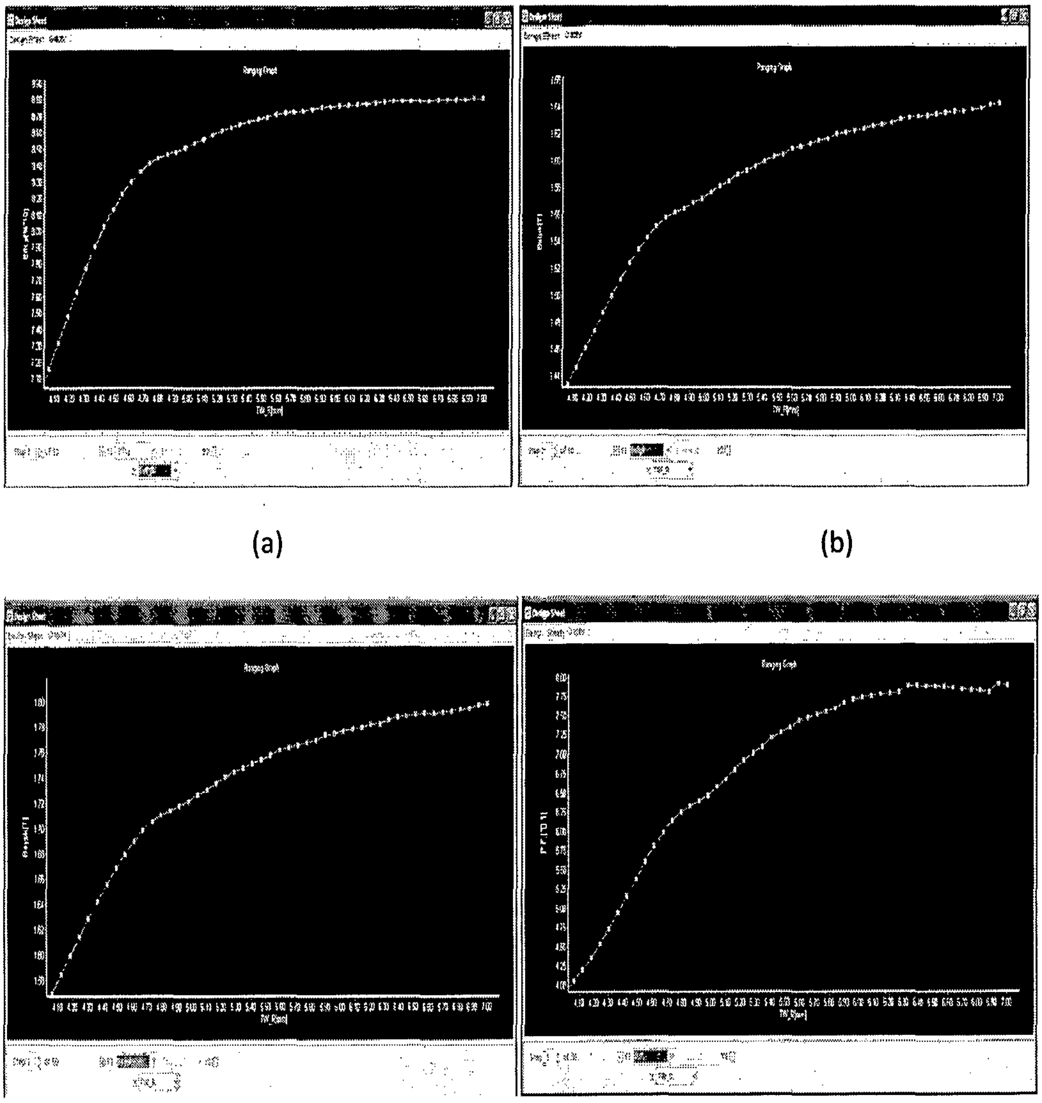
(a) (b)

© (d)

Fig.5.3. stator tooth width\....... (a) Efficiency (b)$B_{tmax}$ (c)$B_{symax}$ (d) PF

Similar analysis could be done for the stator tooth width. It is seen that all the performance parameters attain some constant value after a certain variation in the tooth width. The effect is certainly enormous on designing the performance and the variation in the parameters is over a wide range of values. The performance parameters vary with tooth width for a range of 4mm to 6.5 mm, this is a wide range thus to select the final value of the tooth width which will suffice the requirements, a careful selection is needed.

### 5.7.4. Rotor tooth width



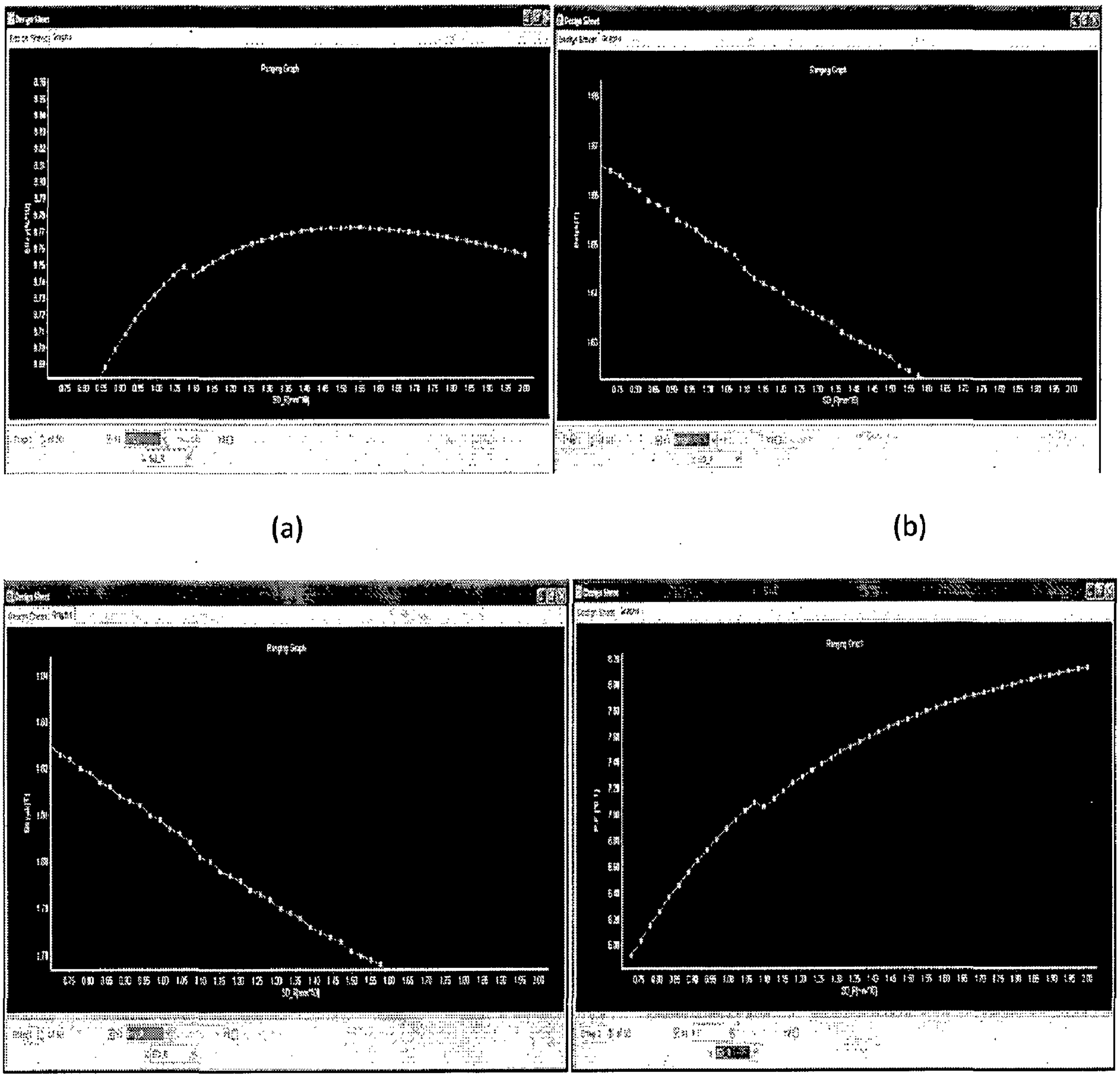
(a) (b)

(c) (d)

Fig.5.4. rotor tooth width\....... (a) efficiency (b)$B_{tmax}$ (c)$B_{symax}$ (d) PF

Here also it could be seen that the parameters are varying over the full range of variation of rotor tooth width. So it is difficult select one value of rotor tooth width for the optimum performance. To decide the suitable value the optimization procedure is required hence it is required to select the rotor tooth width as a variable.

## 5.7.5. Rotor slot depth



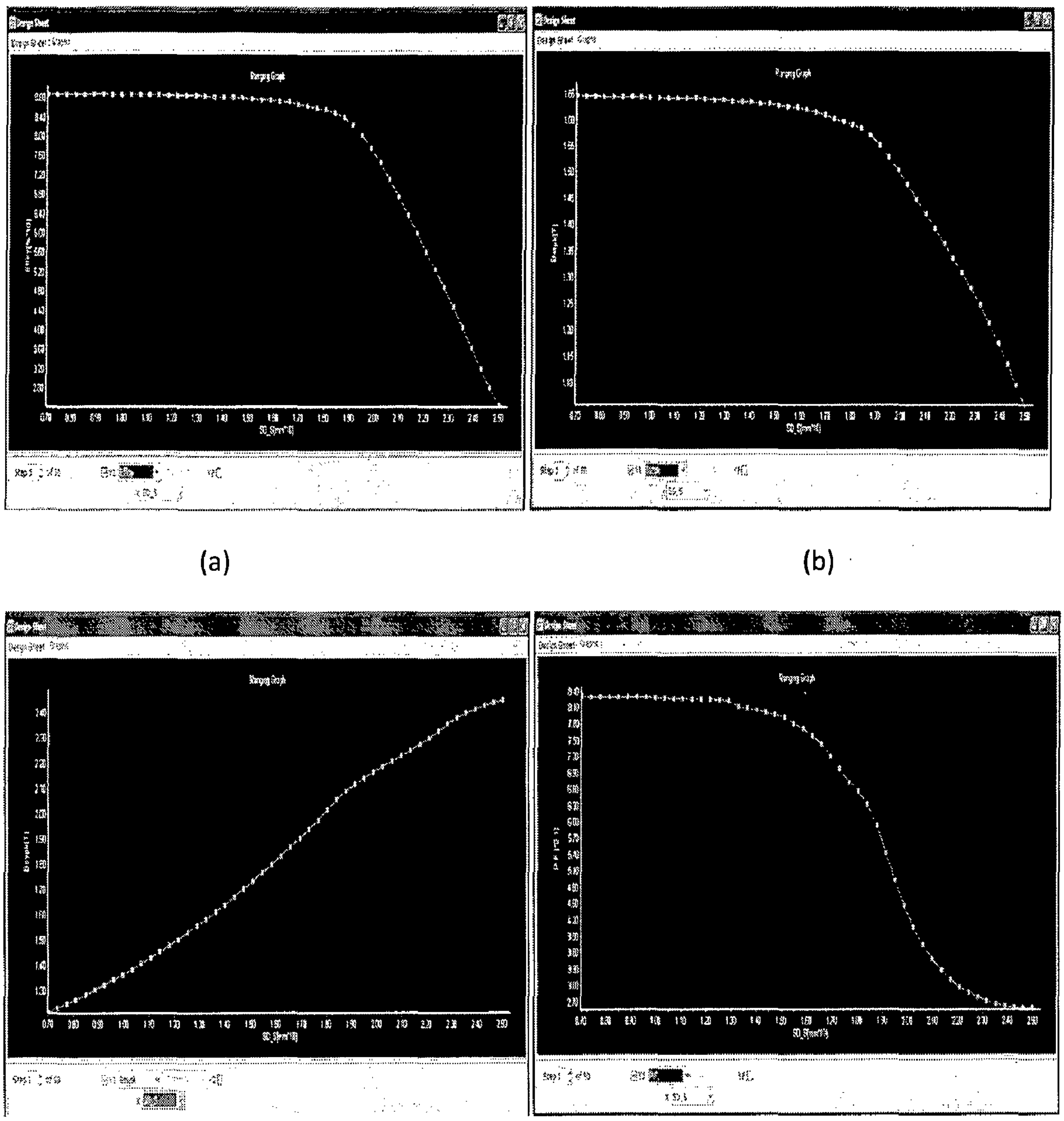
(a) (b)

(C) (d)

Fig.5.5. rotor slot depth\....... (a) Efficiency (b)$B_{tmax}$ (c)$B_{symax}$ (d) PF

For rotor slot depth the variation of the parameters is enormous and complex. There is no peak or droop which can help in deciding one suitable value of design, whereas there are slow changes. To get one suitable value we have to wander around over a range of values, hence it is necessary to select the rotor slot depth as a variable.

## 5.7.6. Stator slot depth



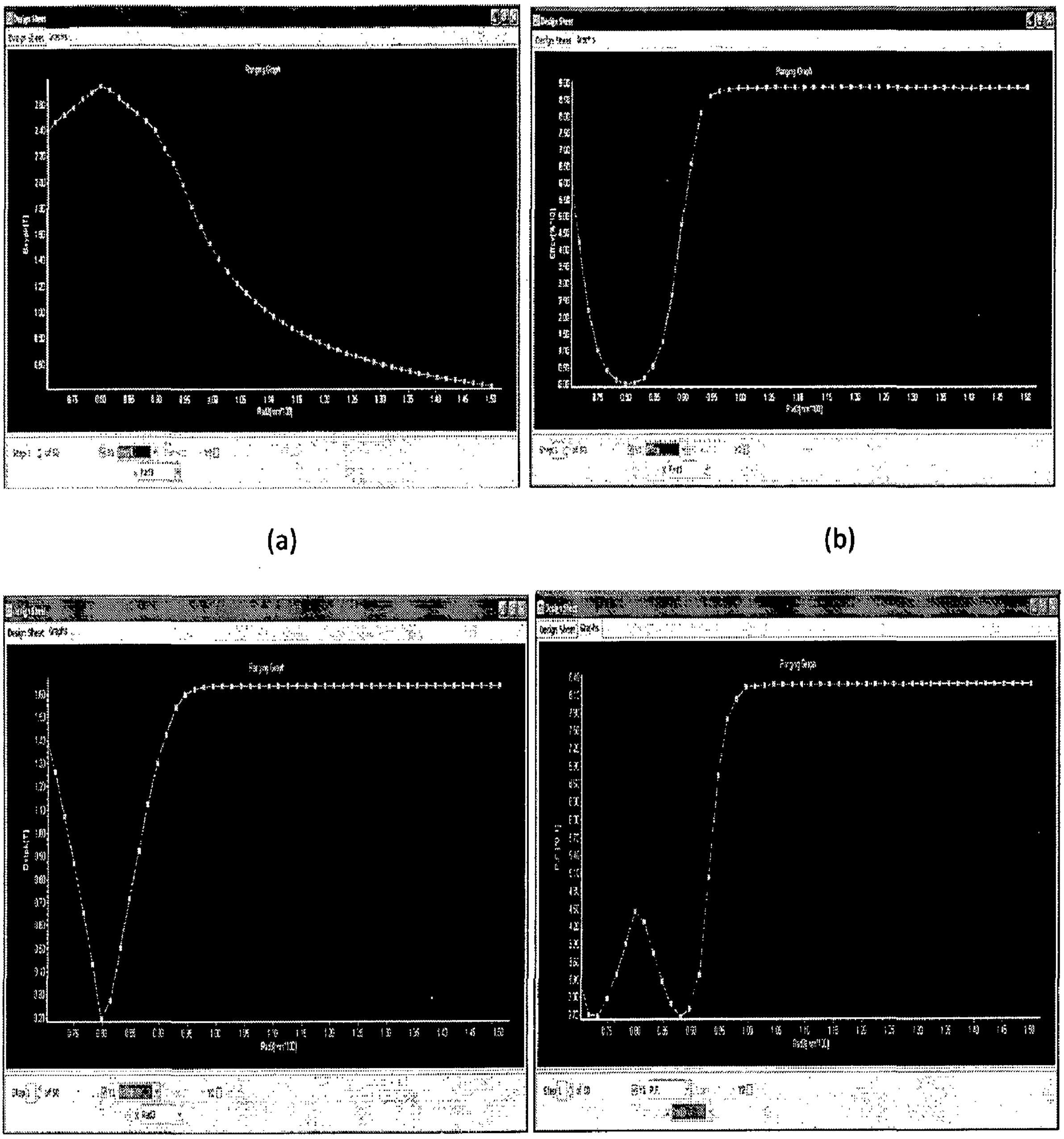
(a) (b)

© (d)

Fig.5.6. stator slot depth\....... (a) Efficiency (b)$B_{tmax}$ (c)$B_{symax}$ (d) PF

The stator slot depth shows high variation at the farther end of the plots for most of the parameters. Thus it is not much significant in deciding the efficiency, stator tooth density and power factor. But for the constraints of back core density it is necessary to keep a check on the value of stator slot depth, hence is taken as variable.

## 5.7.7. Outer radius of stator



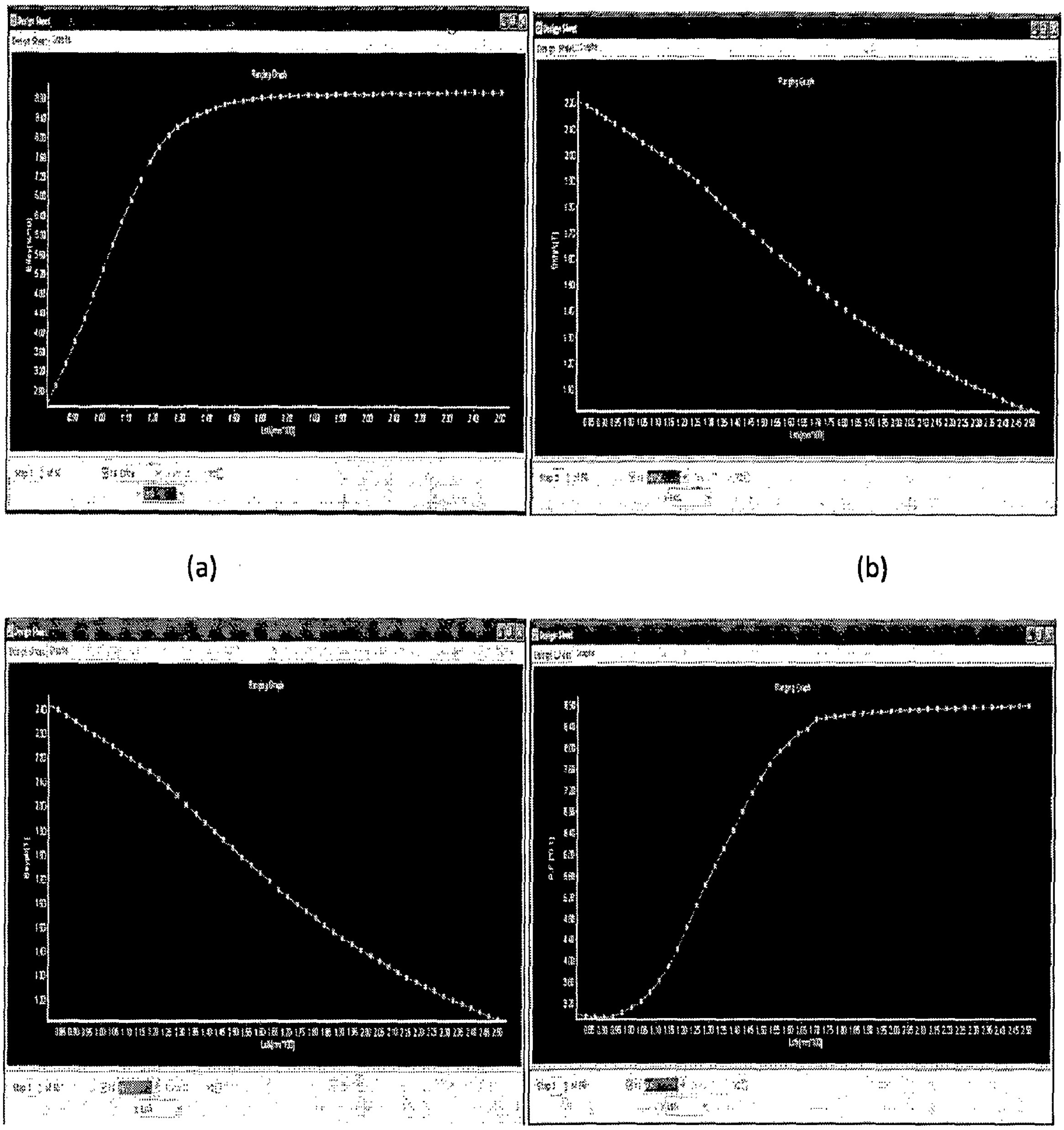
(a) (b)

© (d)

Fig.5.7. outer radius of stator\....... (a) Efficiency (b)$B_{tmax}$ (c)$B_{symax}$ (d) PF

Among most of the variables considered yet outer rotor radius plots are the most non uniform plots. Due to the variation of the efficiency over the whole range of value it is necessary to consider it as a variable, but from the plots it is sure that beyond 110 mm the flux densities are high so it is better to choose a value below this value. But the power factor approves for values higher than prementioned value. So it is chosen as a variable.

### 5.7.8. Length of stack



(a)

(b)

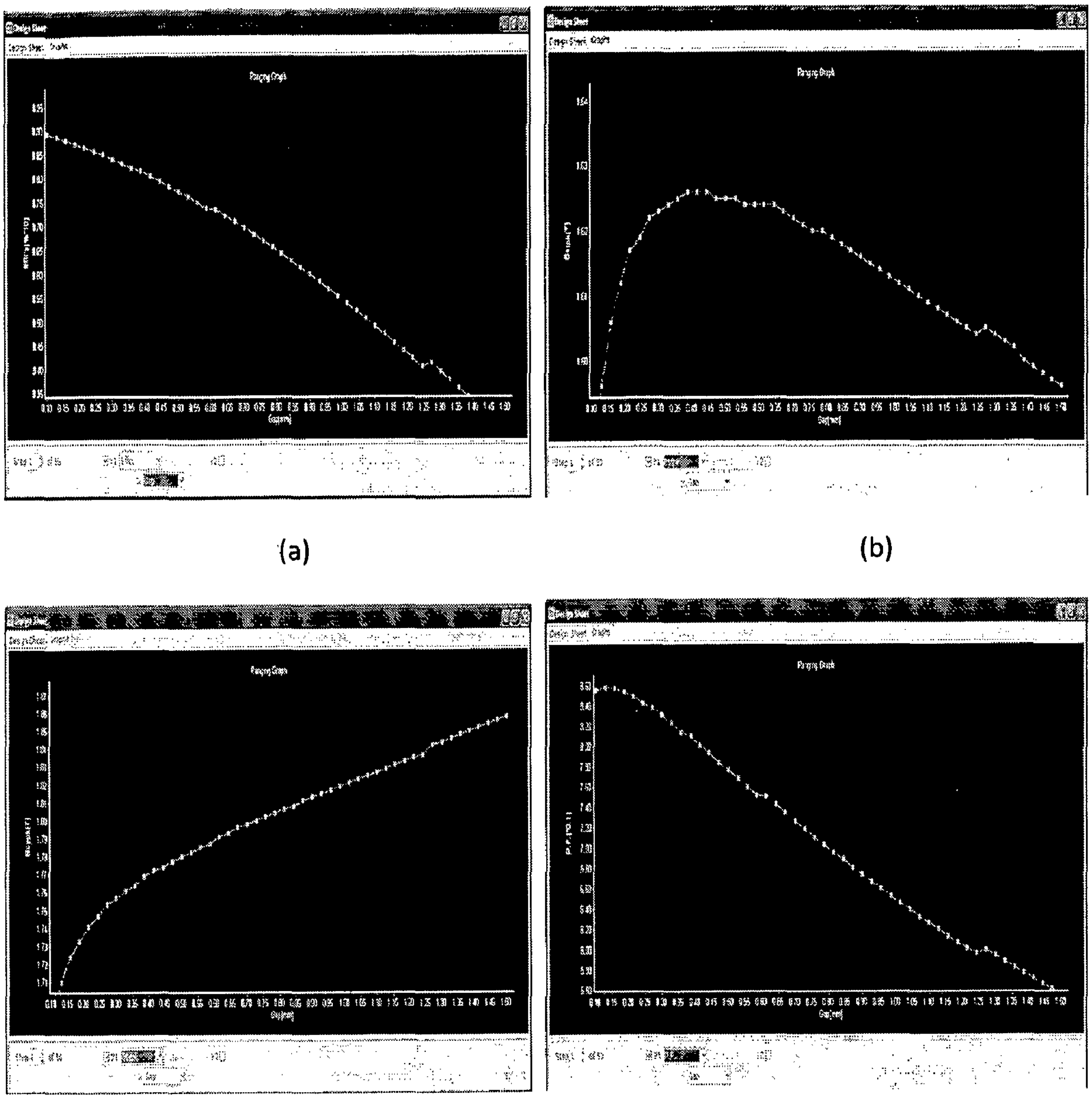
©

(d)

fig.5.8. stator stack length\……. (a) Efficiency (b)$B_{tmax}$ (c)$B_{symax}$ (d) PF

Length of the stack plays a very important role in various aspects, especially peak flux densities of stator and rotor. Thus the length of stack without any argument has to be selected carefully and necessarily chosen as a variable.

## 5.7.9. Air gap length



(a) (b)

© (d)

fig.5.9. air gap length\....... (a) Efficiency (b)$B_{tmax}$ (c)$B_{symax}$ (d) PF

The much variation of the air gap length is not possible. Also the effect of the air gap length on the performance parameters is best near the lower range of values. By considering different aspects all mechanical and electromagnetic the value mostly chosen is 0.35mm. so there is not much requirement to chose air gap length as a variable. But the case is different for adjustable speed drives, which is discussed later.

By looking at the above plots it could be inferred that the effect of these design variables is quite complex and also they affect the performance parameters on a large scale. With some of the parameters the plots show steady increase or decrease of the performance parameters, while with others the plots are quite complex. Hence if these design variables are chosen carefully a good performance Induction motor could be designed.

However for the sinusoidal operation induction motors the air gap length is usually chosen between 0.35-0.5 mm and hence will not be taken as a design variable. But for the adjustable speed drive induction motor the zig zag tooth losses, and tooth pulsation losses make a major part of extra losses. These losses solely depend on ratio of stator slot opening and air gap length hence for adjustable speed drives the two extra variables will be chosen, i.e. stator slot opening and air gap lengthThe variables chosen are tabulated as follows

| Sinusoidal supply induction motors | |
|---|---|
| 1) Outer radius of stator | Rado |
| 2) Rotor radius | Rad1 |
| 3) Length of stack | Lstk |
| 4) Stator slot depth | $h_s$ |
| 5) Stator tooth width | tws |
| 6) Rotor slot depth | $h_r$ |
| 7) Rotor tooth width | twr |
| Adjustable speed drive motors | |
| 1) Outer radius of stator | Rado |
| 2) Rotor radius | Rad1 |
| 3) Length of stack | Lstk |
| 4) Stator slot depth | $h_s$ |
| 5) Stator tooth width | tws |
| 6) Rotor slot depth | $h_r$ |
| 7) Rotor tooth width | twr |
| 8) Stator slot opening | $b_{os}$ |

| | |
|---|---|
| 9) Air gap length | $l_g$ |

Table.5.1. variables chosen for design optimization

With the selection of the objective function, constraints and the variables, the prerequisites of the optimization of induction motor design are completed. Now the procedure of the optimization should be clear. The algorithm and flow chart of the Rosenbrock's method is already given in chapter 2. With the introduction of SPEED software there are few changes in the flow chart. The flowchart for adjustable speed drive motor design are shown in the fig.5.10. on next page.

The "Evaluate objective function and constraints" block actually consists of a number of steps as given below

- Transfer the new variable vector point to SPEED PC-IMD.
- Do steady state analysis of the new design.
- Retransfer the calculated value of sine losses to MATLAB and store it in a variable.
- Calculate the time harmonic losses in MATLAB with the help of expressions for all the harmonic orders.
- Add the sine losses transferred from SPEED PC-IMD and losses calculated in MATLAB.
- Transfer the constraints value from SPEED PC-IMD.

Hence the total optimized design is obtained.

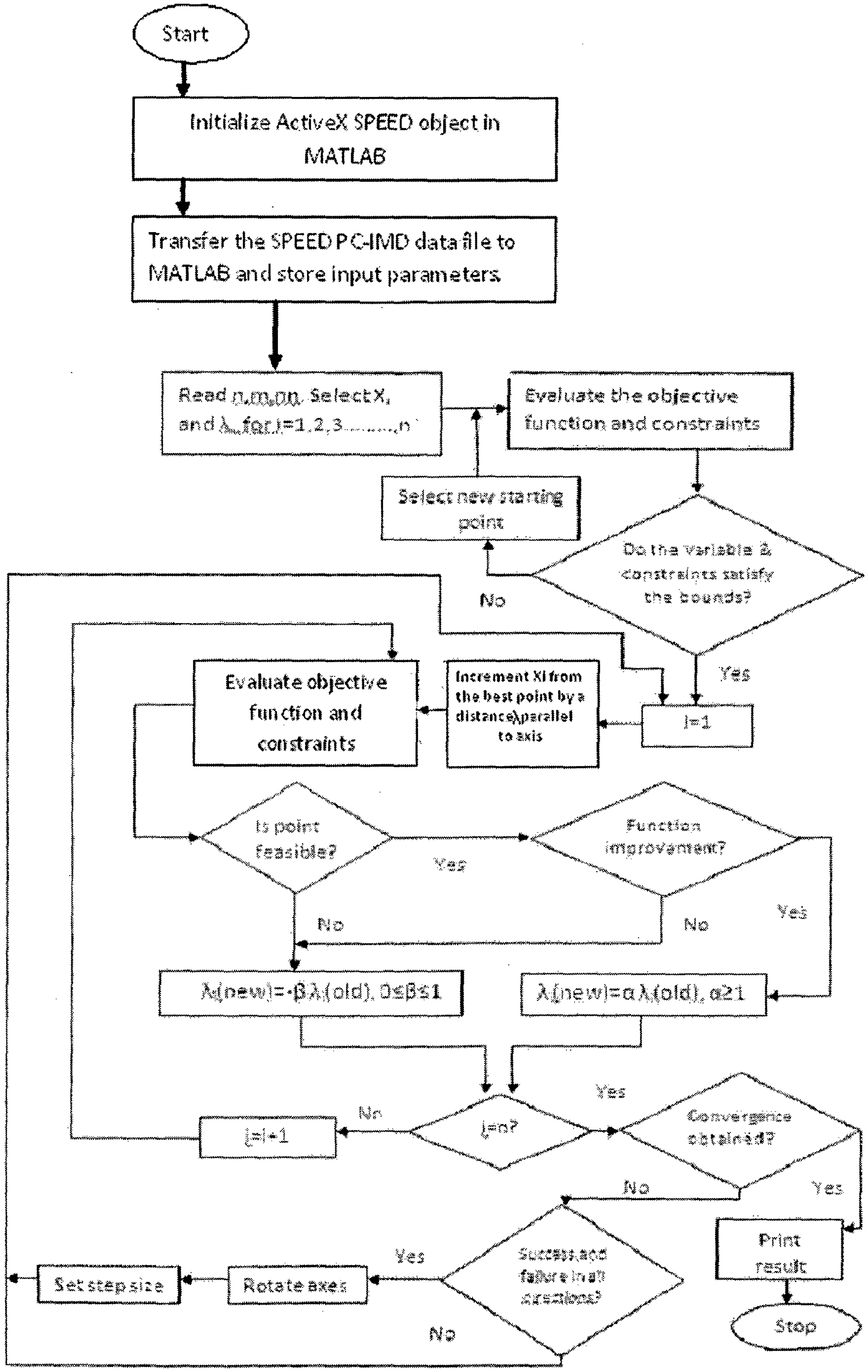


Fig.5.10. Flow chart of the optimization program in MATLAB

## 5.8. Conclusion

The advent of the computer technology had not only brought about changes in the optimization process speed and efficiency but have also provided a lot of ease in design of induction motors. With the combination of MATLAB optimization program and SPEED machine design data files the design and optimization had become an easy procedure.

The problem formulation of the optimization of design of induction motor has been summarized in the chapter. Also it had been noticed that there are several differences between the design of Induction motor for direct on line operation and for semiconductor supply operation. How these design differences affect the procedure of design of motor has been summed up. The ease which is provided by SPEED to initiate such designs is worth noting.

At this stage, we have the complete problem formulation and the flowchart of the design procedure. The running of the optimization procedure will provide the final results.

# 6. Results and discussions

An analysis of the results of the design optimization program in SPEED PC-IMD 3.5.2.3 along with MATLAB is carried out next. A motor of 7.5kW, 400V having base speed of 1500 rpm is designed. The inverter being considered is square wave voltage source inverter. The harmonics of the order 6n±1 upto n=3 are being considered as the magnitude of harmonics above 19th order is not significant. The ratings of the machine and other specifications are given in appendix A.

## 6.1. Results of design of sinusoidal supply induction motor

With the discussions done till now, it is well known that there is no need to assign the parameters by the designer. Just by putting the specification the initial design is provided by SPEED. Hence before running the optimization program there is a need of generating one initial design of the motor of desired ratings. For the sinusoidal supply motors such design or data file is generated in PC-IMD 3.5.2.3 with the name disin.im1. After creation of this motor design the optimization procedure is run and the optimized result is generated. The result is given in form of tabulated data for both unoptimized and optimized sinusoidal supply induction motor

*Results*

| Item | SPEED unoptimized design | Optimized for sinusoidal supply |
|---|---|---|
| Assigned parameters | | |
| 1. Frequency | 50 Hz | 50 Hz |
| 2. Torque to volume ratio | 25.00 Nm/m$^3$ | 25.00 Nm/m$^3$ |
| 3. Number of stator slots | 36 | 36 |
| 4. Number of rotor bars | 28 | 28 |
| 5. Cage type | Type 5 | Type 5 |
| Variables | | |

| | | |
|---|---|---|
| 1. Rotor radius | 65.2524 mm | 71.5627 mm |
| 2. Stator outer radius | 96.4429 mm | 98.3129 mm |
| 3. Length of stack | 154.2059 mm | 157.0397 mm |
| 4. Stator slot depth | 15.5952 mm | 5.1123 mm |
| 5. Stator tooth width | 6.4185 mm | 7.1794 mm |
| 6. Rotor bar depth | 15.2956 mm | 25.1488 mm |
| 7. Rotor tooth width | 6.9925 mm | 7.8139 mm |
| Constraints | | |
| 1. Stator yoke flux density | 1.7784 Wb/m$^2$ | 1.4003 Wb/m$^2$ |
| 2. Maximum stator tooth flux density | 1.6239 Wb/m$^2$ | 1.4491 Wb/m$^2$ |
| 3. No load to full load current ratio | 0.5713 | 0.3786 |
| 4. Full load slip | 0.0349 | 0.0212 |
| 5. Starting to full load torque ratio | 1.9 | 1.5 |
| 6. Per unit breakdown torque | 3.7505 | 3.6411 |
| 7. Power factor | 0.7745 | 0.8659 |
| Objective function | | |
| **1. Efficiency** | **87.7416%** | **90.64%** |

Table.6.1. Comparison of unoptimized and optimized results for sinusoidal supply operation

It is noticed, that the optimized design of the induction motor has changed the efficiency of the induction motors by a considerable keeping the constraints well in limit. The various changes brought about by the change of design parameters are discussed below.

- **Rotor radius** is increased after the optimization. Due the increase of the rotor radius the stator and rotor slot pitch had increased due to which the maximum flux density of stator and rotor tooth had reduced. The reduction in the peak flux densities reduces the core losses in the motor.

- **Stator outer radius** has also been set to a higher value due to the increased rotor radius. But the difference between the rotor radius and stator outer radius is reduced. Thus there is almost same weight of iron is present in stator as before.
- **Length of stack** is also increased which results in reduction of back core flux densities due to increased cross section area. But also the increase of length results in increase of rotor and stator resistance. Thus the increase of length has to be chosen keeping the two factors in mind. The increase of length of stack results in increase of copper losses, reduction of breakdown torque.
- In **Stator slot dimensions** reduction of slot depth and increase of tooth width reduce the flux density.
- **Rotor slot dimensions** in rotor slot it is seen that the depth of rotor bar has increased considerably. This increases area of cross section of rotor bars hence the rotor copper losses, which form the main part of the copper losses is reduced. It could be noticed that due reduction of rotor resistance the per unit starting torque has reduced to the limiting value of the constraint. Thus the reduction in rotor resistance reduces the starting torque heavily.

The torque speed characteristics of the optimized induction motor are given below by medium thickness curve and efficiency are given by thickest line. The curves are obtained from the SPEED PC-IMD.

### 6.1.1. Torque speed characteristics of optimized machine

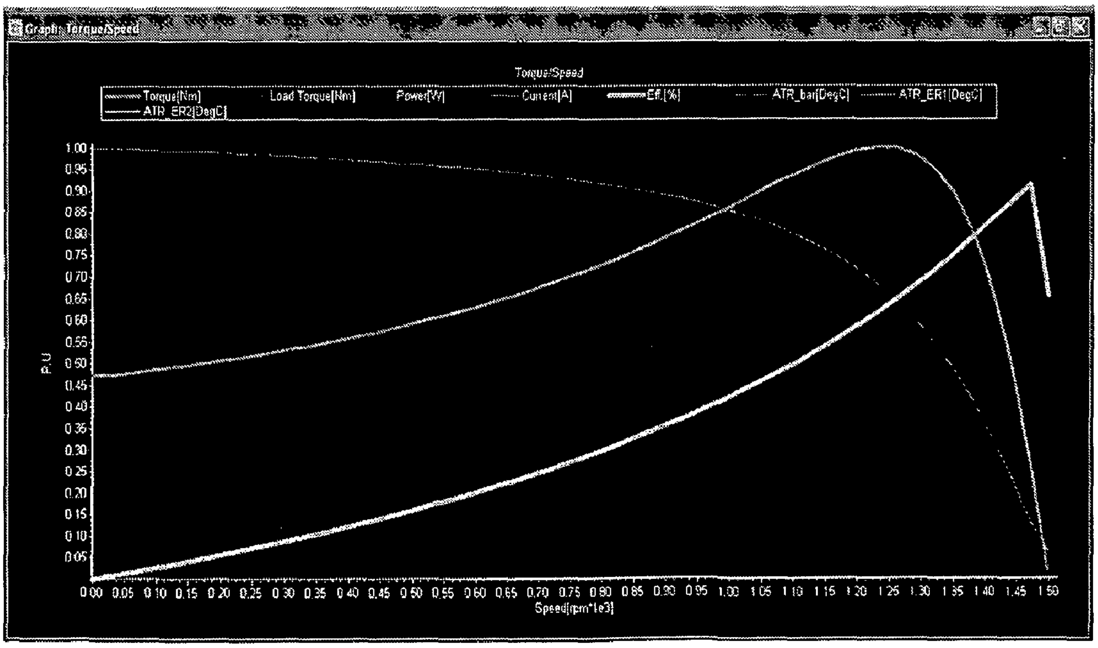
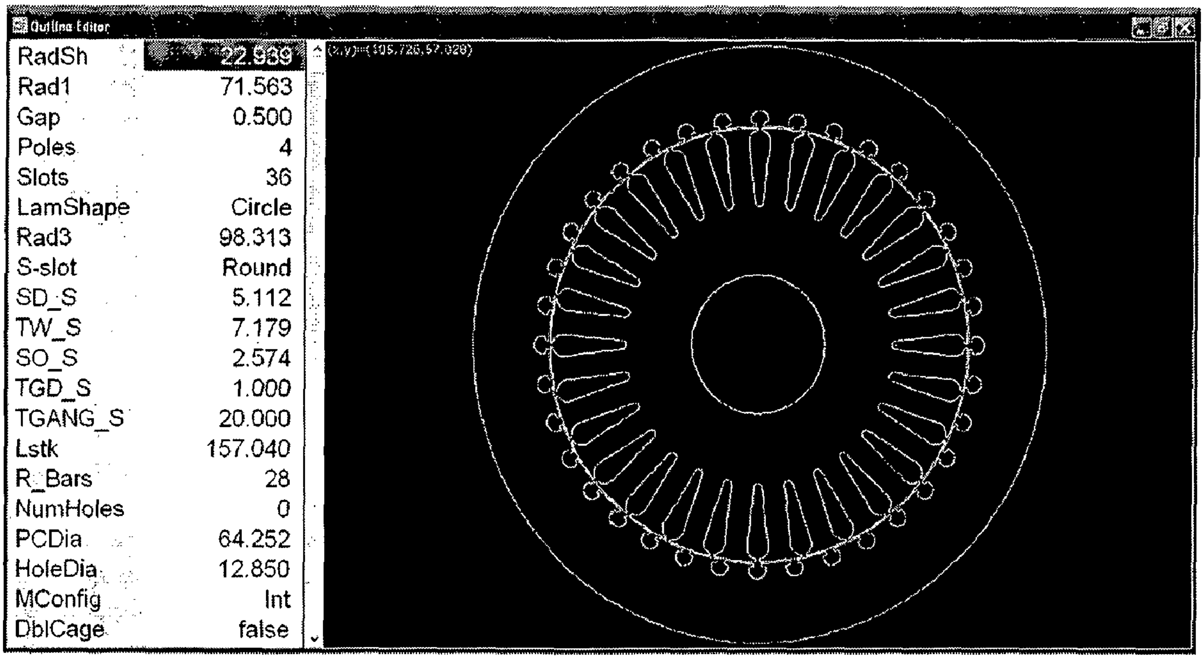


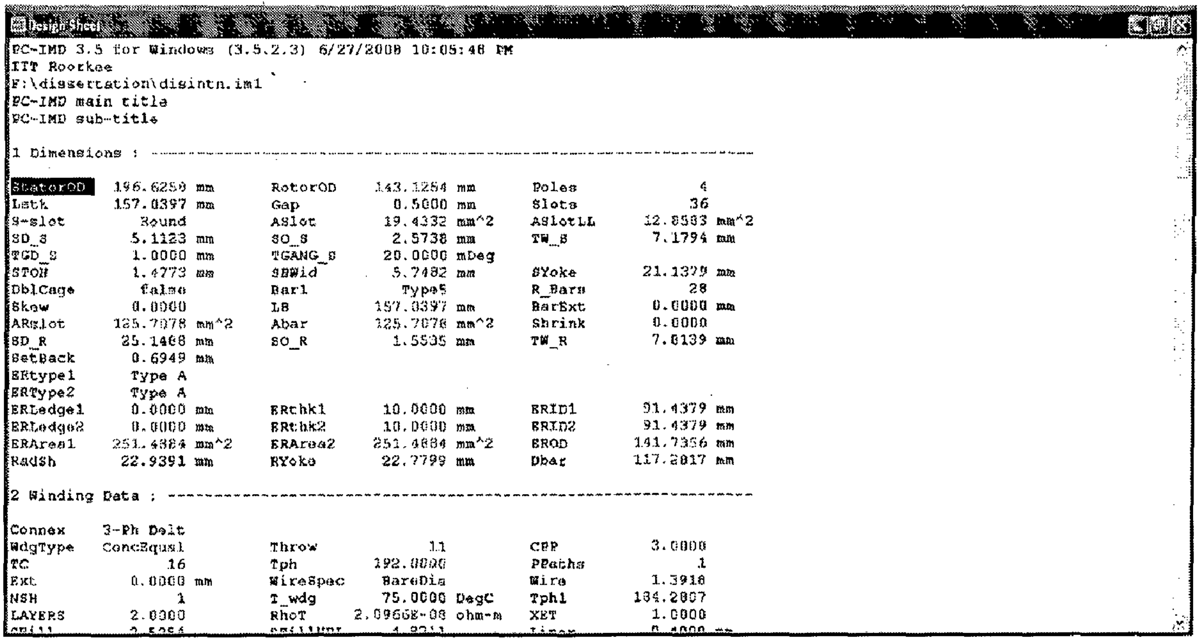
Fig.6.1. torque speed characteristics of the optimized induction motor



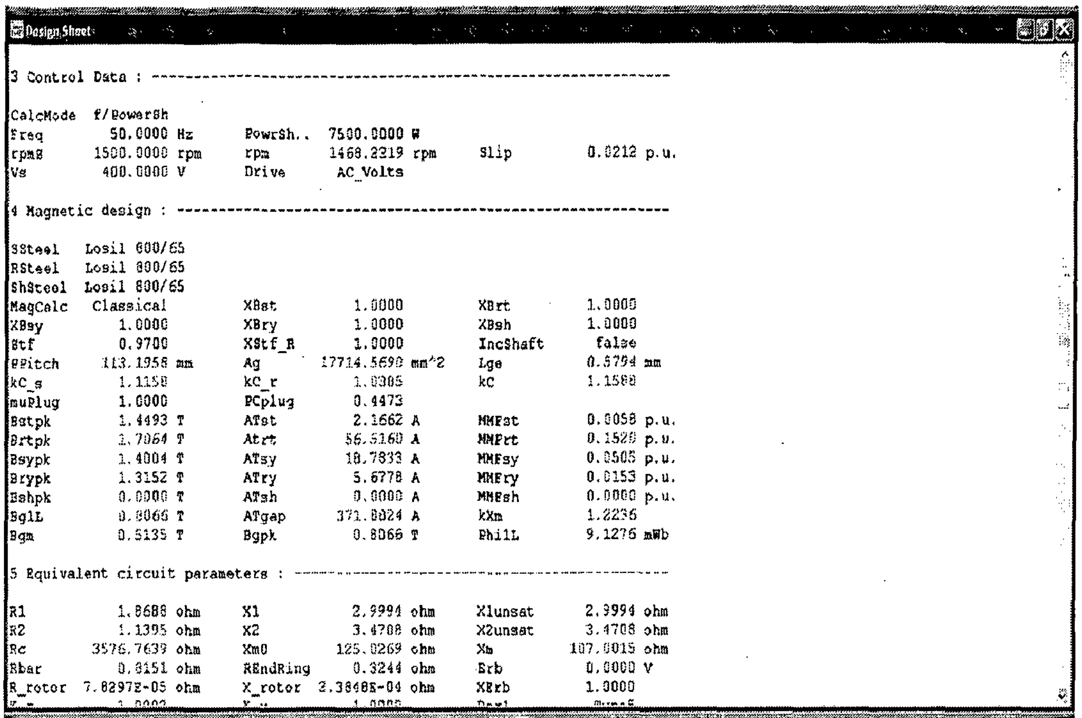
| | |
|---|---|
| RadSh | 22.939 |
| Rad1 | 71.563 |
| Gap | 0.500 |
| Poles | 4 |
| Slots | 36 |
| LamShape | Circle |
| Rad3 | 98.313 |
| S-slot | Round |
| SD_S | 5.112 |
| TW_S | 7.179 |
| SO_S | 2.574 |
| TGD_S | 1.000 |
| TGANG_S | 20.000 |
| Lstk | 157.040 |
| R_Bars | 28 |
| NumHoles | 0 |
| PCDia | 64.252 |
| HoleDia | 12.850 |
| MConfig | Int |
| DblCage | false |

Fig.6.2. sinusoidal operated, optimized Motor cross section

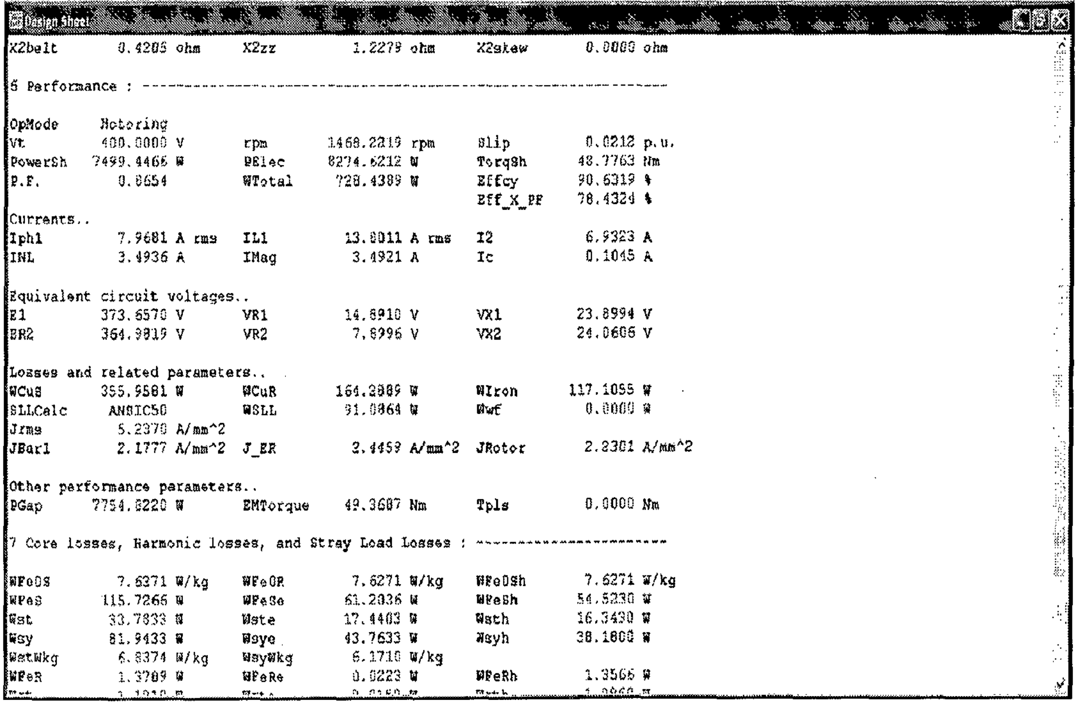
Also for the study of cross section of motor the final cross section of sinusoidal supply optimized machine are generated through SPEED PC-IMD outline editor. Also the sections of the design sheet with other important data are shown in design sheets.



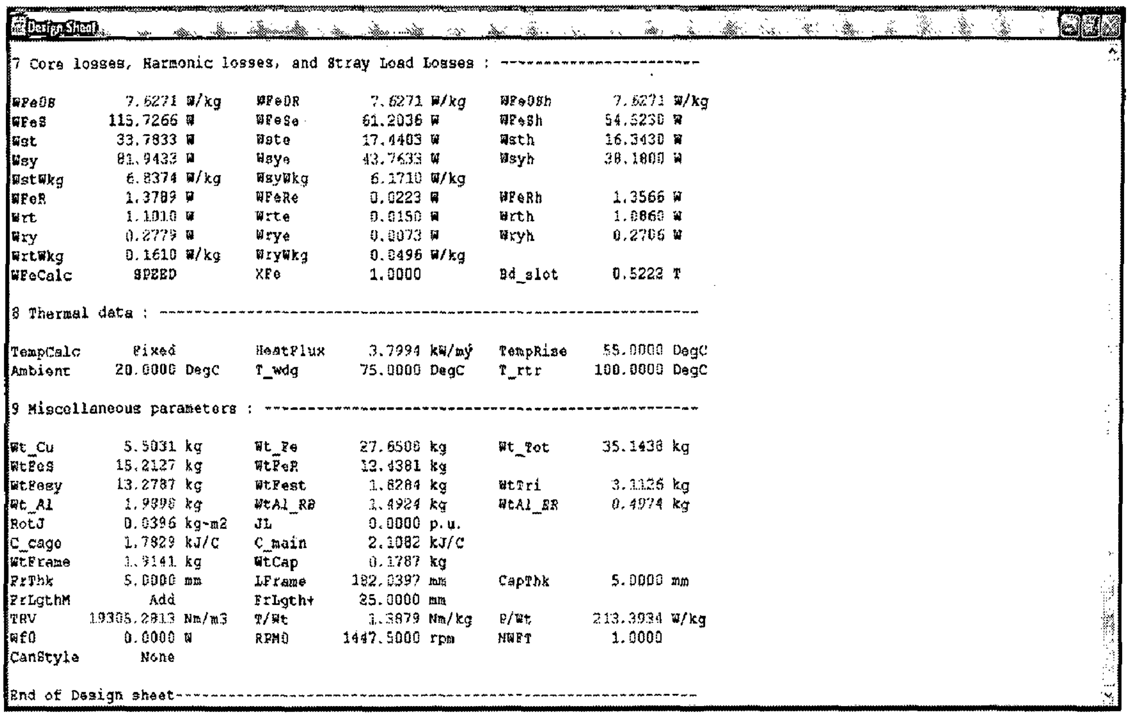
```
PC-IMD 3.5 for Windows (3.5.2.3) 6/27/2008 10:05:48 PM
IIT Roorkee
F:\dissertation\disintn.im1
PC-IMD main title
PC-IMD sub-title

1 Dimensions : ---------------------------------------------------------------

StatorOD    196.6250 mm       RotorOD      143.1264 mm       Poles              4
Lstk        157.0397 mm       Gap            0.5000 mm       Slots             36
S-slot         Round          ASlot         19.4332 mm^2     ASlotLL      12.8583 mm^2
SD_S          5.1123 mm       SO_S           2.5738 mm       TW_S          7.1794 mm
TGD_S         1.0000 mm       TGANG_S       20.0000 mDeg
STOH          1.4773 mm       SBWid          5.7482 mm       SYoke        21.1329 mm
DblCage        false          Bar1            Type5          R_Bars            28
Skew          0.0000          LB           157.0397 mm       BarExt        0.0000 mm
ARslot      125.7078 mm^2     Abar         125.7078 mm^2     Shrink        0.0000
SD_R         25.1468 mm       SO_R           1.5535 mm       TW_R          7.8139 mm
SetBack       0.6949 mm
ERtype1       Type A
ERType2       Type A
ERLedge1      0.0000 mm       ERthk1        10.0000 mm       ERID1        91.4379 mm
ERLedge2      0.0000 mm       ERthk2        10.0000 mm       ERID2        91.4379 mm
ERArea1     251.4884 mm^2     ERArea2      251.4884 mm^2     EROD        141.7356 mm
RadSh        22.9391 mm       RYoke         22.7799 mm       Dbar        117.2817 mm

2 Winding Data ; -------------------------------------------------------------

Connex     3-Ph Delt
WdgType    ConcEqual          Throw              11          CPP           3.0000
TC                16          Tph          192.0000          PPaths             1
Ext           0.0000 mm       WireSpec       BareDia         Wire          1.3918
NSH                1          T_wdg         75.0000 DegC     Tph1        184.2807
LAYERS        2.0000          RhoT      2.0966E-08 ohm-m     XET           1.0000
```



```
3 Control Data : -------------------------------------------------------------

CalcMode  f/PowerSh
Freq         50.0000 Hz       PowrSh..  7500.0000 W
rpmS       1500.0000 rpm      rpm       1468.2219 rpm     Slip          0.0212 p.u.
Vs          400.0000 V        Drive      AC_Volts

4 Magnetic design : ----------------------------------------------------------

SSteel   Losil 800/65
RSteel   Losil 800/65
ShSteel  Losil 800/65
MagCalc   Classical           XBst         1.0000         XBrt          1.0000
XBsy          1.0000          XBry         1.0000         XBsh          1.0000
Stf           0.9700          XStf_R       1.0000         IncShaft       false
PPitch      113.1958 mm       Ag       17714.5690 mm^2    Lge           0.5794 mm
kC_s          1.1150          kC_r         1.0385         kC            1.1580
muPlug        1.0000          PCplug       0.4473
Bstpk         1.4493 T        ATst         2.1662 A       MMFst         0.0058 p.u.
Brtpk         1.7064 T        Atrt        56.5160 A       MMFrt         0.1520 p.u.
Bsypk         1.4004 T        ATsy        18.7833 A       MMFsy         0.0505 p.u.
Brypk         1.3152 T        ATry         5.6778 A       MMFry         0.0153 p.u.
Bshpk         0.0000 T        ATsh         0.0000 A       MMFsh         0.0000 p.u.
Bg1L          0.8066 T        ATgap      371.8024 A       kXm           1.2236
Bgm           0.5135 T        Bgpk         0.8066 T       Phi1L         9.1276 mWb

5 Equivalent circuit parameters : --------------------------------------------

R1            1.8688 ohm      X1           2.9994 ohm     X1unsat       2.9994 ohm
R2            1.1395 ohm      X2           3.4708 ohm     X2unsat       3.4708 ohm
Rc         3576.7639 ohm      Xm0        125.0269 ohm     Xm          107.0015 ohm
Rbar          0.8151 ohm      REndRing     0.3244 ohm     Erb           0.0000 V
R_rotor  7.8297E-05 ohm       X_rotor  2.3868E-04 ohm     XErb          1.0000
```



```
X2belt        0.4205 ohm      X2zz         1.2279 ohm     X2skew        0.0000 ohm

6 Performance : --------------------------------------------------------------

OpMode     Motoring
Vt          400.0000 V        rpm       1468.2219 rpm     Slip          0.0212 p.u.
PowerSh    7499.4466 W        PElec     8274.6212 W       TorqSh       48.7763 Nm
P.F.          0.8654          WTotal     728.4389 W       Effcy        90.6319 %
                                                          Eff_X_PF     78.4324 %
Currents..
Iph1          7.9681 A rms    IL1         13.8011 A rms   I2            6.9323 A
INL           3.4936 A        IMag         3.4921 A       Ic            0.1045 A

Equivalent circuit voltages..
E1          373.6570 V        VR1         14.8910 V       VX1          23.8994 V
ER2         364.9819 V        VR2          7.8996 V       VX2          24.0605 V

Losses and related parameters..
WCuS        355.9581 W        WCuR       164.2889 W       WIron       117.1055 W
SLLCalc     ANSIC50           WSLL        91.0864 W       Wwf           0.0000 W
Jrms          5.2370 A/mm^2
JBar1         2.1777 A/mm^2   J_ER         2.4459 A/mm^2  JRotor        2.2301 A/mm^2

Other performance parameters..
PGap       7754.8220 W        EMTorque    49.3687 Nm      Tpls          0.0000 Nm

7 Core losses, Harmonic losses, and Stray Load Losses : ----------------------

WFe0S         7.6271 W/kg     WFe0R        7.6271 W/kg    WFe0Sh        7.6271 W/kg
WFeS        115.7266 W        WFeSe       61.2036 W       WFeSh        54.5230 W
Wst          33.7833 W        Wste        17.4403 W       Wsth         16.3430 W
Wsy          81.9433 W        Wsye        43.7633 W       Wsyh         38.1800 W
WstWkg        6.8374 W/kg     WsyWkg       6.1710 W/kg
WFeR          1.3789 W        WFeRe        0.0223 W       WFeRh         1.3566 W
```



```
7 Core losses, Harmonic losses, and Stray Load Losses : ----------------------

WFeOS         7.6271 W/kg    WFeOR         7.6271 W/kg    WFeOSh        7.6271 W/kg
WFeS        115.7266 W       WFeSe        61.2036 W       WFeSh        54.5230 W
Wst          33.7833 W       Wste         17.4403 W       Wsth         16.3430 W
Wsy          81.9433 W       Wsye         43.7633 W       Wsyh         38.1800 W
WstWkg        6.8374 W/kg    WsyWkg        6.1710 W/kg
WFeR          1.3789 W       WFeRe         0.0223 W       WFeRh         1.3566 W
Wrt           1.1010 W       Wrte          0.0150 W       Wrth          1.0860 W
Wry           0.2779 W       Wrye          0.0073 W       Wryh          0.2706 W
WrtWkg        0.1610 W/kg    WryWkg        0.0496 W/kg
WFeCalc       SPEED          XFe           1.0000         Bd_slot       0.5222 T

8 Thermal data : ------------------------------------------------------------

TempCalc      Fixed          HeatFlux      3.7994 kW/mý   TempRise     55.0000 DegC
Ambient      20.0000 DegC    T_wdg        75.0000 DegC    T_rtr       100.0000 DegC

9 Miscellaneous parameters : ---------------------------------------------

Wt_Cu         5.5031 kg      Wt_Fe        27.6508 kg      Wt_Tot       35.1438 kg
WtFeS        15.2127 kg      WtFeR        12.4381 kg
WtFesy       13.2787 kg      WtFest        1.8284 kg      WtTri         3.1126 kg
Wt_Al         1.9898 kg      WtAl_RB       1.4924 kg      WtAl_ER       0.4974 kg
RotJ          0.0396 kg-m2   JL            0.0000 p.u.
C_cage        1.7829 kJ/C    C_main        2.1082 kJ/C
WtFrame       1.9141 kg      WtCap         0.1787 kg
FrThk         5.0000 mm      LFrame      182.0397 mm      CapThk        5.0000 mm
FrLgthM        Add           FrLgth+      25.0000 mm
TRV       19305.2813 Nm/m3   T/Wt          1.3879 Nm/kg   P/Wt        213.3934 W/kg
Wf0           0.0000 W       RPM0       1447.5000 rpm     NWFT          1.0000
CanStyle       None

End of Design sheet-----------------------------------------------------------
```

Fig 6.3. Section of design sheet

## 6.2. Design optimization for adjustable speed drive

The effect of the harmonics on the losses of the induction machine has been discussed theoretically. To see the effect through computer simulation the machine optimized for the sinusoidal supply is made to run on the harmonic supply and the extra losses are calculated in the MATLAB program. The input for considering the ASD is output of square wave voltage source inverter. The comparison among the two is summed up in tabulated form.

*Results*

| Item | Operation of optimized machine under sinusoidal supply | Operation of conventional optimized machine under non-sinusoidal supply |
|---|---|---|
| Assigned parameters | | |
| 1.Frequency | 50Hz | 50 Hz |
| 2.Torque to volume ratio | 25.00 Nm/m$^3$ | 25.0 Nm/m$^3$ |
| 3.Number of stator slots | 36 | 36 |
| 4.Number of rotor bars | 28 | 28 |

| | | |
|---|---|---|
| 5.Cage type | Type 5 | Type 5 |
| Variables | | |
| 1.Rotor radius | 71.5627 mm | 71.5627 |
| 2.Stator outer radius | 98.3129 mm | 98.3129 |
| 3.Length of stack | 157.0397 mm | 157.397 |
| 4.Stator slot depth | 5.1123mm | 5.1123 mm |
| 5.Stator tooth width | 7.1794mm | 7.1794 mm |
| 6.Rotor bar depth | 25.1488mm | 25.1488 mm |
| 7.Rotor tooth width | 7.8139 mm | 7.8139 mm |
| Objective function | | |
| 1.Efficiency | 90.64% | 86.55% |

Table 6.2. Comparison of sinusoidal and adjustable speed drive operation

It could be seen very clearly that the machine which was optimized for maximum efficiency under sinusoidal supply is giving less efficiency for ASD operations. The extra harmonic losses are due to skin effect increase of resistance. The extra losses are tabulated below.

*Results*

| Losses under harmonic supply | value |
|---|---|
| Fundamental losses | 987.6571 W |
| Time harmonic copper losses | 178.3911 W |
| Time harmonic stator core loss | 0.123 W |
| Time harmonic rotor core loss | 0.123 W |
| Time harmonic stator slot wall loss | 0.0021 W |

| | |
|---|---|
| Time harmonic rotor slot wall loss | 0.00097 W |
| Time harmonic zig zag loss | 0.0037 W |

Table. 6.3. Time harmonic losses in normal optimized machine

It is inferred from the table of losses that the main component of the increased harmonic losses are time harmonic copper losses. This explains the need of special design for non sinusoidal operation of induction motors.

## 6.3. Results of design optimization for adjustable speed drive

*Results*

| Item | Conventional optimized machine operating on sinusoidal supply | Conventional Optimized motor operating on non sinusoidal supply | ASD optimized motor operating on non sinusoidal supply |
|---|---|---|---|
| Assigned parameters | | | |
| Frequency | 50 Hz | 50 Hz | 50 Hz |
| Torque to volume ratio | 25.00 Nm/m$^3$ | 25.00 Nm/m$^3$ | 25.00 Nm/m$^3$ |
| Number of stator slots | 36 | 36 | 36 |
| Number of rotor bars | 28 | 28 | 28 |
| Cage type | Type 5 | Type 5 | Type 3 |
| Variables | | | |
| Rotor radius | 71.5627 mm | 71.5627 mm | 65.2524 mm |
| Stator outer radius | 98.3129 mm | 98.3129 mm | 116.4429 mm |
| Length of stack | 157.0397 mm | 157.0397 mm | 156.2059 mm |
| Stator slot depth | 5.1123 mm | 5.1123 mm | 10.3952 mm |
| Stator tooth width | 7.1794 mm | 7.1794 mm | 6.6185 mm |

| | | | |
|---|---|---|---|
| Rotor bar depth | 25.1488 mm | 25.1488 mm | 22.4 mm |
| Rotor tooth width | 7.8139 mm | 7.8139 mm | 7.2 mm |
| Stator slot opening | 2.574 mm | 2.574 mm | 2.44 mm |
| Air gap length | 0.5 mm | 0.5 mm | 0.46 mm |
| Constraints | | | |
| Stator yoke flux density | 1.4003 Wb/m$^2$ | 1.4003 Wb/m$^2$ | 0.6993 Wb/m$^2$ |
| Maximum stator tooth flux density | 1.4491 Wb/m$^2$ | 1.4491 Wb/m$^2$ | 1.4492 Wb/m$^2$ |
| No load to full load current ratio | 0.3786 | 0.3786 | 0.4083 |
| Full load slip | 0.0212 | 0.0212 | 0.0276 |
| Starting to full load torque ratio | 1.5 | 1.5 | -NA- |
| Per unit breakdown torque | 3.6411 | 3.6411 | 3.095 |
| Power factor | 0.8659 | 0.8659 | 0.8697 |
| Losses | | | |
| Fundamental losses | 987.6571 | 987.6571 | 807.112 |
| Time harmonic copper losses | 0.00 | 178.3911 | 74.4422 |
| Time harmonic stator core loss | 0.00 | 0.123 | 0.08 |
| Time harmonic rotor core loss | 0.00 | 0.123 | 0.08 |
| Time harmonic stator slot wall loss | 0.00 | 0.0021 | 0.0007 |
| Time harmonic rotor slot wall loss | 0.00 | 0.00097 | 0.0129 |

| | | | |
|---|---|---|---|
| Time harmonic zig zag loss | 0.00 | 0.0037 | 0.0042 |
| Objective function | | | |
| **Efficiency** | **90.64%** | **86.55%** | **89.9822%** |

Table.6.4. comparison of the conventional optimized machine and ASD optimized machine on ASD and sinusoidal supply

The effect of variables in reduction of efficiency has already been discussed in the sinusoidal supply optimization design, discussions. The reduction in resistance could be interrelated. The only difference in this optimization other than dimensions is of rotor slots. It has been reported that the rotor bars which are wider near air gap, and narrower at other end provide better operation at high frequencies. Thus type 3 rotor bar has been chosen.

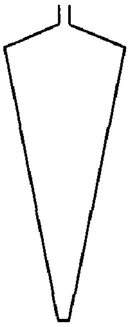


Fig.6.4. Type 3 rotor bar

The other effects will be summarized looking at the constraints. The main points are summed up as follows.

- It could be seen that the outer stator radius has increased considerably thus resulting in heavy reduction of **stator back core flux density**. This is done specially to reduce the core losses in the machine.
- As the tooth width of both stator and rotor are reduced still maintaining almost similar **tooth flux density**.
- Here the per unit breakdown torque value is worth noting. The per unit breakdown torque are **inversely proportional to the leakage reactance**. Here, per unit breakdown torque has **reduced by 15%** showing clearly an increase in the leakage reactance of the machine.
- The **increase in leakage reactance** is due to the reduction of tooth widths. The reduction in tooth width increases the leakage flux of the machine hence increasing the leakage reactance. Also the stator slot depth has increased resulting in increase of stator leakage reactance. The leakage reactance is the main factor in suppression of the harmonic currents in the machine as the value of reactance is frequency dependent and increases at higher values frequencies.

- There is an appreciable reduction in current value, due to leakage reactance which had reduced the fundamental losses as well as harmonic copper losses. The effect of increase of leakage reactance is more pronounced for time harmonic. This is inferred because the harmonic copper losses has been reduced to even **less than 50% of the losses** of sinusoidal supply operating optimized machine.
- During the running of optimization problem it was seen that when the program was trying to increase the value of rotor bar depth beyond the optimized value, the SPEED PC-IMD was reporting the error, "beyond the machine capability limits". Thus the rotor bar depth is limited to the given value.

## 6.3.1. Speed torque characteristics of motor designed for ASD

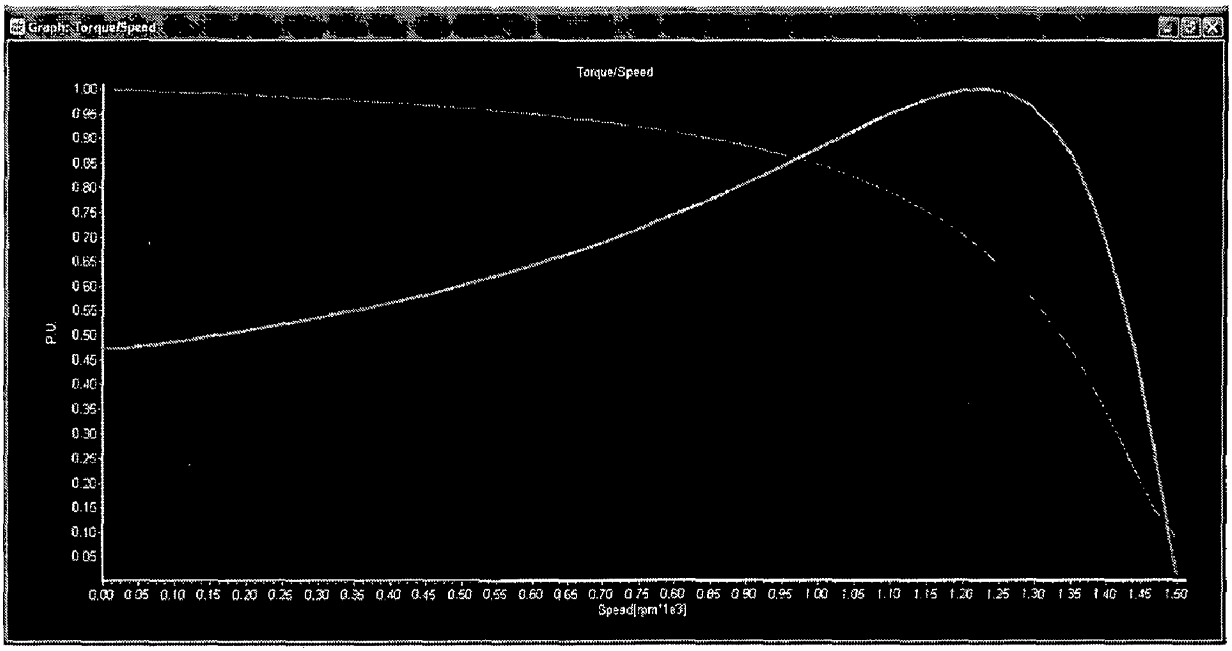
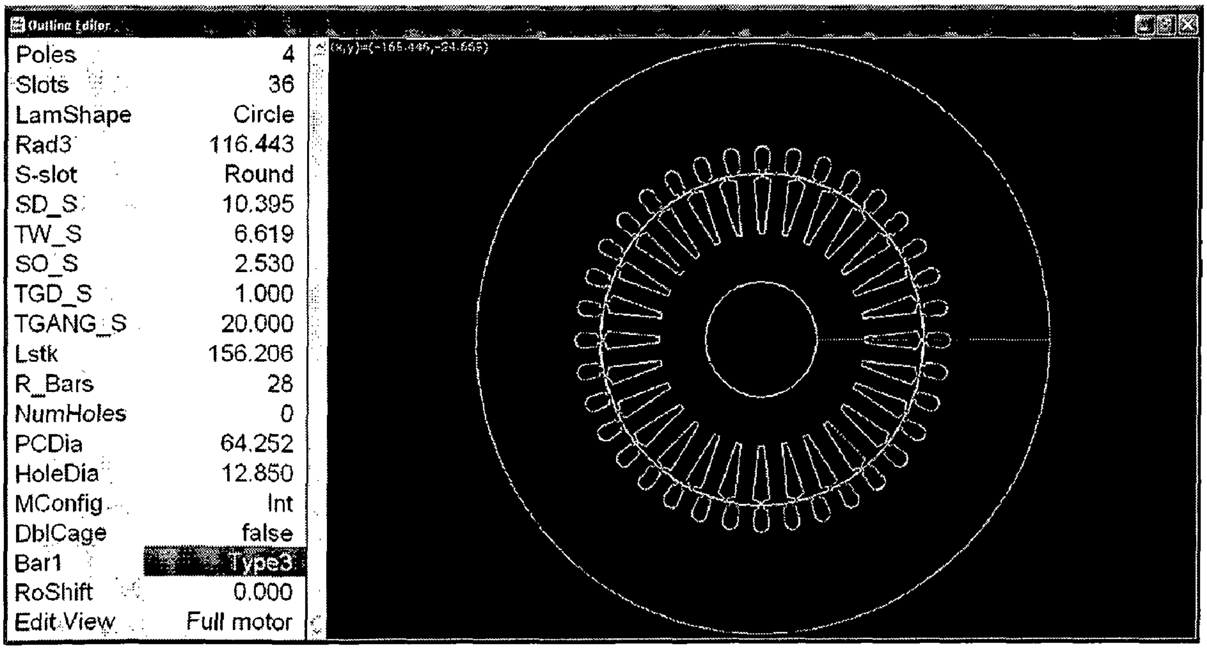


Fig 6.5. Speed torque curves

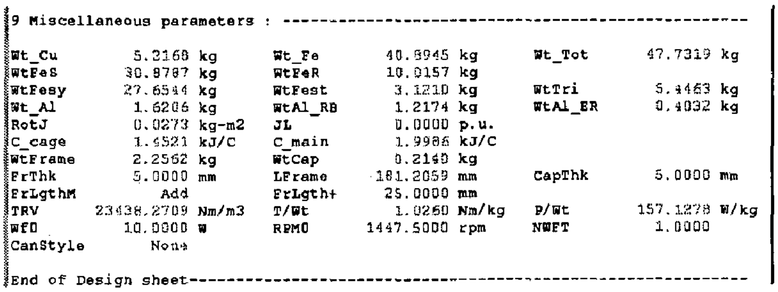
The speed torque curves of the machine at base speed are given in the fig above. The cross section of the ASD operated optimized induction machine design is given below.

From the cross sectional view of the machine it is clear that the ASD design is bigger in size as compared to the sinusoidal operating machine. This could be even cross checked by seeing the weight of machine in design sheet.



| | |
|---|---|
| Poles | 4 |
| Slots | 36 |
| LamShape | Circle |
| Rad3 | 116.443 |
| S-slot | Round |
| SD_S | 10.395 |
| TW_S | 6.619 |
| SO_S | 2.530 |
| TGD_S | 1.000 |
| TGANG_S | 20.000 |
| Lstk | 156.206 |
| R_Bars | 28 |
| NumHoles | 0 |
| PCDia | 64.252 |
| HoleDia | 12.850 |
| MConfig | Int |
| DblCage | false |
| Bar1 | Type3 |
| RoShift | 0.000 |
| EditView | Full motor |

Fig. 6.6. Cross section of motor



```
9 Miscellaneous parameters : ------------------------------------------------

Wt_Cu          5.2168 kg        Wt_Fe         40.8945 kg        Wt_Tot        47.7319 kg
WtFeS         30.8787 kg        WtFeR         10.0157 kg
WtFesy        27.6544 kg        WtFest         3.1210 kg        WtTri          5.4463 kg
Wt_Al          1.6206 kg        WtAl_RB        1.2174 kg        WtAl_ER        0.4032 kg
RotJ           0.0273 kg-m2     JL             0.0000 p.u.
C_cage         1.4521 kJ/C      C_main         1.9986 kJ/C
WtFrame        2.2562 kg        WtCap          0.2140 kg
FrThk          5.0000 mm        LFrame       181.2059 mm        CapThk         5.0000 mm
FrLgthM           Add           FrLgth+       25.0000 mm
TRV        23438.2709 Nm/m3     T/Wt           1.0260 Nm/kg     P/Wt         157.1278 W/kg
Wf0           10.0000 W         RPM0        1447.5000 rpm       NWFT           1.0000
CanStyle         None

End of Design sheet---------------------------------------------------------
```

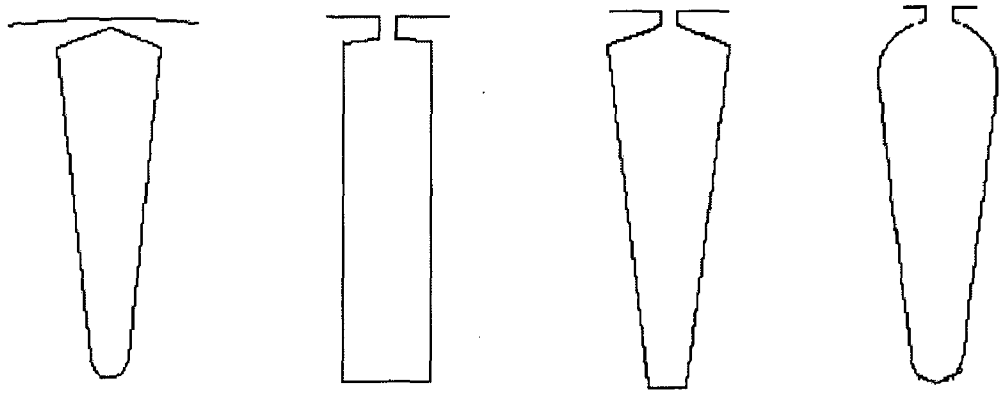
Fig. 6.7. Section of design sheet

The total weight of iron in the machine is **12 kg higher** than the previous optimized design.

## 6.4. Comparison of design with different slot shapes

As it has been discussed in the theory and the previous results that the skin effect increase in the rotor resistance is the main reason of the increase in the rotor resistance of the motor and in turn result in the increased losses of the motor at harmonic frequencies. Thus the shape of rotor should be carefully selected.

To check the effect of rotor shapes on the motor performance the motor optimized for ASD is made to run on PC-IMD by just changing the shape of the rotor bars keeping other parameters same. The different rotor bar shapes under trial are shown in fig. 6.8.



Type 0 Type 2 Type 3 Type 5

Fig.6.8. Types of SPEED PC-IMD slots for comparison

The results thus obtained are tabulated below.

*Results*

| Item | Type 0 | Type 2 | Type 3 | Type 5 |
|---|---|---|---|---|
| Variable | | | | |
| Rotor radius | 65.2524 mm | 65.2524 mm | 65.2524 mm | 65.2524 mm |
| Stator outer radius | 116.4429 mm | 116.4429 mm | 116.4429 mm | 116.4429 mm |
| Length of stack | 156.2059 mm | 156.2059 mm | 156.2059 mm | 156.2059 mm |
| Stator slot depth | 10.3952 mm | 10.3952 mm | 10.3952 mm | 10.3952 mm |
| Stator tooth width | 6.6185 mm | 6.6185 mm | 6.6185 mm | 6.6185 mm |
| Rotor bar depth | 22.4 mm | 22.4 mm | 22.4 mm | 22.4 mm |
| Rotor tooth width | 7.2 mm | 7.2 mm | 7.2 mm | 7.2 mm |
| Stator slot opening | 2.44 mm | 2.44 mm | 2.44 mm | 2.44 mm |
| Air gap length | 0.46 mm | 0.46 mm | 0.46 mm | 0.46 mm |
| Constraints | | | | |
| Stator yoke flux density | 0.7314 Wb/m$^2$ | 0.6933 Wb/m$^2$ | 0.6933 Wb/m$^2$ | 0.7339 Wb/m$^2$ |
| Maximum stator tooth flux density | 1.5679 wb/m$^2$ | 1.4863 Wb/m$^2$ | 1.4992 Wb/m$^2$ | 1.5734 Wb/m$^2$ |
| No load to full load current ratio | 0.4583 | 0.7639 | 0.4083 | 0.4817 |

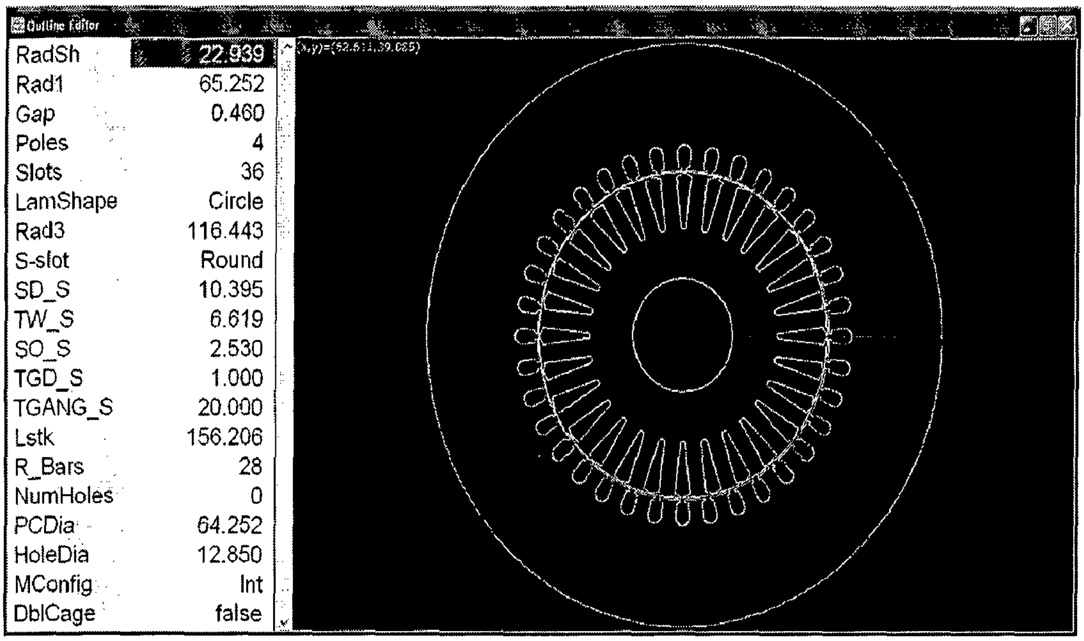
| | | | | |
|---|---|---|---|---|
| Full load slip | 0.0252 | 0.0273 | 0.0276 | 0.0252 |
| Per unit breakdown torque | **2.76** | 3.216 | 3.095 | 3.1433 |
| Power factor | 0.8289 | 0.5657 | 0.8697 | 0.8369 |
| Losses | | | | |
| Fundamental losses | 817.7217 W | 1048.6 W | 807.112 W | 808.8081 W |
| Time harmonic copper losses | 99.7445 W | **243.033 W** | 74.4422 W | 112.0103 W |
| Time harmonic stator core loss | 0.122 W | 0.224 W | 0.08 W | 0.257 W |
| Time harmonic rotor core loss | 0.24 W | 0.36 W | 0.08 W | 0.542 W |
| Time harmonic stator slot wall loss | 0.0018 W | 0.0011 W | 0.0007 W | 0.002 W |
| Time harmonic rotor slot wall loss | 0.000689 W | 0.0055 W | 0.0129 W | 0.000725 W |
| Time harmonic zig zag loss | 0.0093 W | 0.0224 W | 0.0042 W | 0.0091 W |
| Objective function | | | | |
| Efficiency | 89.1% | **86.28%** | **89.98%** | 89.06% |

Table.6.5. comparison of different rotor bar shapes

It is seen that the maximum efficiency is obtained for the **type 3** slot. The comparable results are obtained for **type 5** slots due to almost same shape. The efficiency for the slot **type 0** is also comparable but the breakdown torque is reduced considerably. This is due to increase in leakage flux and hence the leakage reactance of the motor. Thus the closed slots are not suitable for the ASD induction motors. Also the leakage reactance increase brings about a reduction in the power factor of the machine.

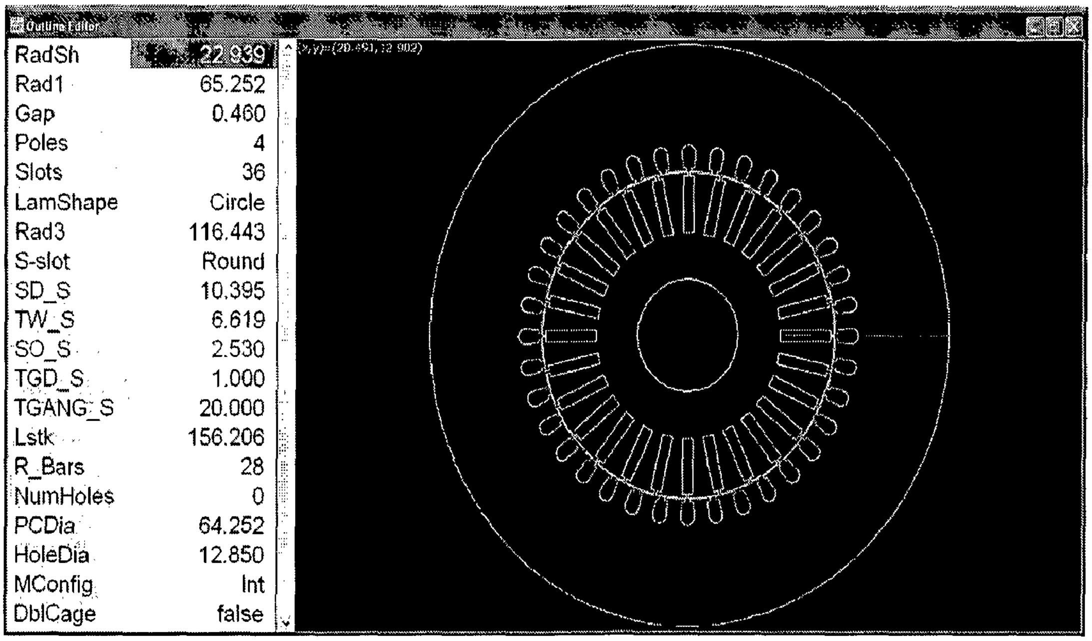
The worst performance is for the slot **type 2.** The skin effect is most pronounced in such rotor bars. Due to the less area near the air gap the provided area of current flow is reduced to a great extent, thus resulting in high rotor copper losses at high frequencies.

The cross section of the induction motor with all the type of rotor bars is given in fig. 6.9, fig.6.10, fig.6.11.



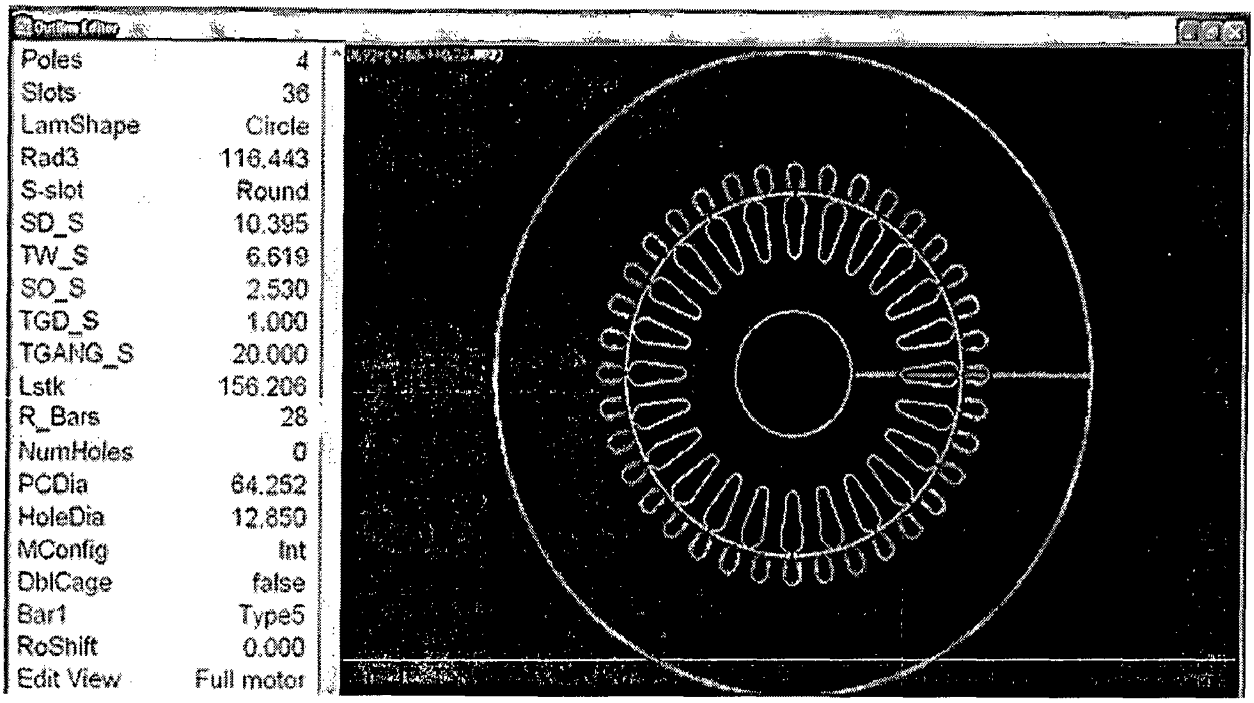
| | |
|---|---|
| RadSh | 22.939 |
| Rad1 | 65.252 |
| Gap | 0.460 |
| Poles | 4 |
| Slots | 36 |
| LamShape | Circle |
| Rad3 | 116.443 |
| S-slot | Round |
| SD_S | 10.395 |
| TW_S | 6.619 |
| SO_S | 2.530 |
| TGD_S | 1.000 |
| TGANG_S | 20.000 |
| Lstk | 156.206 |
| R_Bars | 28 |
| NumHoles | 0 |
| PCDia | 64.252 |
| HoleDia | 12.850 |
| MConfig | Int |
| DblCage | false |

Fig.6.9.Type 0 rotor bars



| | |
|---|---|
| RadSh | 22.939 |
| Rad1 | 65.252 |
| Gap | 0.460 |
| Poles | 4 |
| Slots | 36 |
| LamShape | Circle |
| Rad3 | 116.443 |
| S-slot | Round |
| SD_S | 10.395 |
| TW_S | 6.619 |
| SO_S | 2.530 |
| TGD_S | 1.000 |
| TGANG_S | 20.000 |
| Lstk | 156.206 |
| R_Bars | 28 |
| NumHoles | 0 |
| PCDia | 64.252 |
| HoleDia | 12.850 |
| MConfig | Int |
| DblCage | false |

Fig.6.10. Type 2 rotor bars



| | |
|---|---|
| Poles | 4 |
| Slots | 36 |
| LamShape | Circle |
| Rad3 | 116.443 |
| S-slot | Round |
| SD_S | 10.395 |
| TW_S | 6.619 |
| SO_S | 2.530 |
| TGD_S | 1.000 |
| TGANG_S | 20.000 |
| Lstk | 156.206 |
| R_Bars | 28 |
| NumHoles | 0 |
| PCDia | 64.252 |
| HoleDia | 12.850 |
| MConfig | Int |
| DblCage | false |
| Bar1 | Type5 |
| RoShift | 0.000 |
| Edit View | Full motor |

Fig6.11.Type 5 rotor bars

Hence the different rotor bar shapes have considerable effect on machine's performance.

## 6.5. Conclusion

At the end of this chapter we are ready with the results of

- Sinusoidal supply operating, efficiency optimized, induction motor design operating on sinusoidal frequency.
- Sinusoidal supply operating, efficiency optimized, induction motor design operating on square wave voltage source inverter output.
- ASD operating, efficiency optimized, induction motor design operating on square wave voltage source inverter output.
- ASD operating, efficiency optimized, induction motor design operating on square wave voltage source inverter output with four different rotor bar shapes.

The effect of the harmonics on the conventional induction machine is discussed. The changes in the design for ASD drives are summed up. The different shapes of rotor bars are analyzed.

It could be summed up in the end of the chapter that the main concern of design for the induction motor for ASD to obtain high efficiency should be reduction of skin effect and increase of leakage reactance.

# 7. Conclusion

The optimization of dissertation carried out in the present work gives an optimized design of induction motors operating on conventional power supplies and on power semiconductor power supplies. The selection of constraints and variable is different for the induction motors being powered by sinusoidal supply, as compared to the ASD induction motors. The two main differences in the constraints are

- For conventional motor the starting current and starting torque is one of the main constraint which decides the design of the motor, whereas there are no starting constraints present for the non sinusoidal supply induction motors.
- A high value of breakdown torque is important for both the sinusoidal and non sinusoidal operation but for the motors operating on the VFD an even higher value of the breakdown torque is required. Thus, the limit of per unit breakdown torque put is higher for VFD operation.

From the results obtained, various important points are inferred regarding the effect of harmonics and ways to keep a check on these effects.

It is seen that the main component of losses in the induction motor operating on non sinusoidal supply is the **time harmonic copper losses**. The reasons for high time harmonic copper losses are

- The high frequency harmonics enhance the skin effect to a great extent hence increasing the resistance of rotor to a high value.
- The harmonic currents induced increase the overall RMS value of the current as compared to sinusoidal supply operation.

Hence while the design of induction motor for ASD the main focus is placed on the rotor bar resistance, and increase of leakage reactance.

- The rotor bar resistance mainly depends on the rotor bar shape, its cross sectional area, and the length of the stack. The cross sectional area and the length of stack are the deciding factors for other performance parameters thus have some bounds. Thus the main parameter happens to be the rotor bar shape.
- The leakage reactance also depends on the rotor bar shape and tooth dimensions. Also it is directly related to the length of stack.

The analysis of the various rotor bar shapes is carried out and the result are tabulated. It is inferred that the best slot shape for rotors of ASD motors should have following features.

- Broader near the air gap
- Narrower at the other end
- Semi closed
- Less wedge angle and wedge length
- More cross sectional area

One more point which is noticed here is the optimum motor design for ASD is bigger in size as compared to conventional motors, i.e. they have a bigger outer stator diameter.

From all these points it is clearly inferred that the design of the induction machine is an important consideration when motors are applied for ASD. The design of the induction machine if carefully done can improve not only the individual performance of the motor but the whole of the drive system.

In present work one such motor design is given which give high efficiency even with ASDs and hence reduce the temperature rise and improves the reliability of the induction motor.

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# Appendix

## A-1 Motor specification

| | |
|---|---|
| Power Output ,kW | 7.5 |
| Voltage per phase, V | 400 |
| Fundamental supply frequency, Hz | 50 |
| Number of poles | 4 |
| Base speed, RPM | 1500 |
| Rated torque, Nm | 50 |
| Torque to Volume ratio, Nm/m$^3$ | 25 |

## A-2 Assigned Parameters

| | |
|---|---|
| Number of stator slots | 36 |
| Number of rotor slots | 28 |
| Winding factor | 0.96 |
| Air gap length, mm | 0.5 |
| Stator slot opening, mm | 2.5 |
| Rotor slot opening, mm | 1.5 |
| Lamination stacking factor | 0.97 |
| Stator slot shape | Round base with parallel tooth |

## A-3 Graph generated for calculation of β

β is the term which accounts for the tooth pulsation in flux density calculations. The graph is generated for the calculation of β with the help of data taken from [6]. The graph is generated by approximating the data into a polynomial in MATLAB. The polynomial is given below.

$$\beta = 0.0005\left(\frac{b_{os}}{g}\right)^3 - 0.0175\left(\frac{b_{os}}{g}\right)^2 + 0.2068\left(\frac{b_{os}}{g}\right) - 0.0355$$

Plot between $\beta\ vs\ \left(\frac{b_{os}}{g}\right)$ is given below

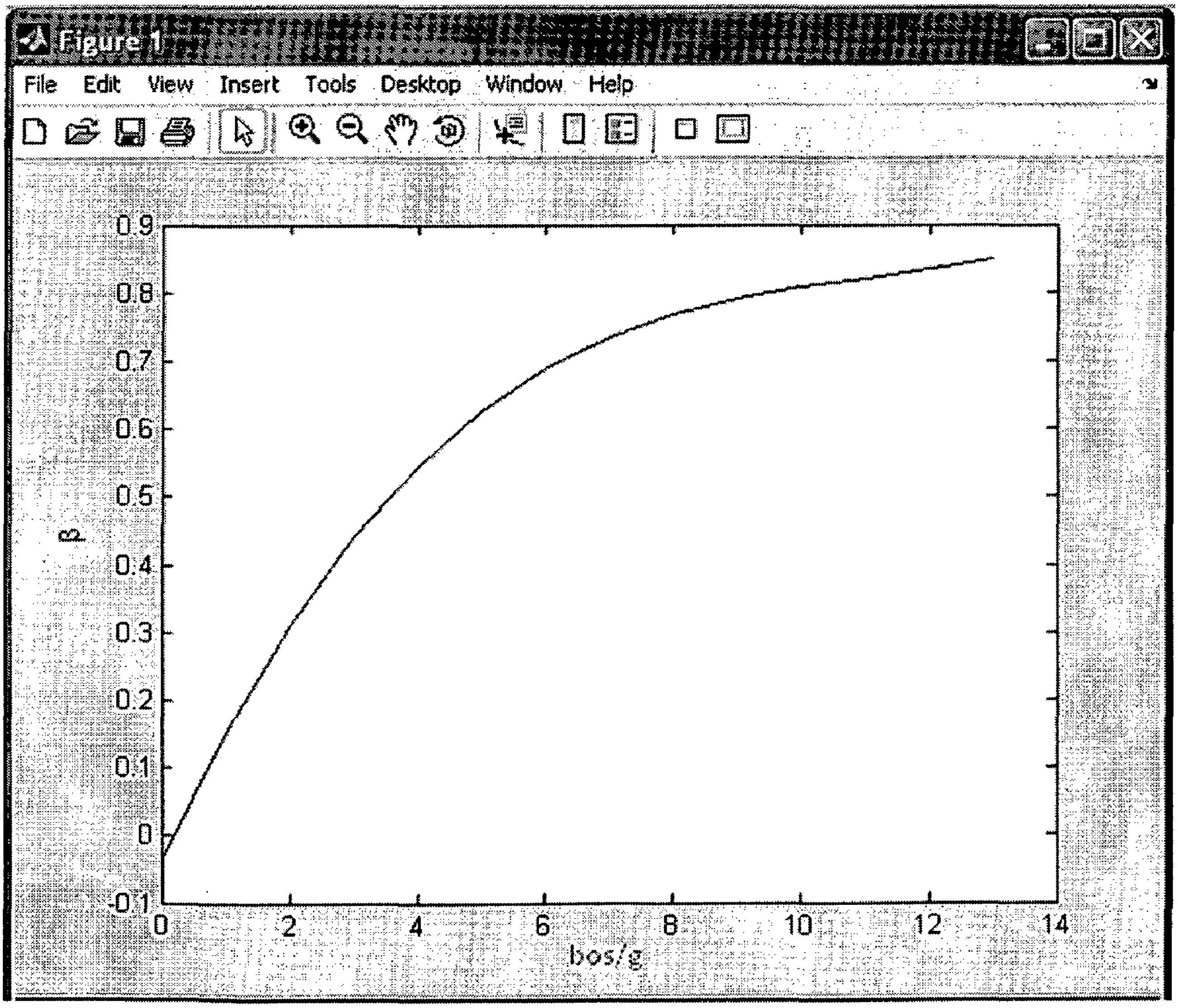

Fig A-1 flux pulsation due to slot opening