EFFICIENCY OPTIMIZATION OF INDUCTION MOTOR USING SPWM INVERTER

by

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A Thesis

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#89550#

APRIL, 1996.

Dedicated to :

my parents, wife
and
daughter

DECLARATION

I hereby declare that this thesis work has not been submitted elsewhere for the award of any degree or diploma or publication.

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ABSTRACT

Induction motor is an important class of electric machine which finds wide applications in industry. It is substantially a constant speed motor. However, the introduction of pulse width modulated inverters make possible variable speed operation of this motor. With SPWM inverter both frequency and voltage can be controlled simultaneously. This technique is used in induction motor drives for constant volts/hertz control. The constant volts/hertz control makes air gap flux constant and hence the maximum torque is constant. The volts/hertz control is also useful for soft start of induction motor. It also improves the transient performance of an induction motor. With constant speed induction motor efficiency falls below the rated power. The main objective of this thesis is to improve the efficiency of induction motor to its maximum achievable level irrespective of load. The volts/hertz control method using SPWM inverter is used for this purpose. The present thesis develops a theoretical model which determines the output power corresponding to maximum efficiency at various frequencies. For a particular output, a frequency is to be set for maximum efficiency, which is practically done by an SPWM inverter. Experimental results are obtained for an wound rotor induction motor and compared with the theoretical results. Good agreement of the experimental results with the theoretical ones suggests the validity of the developed model. It will be seen that efficiency of an induction motor can be maintained at maximum allowable efficiency using volts/hertz control with SPWM inverter under variable load operation.

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LIST OF SYMBOLS AND ABBREVIATIONS

A_c	amplitude of carrier wave
A_r	amplitude of reference signal
f	supply frequency
f_c	carrier frequency
f_r	frequency of rotor voltage
$f_{r\,n}$	nth harmonic secondary frequency
I_i	current at the centre-tap of the transformer
I_n	nth harmonic current
I_r	rotor current
I_s	stator current
$k_{\omega 1}$	stator winding factor
M	modulating index
N	actual rotor speed, rpm
n	number of harmonics
N_{ph1}	stator series turn per phase
N_S	synchronous speed, rpm
P	number of poles
P_c	core loss
P_{dc}	current drawn by unregulated rectifier
P_g	air-gap power
P_{in}	input power
P_o	developed power
P_{out}	output power of induction motor
P_{rcu}	rotor copper loss
R_r	referred rotor resistance per phase
R_S	stator resistance per phase
s	slip
s_n	slip for the nth harmonic
T_d	developed torque
T_{max}	maximum developed torque
V_S	stator voltage per phase
V_{S1}	fundamental component of voltage of SPWM inverter output

ω_S	synchronous speed, rad
X_m	magnetizing reactance
X_r	referred rotor reactance per phase
X_S	stator reactance per phase
δ	pulse width
η	efficiency
σ	triangular factor
φ_r	resultant air-gap flux per pole
Σ	sum of
Hz	cycles per second
m.m.f.	magnetomotive force
PWM	pulse width modulation
SPWM	sine pulse width modulation

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

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Industrial drives are predominantly ac motors of induction type. An estimated 67 percents of ac motors are induction motors, whereas, dc motors occupy only 8 percent of the industrial drives [1]. Induction motors are relatively cheap, simple in construction and can be used in hostile environments [2]. However, with utility power supply these motors are not efficient under variable load conditions. Their efficiency is at optimum usually near the rated conditions and efficiency falls both at higher and lower than rated load. DC motors on the other hand have more flexibility in control but are expensive and require more maintenance. These motors are also subject to more protection during operation in hazardous conditions. With the advent of solid state converters ac motors have gained popularity in variable speed operation with better efficiency with load changes. The efficiency of an induction motor can be maintained at the optimum level with change in speed as load changes. This can be achieved by static frequency changers which change the synchronous speed of rotating m.m.f. and hence the speed of these machines. The main disadvantage of static converter-fed induction machines is the losses due to harmonics of nonsinusoidal voltage and currents. As a result it is the constant effort of researcher to find ways to reduce the effect of harmonics in motors and improve their efficiency. One of the harmonic reduction techniques of static converters is to use pulse-width modulation (PWM) in switching static converters to obtain simultaneous voltage and frequency control. The main purpose of this thesis is to investigate the operation of inverter-fed variable speed induction motors at improved efficiency.

1.2 SURVEY OF INVERTER DRIVES

Literature survey of this thesis incorporates a brief introduction of static inverters and various control strategies of inverter fed induction motors.

1.2.1 Static Inverters

The static inverters act as an interface between the dc link and the ac machines. The function of an inverter is to change the dc input to a symmetrical ac output voltage of desired magnitude and frequency. The two basic types are : A) voltage-fed inverter and B) current-fed inverter. In the voltage-fed inverter, input voltage remains constant, whereas, in current-fed inverter the input current is maintained constant.

A) DC link voltage-fed inverter

The voltage-fed inverters are classified into two types : square-wave inverter and pulse width modulated (PWM) inverter. The lower order harmonic content in square wave inverter is high [1] and its use is limited in low and medium power applications. In PWM techniques the switching devices are switched on and off many times within a half cycle to generate a variable voltage output which is normally low in harmonic content. There are several PWM techniques. The commonly used techniques [3] are :

a) single pulse-width modulation
b) multiple pulse-width modulation
c) sinusoidal pulse-width modulation
d) modified sine pulse-width modulation

In the single pulse-width modulation control, there is only one pulse per half cycle. The width of the pulse is varied to control the inverter output voltage. The frequency change is also achieved in the same circuit (figure 1.1). In single pulse-width modulation the harmonics at the inverter output increases as the width of the pulses are reduced. The harmonic contents at lower output voltages can be significantly reduced by using several pulses in each half cycle (figure 1.2). This is termed as multiple pulse-width modulation. The most commonly used technique is sinusoidal pulse-width modulation (figure 1.3). In this technique an isosceles triangle carrier wave is compared with the sine wave signal and the cross-over points determine the points of commutation [4]. Except at low frequency range, the carrier is synchronized with the modulating signal, and an even integral (multiple of three) ratio is maintained to improve the harmonic content. The fundamental output voltage is varied by variation of modulation index. If the modulation index is less than unity, only the carrier frequency harmonics with the fundamental frequency related sidebands appear at the output. This type of waveform results in less harmonic heating and torque pulsation compared to a square wave in an induction motor. In SPWM the width of the pulses that are nearer to the peak of

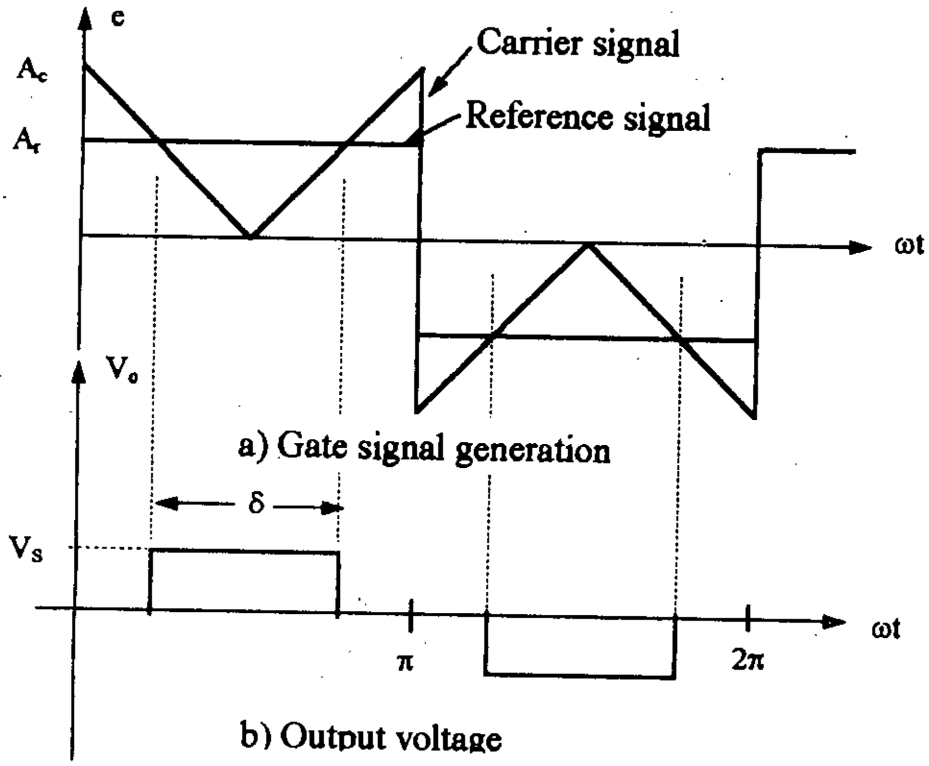
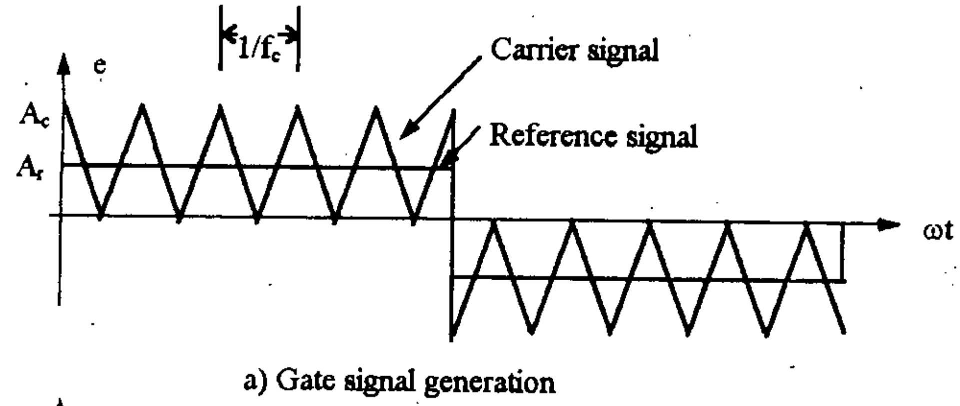
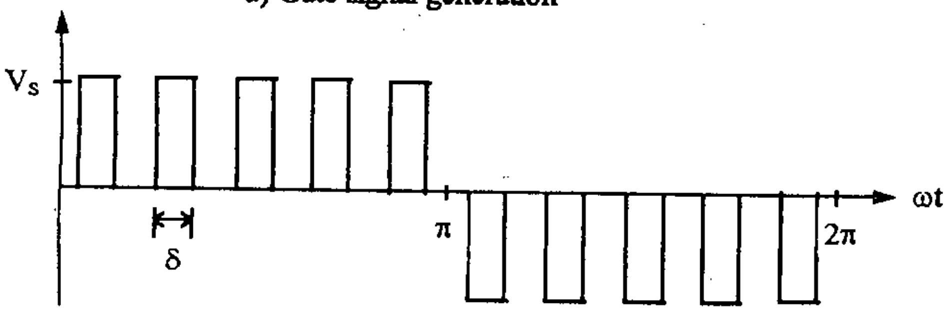


Figure1.1 Single pulse-width modulation



a) Gate signal generation



b) Output voltage

Figure 1.2 Multiple pulse-width modulation

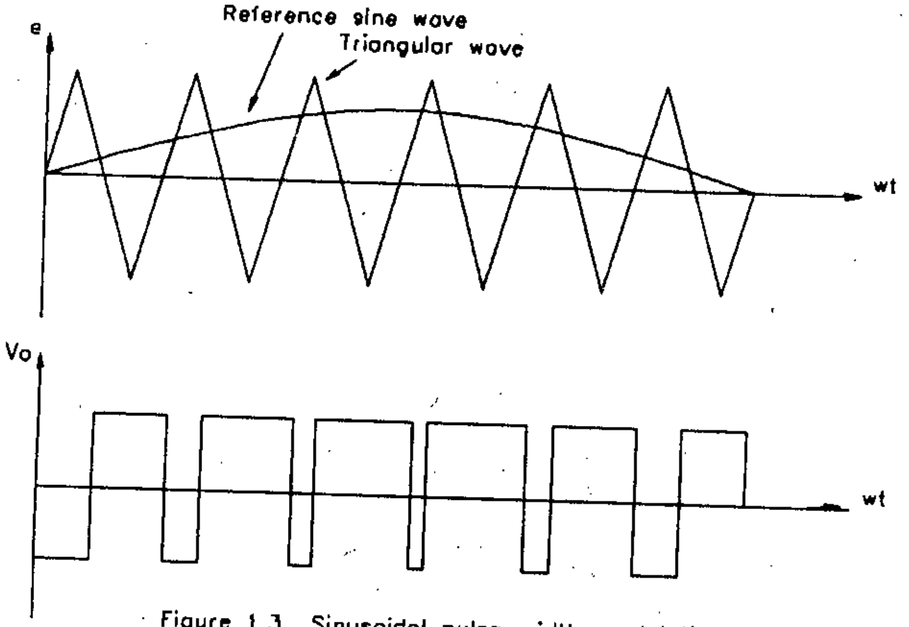


Figure 1.3 Sinusoidal pulse-width modulation

the sine wave don't change significantly with the variation of modulation index. A modified technique is employed, called modified sinusoidal pulse-width modulation, in which the carrier wave is applied during the first and last 60° intervals per half cycle. In this technique the fundamental component is increased and the harmonic characteristics are improved. It reduces the number of switching points and thereby reduces switching losses (figure 1.4). However, most improved techniques are developed recently. These include :

1) staircase modulation
2) stepped modulation
3) trapezoidal modulation
4) harmonic injection modulation
5) delta modulation

In staircase modulation [5], the modulating signal is a staircase wave, as shown in figure 1.5. The levels of staircase are calculated to eliminate specific harmonics. This modulation technique is recommended for greater than 15 pulses per cycle. This type of control provides a high quality output voltage with a fundamental value upto 0.94 V_s . In stepped modulation [6] the modulating sine wave is devided into specified intervals to eliminate specific harmonics (figure 1.6). In trapezoidal modulation the gating signals are generated by comparing a triangular carrier wave with a modulating trapezoidal wave [3,7] as shown in figure 1.7. The trapezoidal wave can be obtained from a triangular wave by limiting its magnitude to $\pm Ar$, which is related to the peak value $A_{r\,m}$ by $Ar = \sigma A_{r\,m}$ where σ is called the triangular factor, because the waveform becomes a triangular wave when $\sigma = 1$. The modulating index M is, $M = A_r/A_c$. this type of modulation

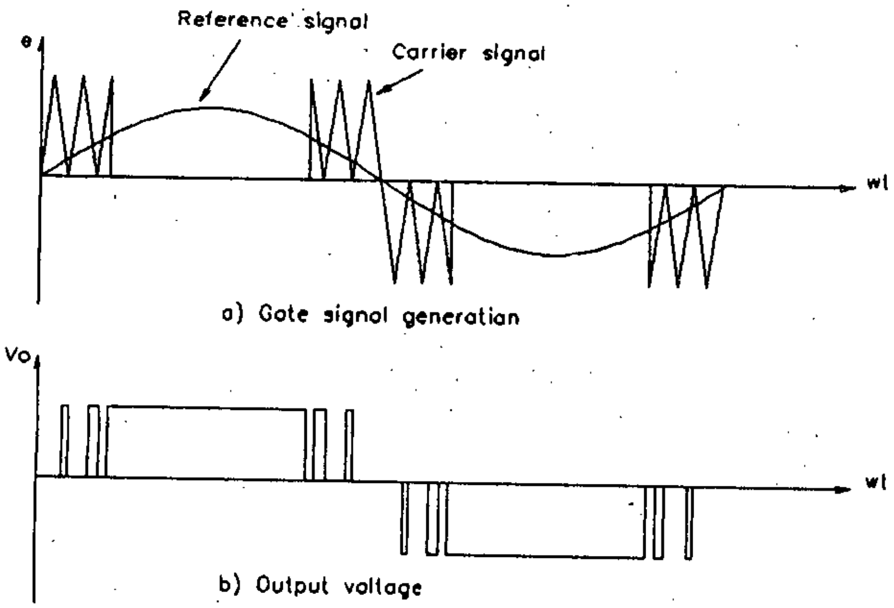
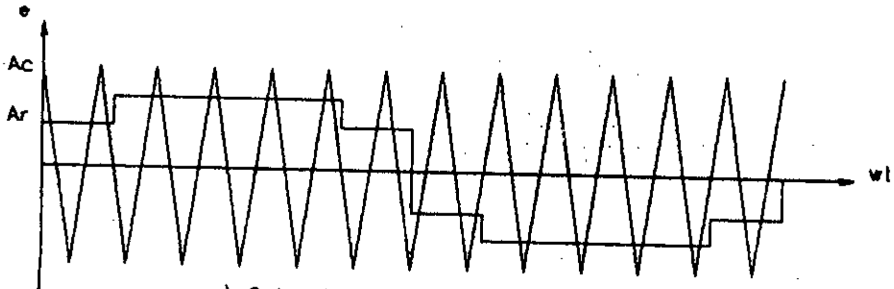
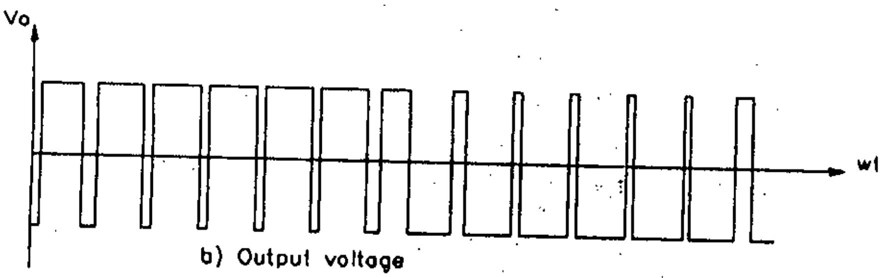


Figure 1.4 Modified sine pulse-width modulation

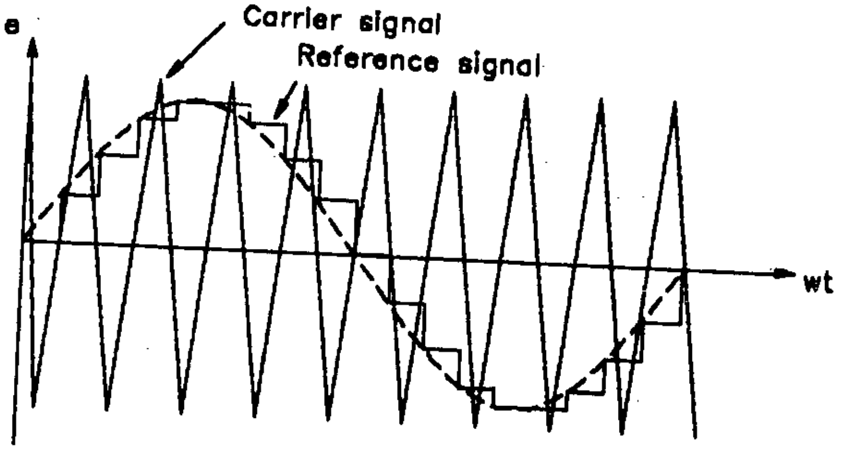


a) Gate signal generation

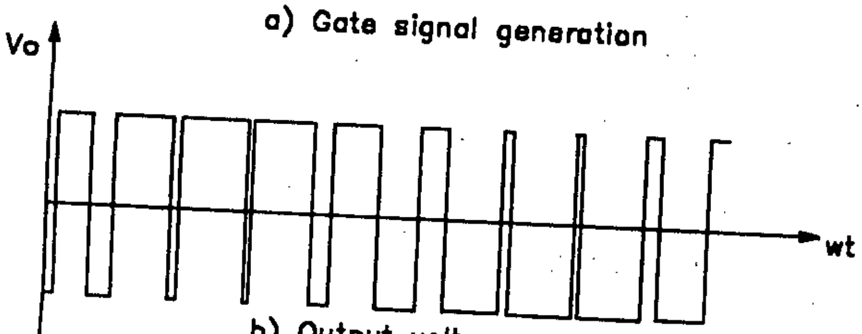


b) Output voltage

Figure 1.5 Staircase modulation

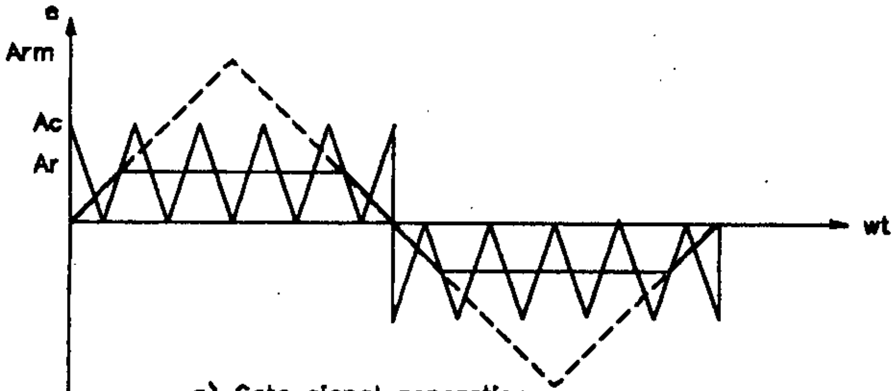


a) Gate signal generation

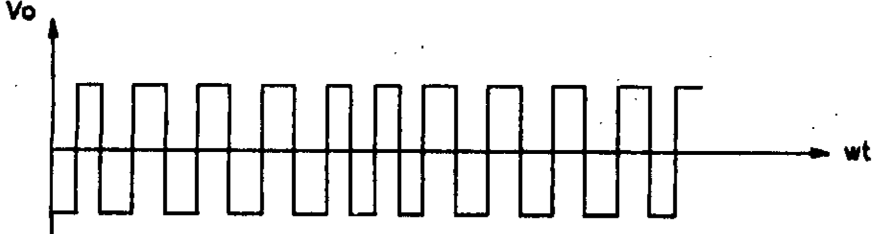


b) Output voltage

Figure 1.6 Stepped modulation



a) Gate signal generation



b) Output voltage

Figure 1.7 Trapezoidal modulation

increases the peak fundamental output voltage up to 1.05 V_S, but the output contains lower order harmonics. In harmonic injected modulation, the modulating signal is generated by injecting selected harmonics to the sine wave. It provides a higher fundamental amplitude and low distortion of the output voltage. In delta modulation [8] a triangular wave is allowed to oscillate within a defined window ΔV, above and below the reference sine wave V_r. The inverter switching function is generated from the vertices of the triangular wave V_c (figure 1.8). The ratio of voltage to frequency can be conveniently controlled using delta modulation, which is widely used in ac motor control.

B) DC link current-fed inverter

In current-fed inverters [4] the input is a current source. The output current is maintained constant irrespective of load on the inverter and the output voltage is forced to change . Figure 1.9 shows a schematic diagram of current fed inverter drive. A variable dc voltage is generated by a phase controlled rectifier which is converted to a current source by connecting a large inductor in series. The current is symmetrically fed to the three phase machine using inverter and a variable frequency, six stepped current wave is generated. This type of wave cause problem of harmonic heating and torque oscillation at low speed operation. Torque pulsation is minimized by using PWM techniques in the inverter. The current fed inverters have several limitations and hence their use is very much restricted.

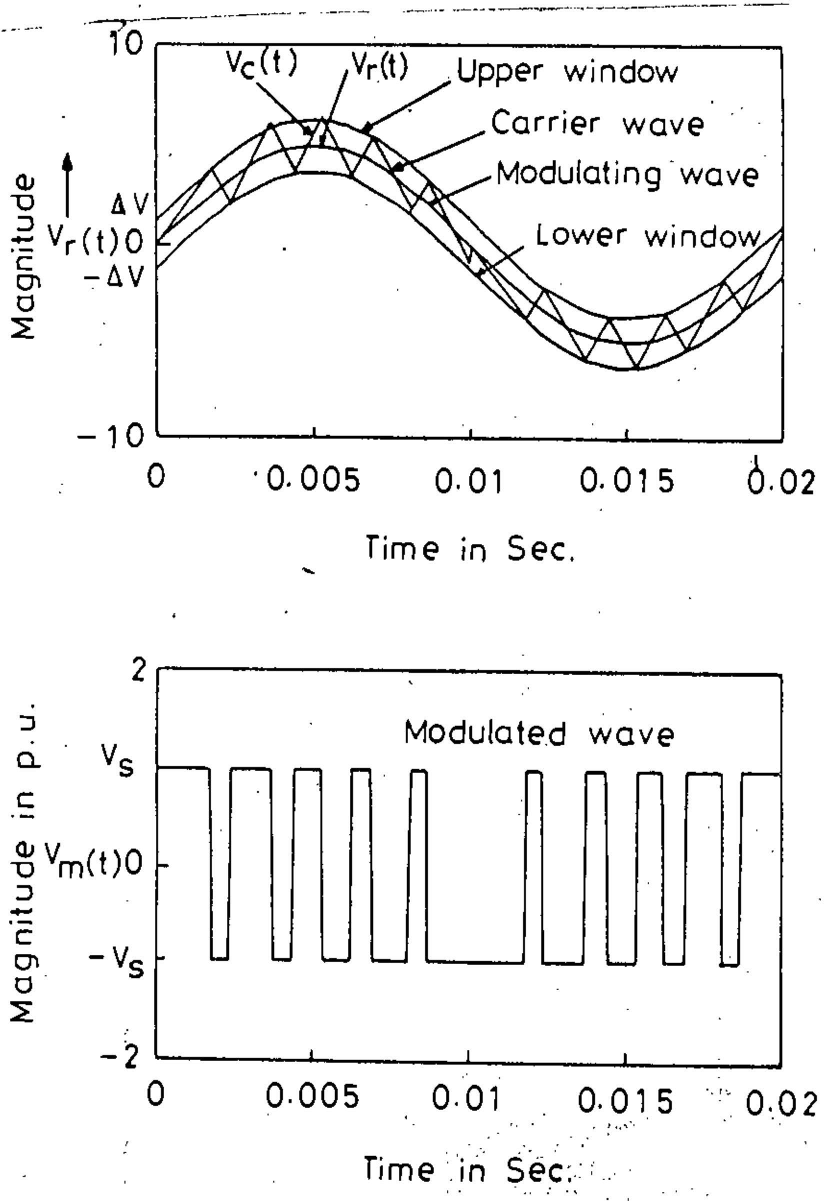


Figure 1.8 Delta modulation

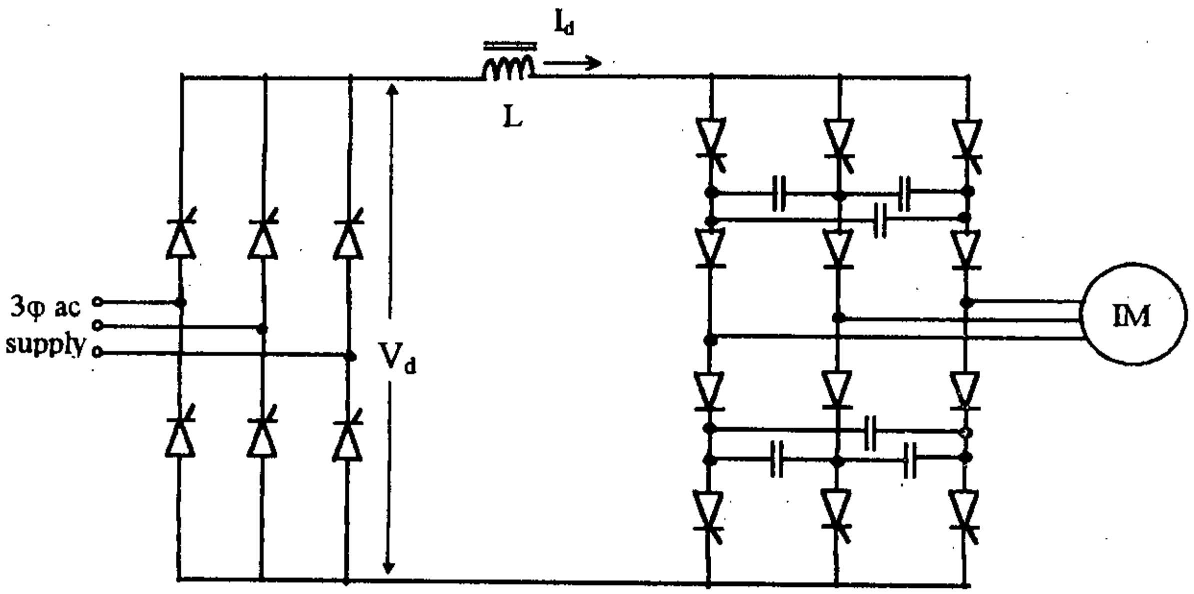


Figure 1. 9 DC link current-fed inverter

1.2.2 Inverter -Fed Induction Motor

An induction motor may be characterized by a transformer equivalent circuit and the following approximate performance expressions can be derived [9]

$$I_r = \frac{V_S}{\sqrt{(R_r / s)^2 + (X_r)^2}} \tag{1.2.1}$$

$$T_d = \frac{3}{\varpi_S} \cdot \frac{V_S^2 (R_r / s)}{(R_r / s)^2 + (X_r)^2} \tag{1.2.2}$$

$$\varphi_r = \frac{1}{4.44 K_{\omega 1} N_{ph1}} \cdot \left(\frac{V_s}{f}\right) \tag{1.2.3}$$

For low values of slip these equation simplifies to ,

$$I_r = \frac{s V_S}{R_r} \tag{1.2.4}$$

$$T_d = \frac{3}{\omega_S} \cdot \frac{s V_S^2}{R_r} \tag{1.2.5}$$

where , all the symbols are in standard notation.

Various methods of controlling the speed of induction motors can be visualized by considering the speed equation,

$$N = (1-s)\, N_s \tag{1.2.6}$$

where, $N_s = 120\, f / P$ (1.2.7)

It is seen from the equation (1.2.6) and (1.2.7) that there are two basic ways of speed control, namely i) slip control for fixed synchronous speed and ii) control of supply frequency [9]. Different control methods have been proposed and used for speed control of induction machines . The most simple and economic method is to vary the stator voltage [9] keeping the supply frequency constant . For a motor operating at full load slip, if the slip is to be doubled for constant load torque , the voltage is to be reduced by a factor of $1/\sqrt{2}$ and the corresponding current Ir rises to $\sqrt{2}$ times of full load value. Under such condition the motor will then get overheated. This method is normally used in fans, pumps, and blower drives in which torque is proportional to the square of speed. The torque speed characteristics of an induction motor with variable stator voltage is shown in figure 1.10.The more efficient method of speed control is to change the stator frequency. Since the speed is close to synchronous speed, the operating slip is small, and slip power loss in the rotor circuit is small. The flux increases and reaches saturation as the frequency is reduced below rated frequency. So the motor parameters are no longer valid, and hence the torque speed characteristics. The typical torque speed characteristics for this method of control is shown in figure 1.11. The maximum torque is inversely proportional to the square of the frequency. This corresponds to the behavior of a dc series motor. In order to avoid saturation in stator and rotor cores, which causes increase in the magnetization current, the flux Φ_r is kept constant as f is varied. To achieve this the ratio of V/f is maintained constant. This also ensures constant maximum torque. However, at low frequencies, the air gap flux is reduced as the drop at the stator impedance increases. Hence, the supply voltage is to be increased to maintain the torque level [4]. The typical torque speed characteristics are shown in figure 1.12. Below the base speed, constant flux

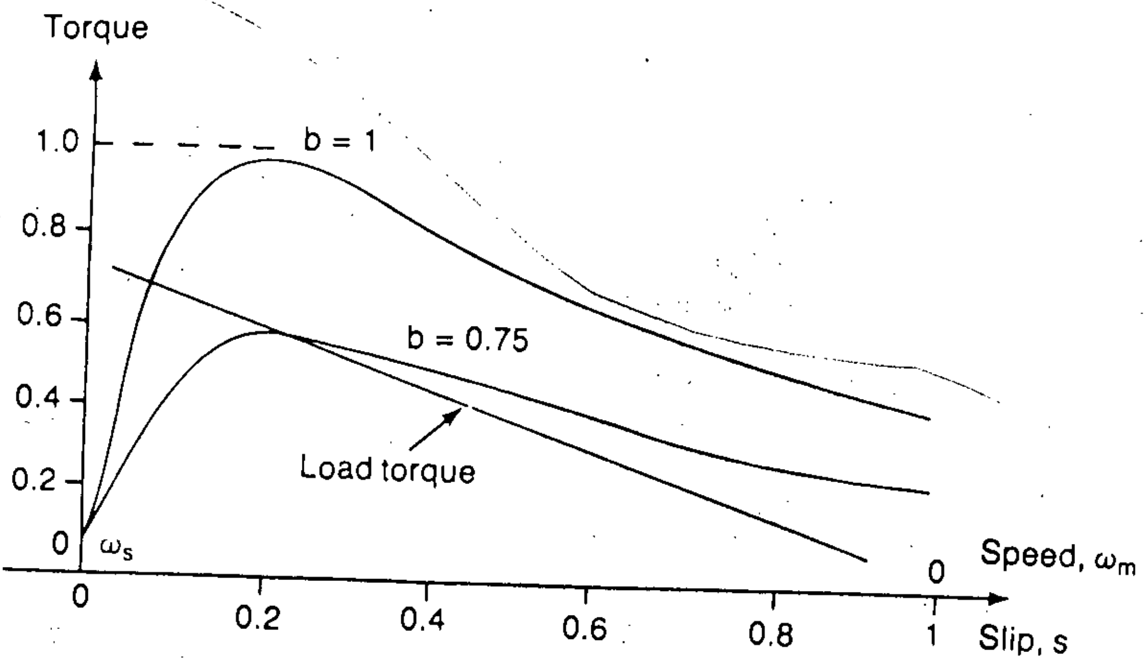


Figure 1.10 Torque speed characteristics with variable stator voltage

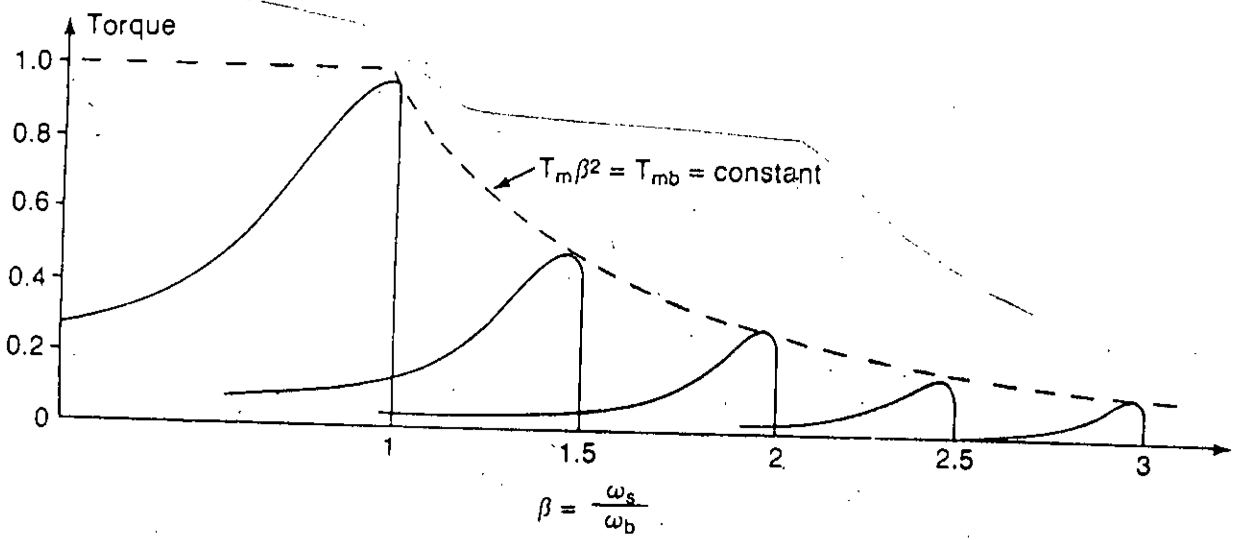


Figure 1.11 Torque speed characteristics with frequency control

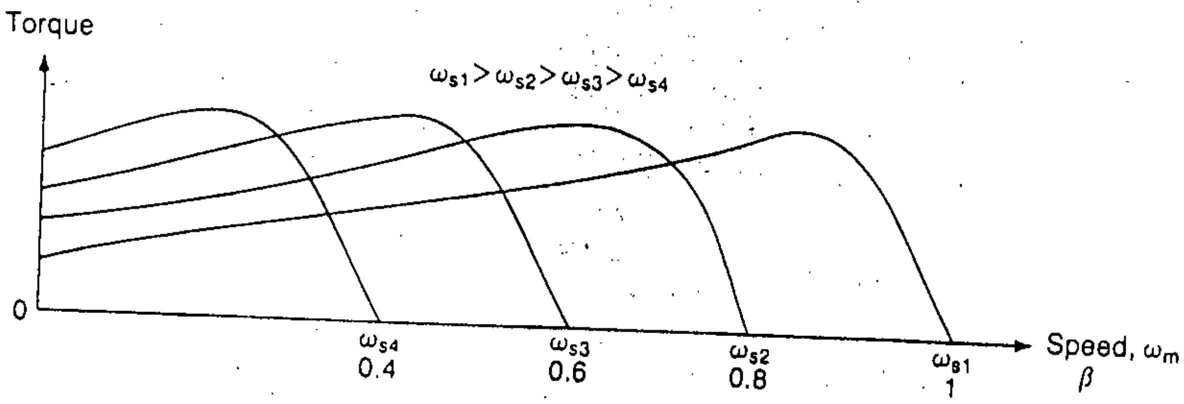


Figure 1.12 Torque speed characteristics with volts/hertz control

operation is used. Beyond the base speed, the machine is said to operate in constant power mode. A closed loop V/f control method with slip regulation was recently introduced for improved drive performance.

The chief attraction of employing induction motor for speed control is its ruggedness, low cost and maintenance free operation as compared to dc motor . Other advantages are [10,2] :

1) the ability of soft start of the drive, thus eliminating high inrush currents to the motor and the resultant voltage drop on the power system.

2) well defined constant torque and constant power operation over a wide range of load with variable frequency operation.

3) extended range of loading.

4) continuous operation.

5) matched loading at all operating conditions.

6) quick responses to load changes.

1.3 CHARACTERISTICS OF INVERTER-FED INDUCTION MOTOR

The rotating m.m.f. produced by ac supply in the stator of an induction motor acts with the m.m.f. produced by rotor currents to create developing torque in the motor . The speed of the rotating m.m.f. is known as synchronous speed (Ns) which depends on the frequency of the supply (f) and the pole number(P) of the machine and is given by ,

$$N_S = \frac{120f}{P} \tag{1.3.1}$$

The rotors of the induction machines rotate slightly less than synchronous speed and the difference in the synchronous speed and the rotor speed (Nr) is known as slip (s) and is expressed as,

$$s = \frac{N_S - N_r}{N_S} \tag{1.3.2}$$

The slip of induction machines depends on the load applied to their shafts and hence varies during variable load operation of the machines. It also determines the rotor frequency (fr) given by,

$$f_r = sf \tag{1.3.3}$$

The equivalent circuit of an induction motor resembles that of a transformer with the exception of the rotor circuit which has additional slip dependent terms. The equivalent circuit of an induction machine is shown in figure 1.13, where,

X_m = magnetizing reactance

R_s = stator resistance per phase

X_s = stator reactance per phase

R_r = referred to rotor resistance per phase

X_r = referred to rotor reactance per phase

The rotor current, developed torque, maximum torque, and corresponding slip can be found from analysis of steady state equations of the equivalent circuit of the induction machine . One of these steady state quantities is the developed torque given by following expression [11],

$$T_d = \frac{3}{s\omega_S} \cdot \frac{V_S^2}{\left[(R_S + R_r/s)^2 + (X_S + X_r)^2\right]} \tag{1.3.4}$$

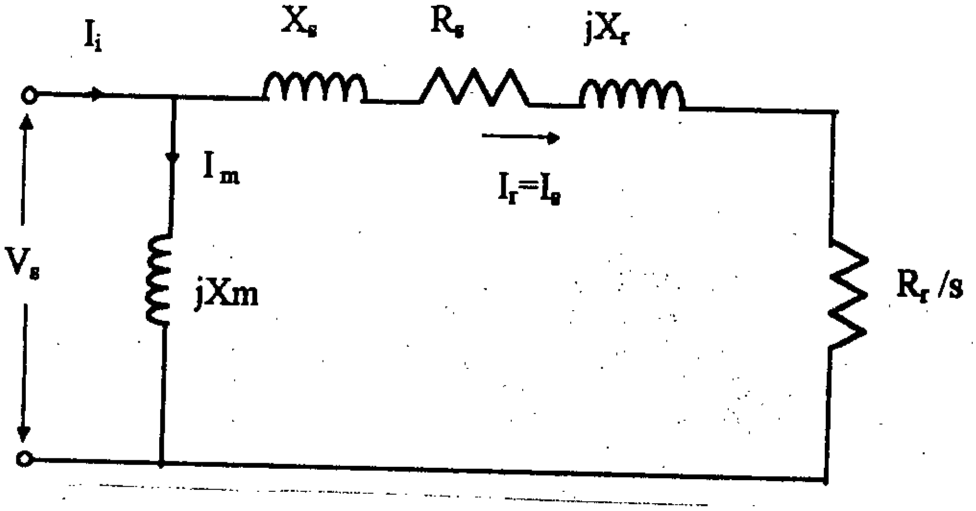


Figure 1.13 Per phase Equivalent circuit of an induction motor

It is clear from the principle of operation of induction motors that frequency and number of poles are the two parameters which can be used to control the speed of these motors. Of the two parameters frequency control by various static frequency changers is the most efficient method of speed control of induction machines. However, machine characteristics at variable speed and additional losses in the machines due to nonsinusoidal supply require substantial effort to find a suitable operating mode of static converter-fed induction machine. The factors that are to be considered in an inverter-fed machine are :

1) V/f control in various steps as frequency is changed to control the speed of the machine,

2) keeping motor losses to a minimum,

3) attain maximum efficiency as load adjusts to a new value . This is achieved by adjusting speed and hence maintaining a certain slip of the machine,

4) achieve a certain torque characteristics,

5) minimize harmonic interference and restrict resonance with natural frequency of the machine,

6) provide soft start etc.

The speed control of induction motor using V/f control method is superior to various other methods in practice . In the V/f control the speed change may be made continuous and precise for a wide range . This mode of control may be understood from the modified torque equation of the motor which is given by ,

$$T_d = \frac{3P}{2\pi} \cdot \left(\frac{V_S}{f}\right)^2 \cdot \frac{sfR_r}{\left[(sR_S + R_r)^2 + s^2(X_S + X_r)^2\right]} \qquad (1.3.5)$$

In order to maintain high torque throughout the control range , air gap flux , i.e, V_S/f should be constant . The torque speed characteristics for various supply frequencies are shown in figure 1.12.

In V/f mode of control, the maximum torque is approximately given by,

$$T_{max} = K \cdot \left(\frac{V_S}{f}\right)^2 \qquad (1.3.6)$$

The above equation suggests that if V /f is maintained constant T_{max} also remains constant, while at lower frequencies R_s becomes comparable to $(X_s + X_r)$ and T_{max} decreases. For higher overload torque, at lower frequencies, it is necessary to boost V_s , even though there is a risk of saturation of the stator iron. Starting torque is greater at lower frequencies and for the same operating slip the torque is greater at higher frequencies. Therefore, at higher operating frequencies, the efficiency (η) also increases because ,

$$\eta \approx 1 - s \qquad (1.3.7)$$

The low frequency operation is not very satisfactory particularly at frequencies below one-fifth of the rated frequency. Both starting and breakdown torque decreases considerably and the no-load current increases to a large extent.

Actual torque of the motor is proportional to the square of the V/f ratio and f given by [12],

$$T \propto \left(\frac{V_S}{f}\right)^2 \cdot f \cdot s \qquad (1.3.8)$$

From the above equation it can be seen how the slip of the induction motor must be varied to provide particular torque speed curve. In figure 1.14 a typical torque speed relationship is shown which could be used for an induction motor to accelerate a load. In mode 1, constant torque is achieved by holding constant air-

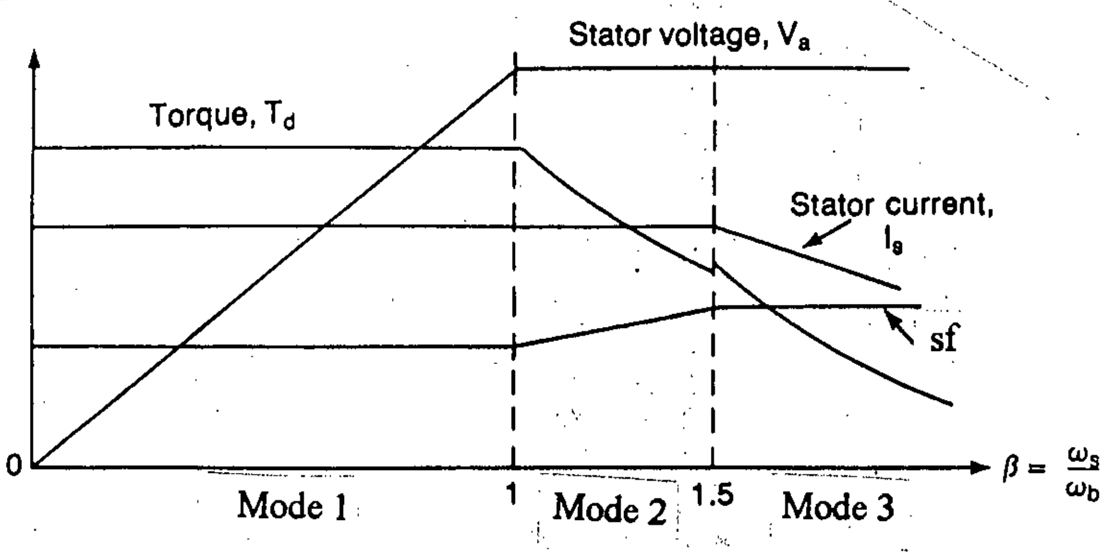


Figure 1.14 Control variables vs. frequency

gap flux (v/f) and constant slip. In mode 2 & 3 the applied voltage is held constant by putting the inverter in square wave mode of operation. The motor flux will reduce, torque will decrease inversely with speed.

1.4 OBJECTIVE OF THE PRESENT WORK

The objective of the present thesis is to develop a mathematical model for the most efficient operation of SPWM inverter fed induction motor under varying load conditions. The model will consider the effect of harmonics introduced due to the switching in SPWM inverters. V/f control method will be used to maintain constant air-gap flux. Analytical results will be verified by experiments.

1.5 THESIS ORGANIZATION

In the present thesis work a mathematical model is developed to determine the suitable operating range of an induction motor to optimize efficiency. The theoretical results are compared with experimental results for verification of developed model.

Chapter 1 of this thesis serves as an introduction of different PWM techniques. A short review of induction motor drives is also presented. The advantage of using V/f control method is also described in this chapter.

The theoretical model for optimization of induction motor efficiency are developed in chapter 2. This model determines the output power corresponding to maximum efficiency for different supply frequencies. It will be seen that the maximum efficiency for any output power is almost constant but it occurs at different supply frequency. The slip corresponding to maximum efficiency is also constant.

Chapter 3 of the present thesis is devoted to the experimental verification of theoretical results. Experiments are performed for SPWM inverter fed induction motor as well as sinusoidal voltage fed induction motor. The practical results are compared with the theoretical results and analyzed in this chapter. The limitation of practical circuit are also discussed.

Finally in chapter 4, concluding remarks on SPWM inverter fed induction motor are made and suggestions for further research in this area are provided.

CHAPTER 2

IMPROVED EFFICIENCY OPERATION OF INDUCTION MOTORS UNDER VARIABLE LOAD

2.1 INTRODUCTION

Usually the maximum efficiency of an induction motor occurs at its rated load. The efficiency decreases when the load connected to it deviates from the rated condition. The supply frequency may be taken as a control variable to improve the efficiency to an enhanced level for variable load operation. This is illustrated in this chapter with necessary theoretical background. The approach of constant v/f ratio control is taken into consideration. Modern induction motor drives use sine pulse width modulated inverter for this purpose. The output of a PWM controlled inverter is not perfectly sinusoidal and contains carrier frequency related harmonics in it. The fundamental voltage produces the average output torque and the harmonics produce increasing losses and torque fluctuations. The contribution of harmonics to the average torque is very small. Approximately a four percent reduction in torque [13] takes place due to harmonics and it can be neglected. The losses which may occur in a cage induction motor owing to harmonics at the input are the primary and the secondary I^2R losses, the core losses and stray load losses etc. Skin effect is to be taken into account in calculating the secondary resistance and leakage reactance for squirrel cage rotor . For low and medium horsepower motors skin effect can be neglected. Stray load and core losses due to harmonics is neglected throughout [14,15] in this study.

At first a theoretical model for improved efficiency operation is developed assuming inverter output voltage to be perfectly sinusoidal with the effect that harmonics will not occur in this case. Another model is developed for actual inverter output voltage waveshapes.

2.2 IMPROVED EFFICIENCY OPERATION WITH PURE SINUSOIDAL SUPPLY

In the study of efficiency improvement of induction motors by frequency variation an ideal sinusoidal voltage is assumed. For experimental verification of results a synchronous generator coupled to a variable speed dc motor is used. The approximate equivalent circuit per phase of an induction motor of figure 1.13 is reproduced in figure 2.1 in a modified form where the equivalent resistance for excitation (or core) loss, R_m is incorporated.

From the equivalent circuit, the referred rotor current is,

$$I_r = I_S = \frac{V_S}{\left[(R_S + R_r/s)^2 + (X_S + X_r)^2\right]^{\frac{1}{2}}} \tag{2.2.1}$$

core loss, $$P_c = \frac{3V_S{}^2}{R_m} \tag{2.2.2}$$

airgap power, $$P_g = 3I_r{}^2 R_r/s \tag{2.2.3}$$

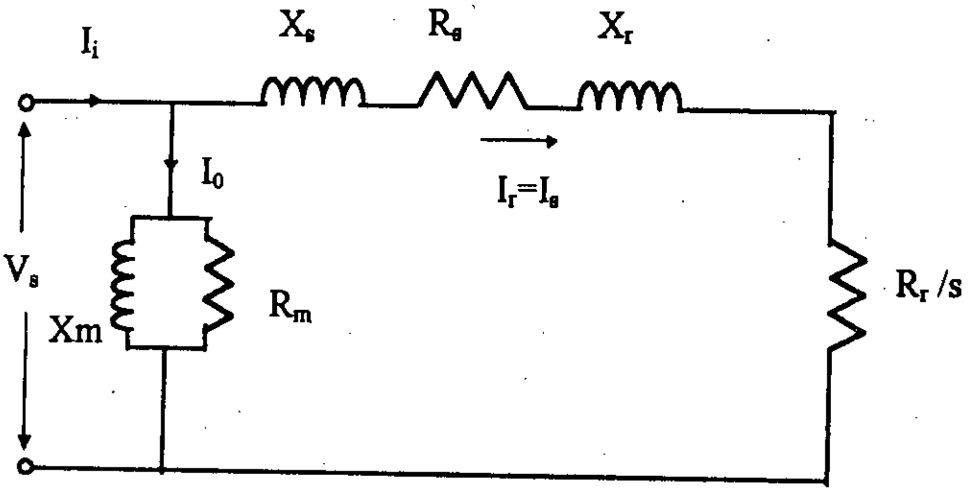


Figure 2.1 Per phase Equivalent circuit of an induction motor

rotor copper loss , $P_{rcu} = 3I_r^2 R_r$ (2.2.4)

developed power , $P_0 = P_g - P_{rcu}$

$= P_g (1\text{-}s)$ (2.2.5)

where ,

I_r is the rotor current,

I_S is the stator current,

V_S is the stator voltage,

P_c is the core loss,

P_g is the air gap power,

R_r is the rotor resistance,

P_{rcu} is the rotor copper loss,

s is the slip,

R_S is the stator resistance and

P_o is the developed power.

From the above relationships , the input and output power can be expressed as,

$$P_{in} = \frac{3V_S{}^2(R_S + R_r / s)}{\left[(R_S + R_r / s)^2 + (X_S + x_r)^2\right]} + \frac{3V_S{}^2}{R_m} \tag{2.2.6}$$

$$P_{out} = \frac{3V_S{}^2 R_r (1-s)/s}{\left[(R_S + R_r / s)^2 + (X_S + X_r)^2\right]} \tag{2 .2 .7}$$

The efficiency is defined as ,

$$\eta = \frac{P_{out}}{P_{in}} \tag{2.2.8}$$

Hence , using equation (2.2.6) and (2.2. 7) we get ,

$$\eta = \frac{\dfrac{3V_S{}^2R_r(1-s)/s}{\left[(R_S+R_r/s)^2+(X_S+X_r)^2\right]}}{\dfrac{3V_S{}^2(R_S+R_r/s)}{\left[(R_S+R_r/s)^2+(X_S+X_r)^2\right]}+\dfrac{3V_S{}^2}{R_m}}$$

or, $$\eta = \frac{R_rR_m(1-s)/s}{R_m(R_S+R_r/s)+(R_S+R_r/s)^2+(X_s+X_r)^2}$$

or, $$\eta = \frac{R_rR_m(s-s^2)}{R_m(s^2R_S+sR_r)+(sR_S+R_r)^2+s^2(X_S+X_r)^2}$$

or, $$\eta = \frac{-s^2R_rR_m+sR_rR_m}{s^2\left[R_mR_S+R_S{}^2+(X_S+X_r)^2\right]+s\left[R_mR_r+2R_SR_r\right]+R_r{}^2}$$

or, $$\eta = \frac{-C_1s^2+C_3s}{C_2s^2+C_4s+C_6} \qquad (2.2.9)$$

where , $C_1 = C_3 = R_rR_m$

$C_2 = R_mR_S + R_S{}^2 + (X_S + X_r)^2$

$C_4 = R_mR_r + 2R_SR_r$

$C_6 = R_r{}^2$

Equation (2.2.9) is differentiated with respect to slip and set equal to zero to find the slip corresponding to maximum efficiency . We get ,

$s^2(C_1C_4 + C_2C_3) + 2C_1C_6\, s - C_3C_6 = 0$

or, $As^2 + Bs - C = 0$ (2.2.10)

where , $A = C_1C_4 + C_2\,C_3$

$= R_rR_m\,[R_s{}^2 + 2R_sR_r + R_m\,(R_s+R_r) + (X_s+X_r)^2$ (2.2.11)

$B = 2C_1C_6$

$= 2R_r{}^3\,R_m$ (2.2.12)

$$C = -R_r^3 R_m \tag{2.2.13}$$

From equation (2.2.10) one gets ,

$$S_{max,\eta} = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \tag{2.2.14}$$

Equation (2.2.14) expresses the slip corresponding to maximum efficiency at various stator frequencies . Putting the value of $S_{max,\eta}$ V_S, and f in equation (2.2.7) we find the output power corresponding to maximum efficiency and the efficiency is found from equation (2.2.8).

2.3 IMPROVED EFFICIENCY OPERATION WITH INVERTER SUPPLY

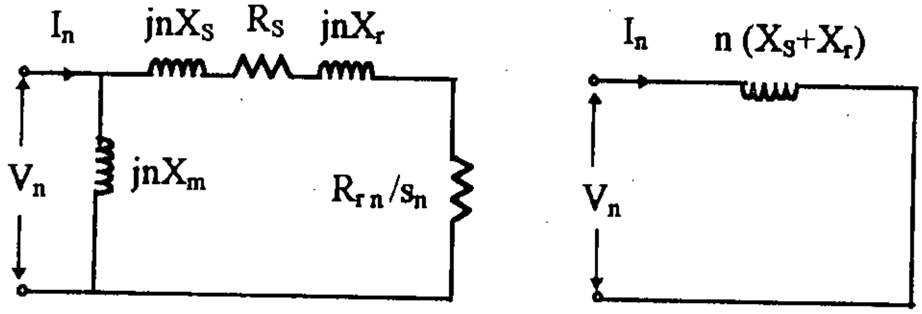
The theoretical analysis of an induction motor operating with periodic nonsinusoidal supply voltages is commenced by assuming that each harmonic present in the supply waveform may be treated separately and the resultant effect is the sum of individual effect. For fundamental component , the equivalent circuit of figure 2.1 is applicable . For nth harmonic , equivalent circuit is as shown in figure 2.2 [15,16]. Each reactance has been increased by a factor n, where , n is the number of harmonics. Slip s_n for the nth harmonic is given by :

$$s_n = \frac{n\omega_{mS} \mp \omega_m}{n\omega_{mS}} \cong 1 \tag{2.3.1}$$

and nth harmonic secondary frequency is,

$$f_{rn} = s_n nf \cong nf \tag{2.3.2}$$

Negative sign is applicable to harmonics which produce forward rotating fields and the positive sign to those which produce backward rotating fields. Since, s_n is close to unity, resistance (R_r/s_n) has a small value. As reactances are very



(a) (b)

Figure 2.2 Harmonic equivalent circuit of an induction motor large compared to resistors, equivalent circuit of figure 2.2(a) can be replaced by the simplified circuit of figure 2.2(b). The nth harmonic current is calculated from ,

$$I_n = \frac{V_n}{nX} = \frac{V_n}{n(X_S + X_r)} \tag{2.3.3}$$

In an ideal symmetrical three phase machine, the third harmonic cannot produce an airgap flux, and hence it is enough to consider harmonic only of the order (6n±1).

Since, the core loss due to harmonics is neglected, the input power can be calculated as,

$$P_{in} = P_{in,f} + W_{c,f} + 3\Sigma\, I_n^2 R_{rn} \tag{2.3.4}$$

or , $$P_{in} = \frac{3V_{S1}^2 (R_S + R_r / s)}{(R_S + R_r / s)^2 + (X_S + X_r)^2} + \frac{3V_{S1}^2}{R_m} + 3\sum_n I_n^2 R_m$$

or, $$P_{in} = \frac{3V_{S1}^2 (R_S + R_r / s)}{(R_S + R_r / s)^2 + (X_S + X_r)^2} + \frac{3V_{S1}^2}{R_m} + K_1 \tag{2.3.5}$$

and the output power is ,

$$P_{out} = \frac{3V_{S1}^2 R_r (1-s)/s}{(R_S + R_r / s)^2 + (X_S + X_r)^2} \tag{2.3.6}$$

where V_{S1} = the fundamental component of inverter output .

and , $K_1 = 3\sum_n I_n^2 R_m$ = a frequency dependent term independent of slip

Now ,the efficiency , $\eta = \frac{P_{out}}{P_{in}}$

or , $$\eta = \frac{\dfrac{3V_{S1}^2 R_r (1-s)/s}{(R_S + R_r / s)^2 + (X_S + X_r)^2}}{\dfrac{3V_{S1}^2 (R_S + R_r / s)}{(R_S + R_r / s)^2 + (X_S + X_r)^2} + \dfrac{3V_{S1}^2}{R_m} + K_1}$$

or ,

$$\eta = \frac{3V_{S1}{}^2 R_r R_m (1-s)/s}{3V_{S1}{}^2 R_m (R_S + R_r/s) + 3V_{S1}{}^2\left[(R_S + R_r/s)^2 + (X_S + X_r)^2\right] + K_1 R_m\left[(R_S + R_r/s)^2 + (X_S + X_r)^2\right]}$$

or ,

$$\eta = \frac{R_r R_m (1-s)/s}{R_m (R_S + R_r/s) + \left[(R_S + R_r/s)^2 + (X_S + X_r)^2\right] + K_2\left[(R_S + R_r/s)^2 + (X_S + X_r)^2\right]}$$

or,

$$\eta = \frac{R_m R_r (s - s^2)}{R_m (s^2 R_S + s R_r) + (K_2 + 1)\left[(s R_S + R_r)^2 + s^2 (X_S + X_r)^2\right]}$$

or,

$$\eta = \frac{K_4 (s - s^2)}{K_6 s^2 + K_8 s + K_{10}} \tag{2.3.7}$$

where , $K_2 = K_1 R_m / 3V_{S1}{}^2$

$K_4 = R_m R_r$

$K_6 = R_m R_S + (K_2 + 1)\{R_s{}^2 + (X_s + X_r)^2\}$

$K_8 = R_m R_r + 2(K_2 + 1) R_S R_r$

$K_{10} = (K_2 + 1) R_r{}^2$

Now , differentiating equation (2.3.7) w.r.t. s and putting $d\eta/ds = 0$ we get ,

$$s^2 [K_4 K_6 + K_4 K_8] + 2K_4 K_{10} s - K_4 K_{10} = 0$$

or ,

$$As^2 + Bs + C = 0 \tag{2.3.8}$$

where , $A = K_4 (K_6 + K_8)$

$B = 2 K_4 K_{10}$

$C = -K_4 K_{10}$

From equation (2.3.8) we get ,

$$s_{max,\eta} = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \tag{2.3.9}$$

Equation (2.3.9) expresses slip corresponding to maximum efficiency at various stator frequencies . Putting the value of $s_{max,\eta}$, V_s, and f in equation (2.3.6) we get the output power corresponding to maximum efficiency and the efficiency is found from equation (2.3.7).

2.4 ANALYTICAL RESULTS

Three different computer programs have been developed to solve equations (2.3.6), (2.3.7) and (2.3.9). The flowchart of these programs used for the analysis are presented in Appendix-II. The first program K1.for calculates losses in induction motor due to harmonics present in SPWM inverter output at different supply frequencies (31-50 Hz). The second program slip.for has been used to determine slips corresponding to maximum efficiencies at frequencies used in the program K1.for. The third program pwro.for determines output powers and efficiencies at different supply frequencies at maximum efficiency condition. The results obtained from the program pwro.for are presented in table 2.1. Column 2 of table 2.1 represents outputs for which the induction motor have to be run at frequencies mentioned in column 1 for maximum efficiency. It is seen from column 3 that maximum efficiency is almost constant at any output and is about 74%. The slip is also constant at maximum efficiency and its value for the particular motor used in the analysis is about 0.086. The plots of figures 2.3 to 2.5 are obtained by manipulating the data of table 2.1. Figure 2.3 shows frequency corresponding to an output power for maximum efficiency. Figure 2.4 shows that maximum efficiency is almost constant for any output power. Figure 2.5 shows that slip is nearly constant for any output power corresponding to maximum efficiency. The

Table 2.1

Theoretical results of frequency and corresponding output, efficiency and slip of SPWM inverter-fed induction motor at maximum efficiency condition

Frequency Hz	Output watt	Efficiency in %	Slip
31	51.85	74.75	0.0851
32	55.41	74.53	0.0854
33	59.19	74.23	0.0859
34	63.07	74.00	0.0863
35	66.98	73.89	0.0866
36	70.93	73.87	0.0867
37	74.92	73.90	0.0868
38	79.05	73.91	0.0871
39	83.42	73.84	0.0871
40	87.79	73.85	0.0872
41	92.30	73.85	0.0872
42	96.79	73.90	0.0872
43	101.27	74.00	0.0871
44	105.69	74.15	0.0867
45	110.09	74.32	0.0863
46	114.57	74.47	0.0859
47	119.40	74.53	0.0857
48	124.37	74.56	0.0856
49	129.52	74.58	0.0856
50	134.94	74.55	0.0857

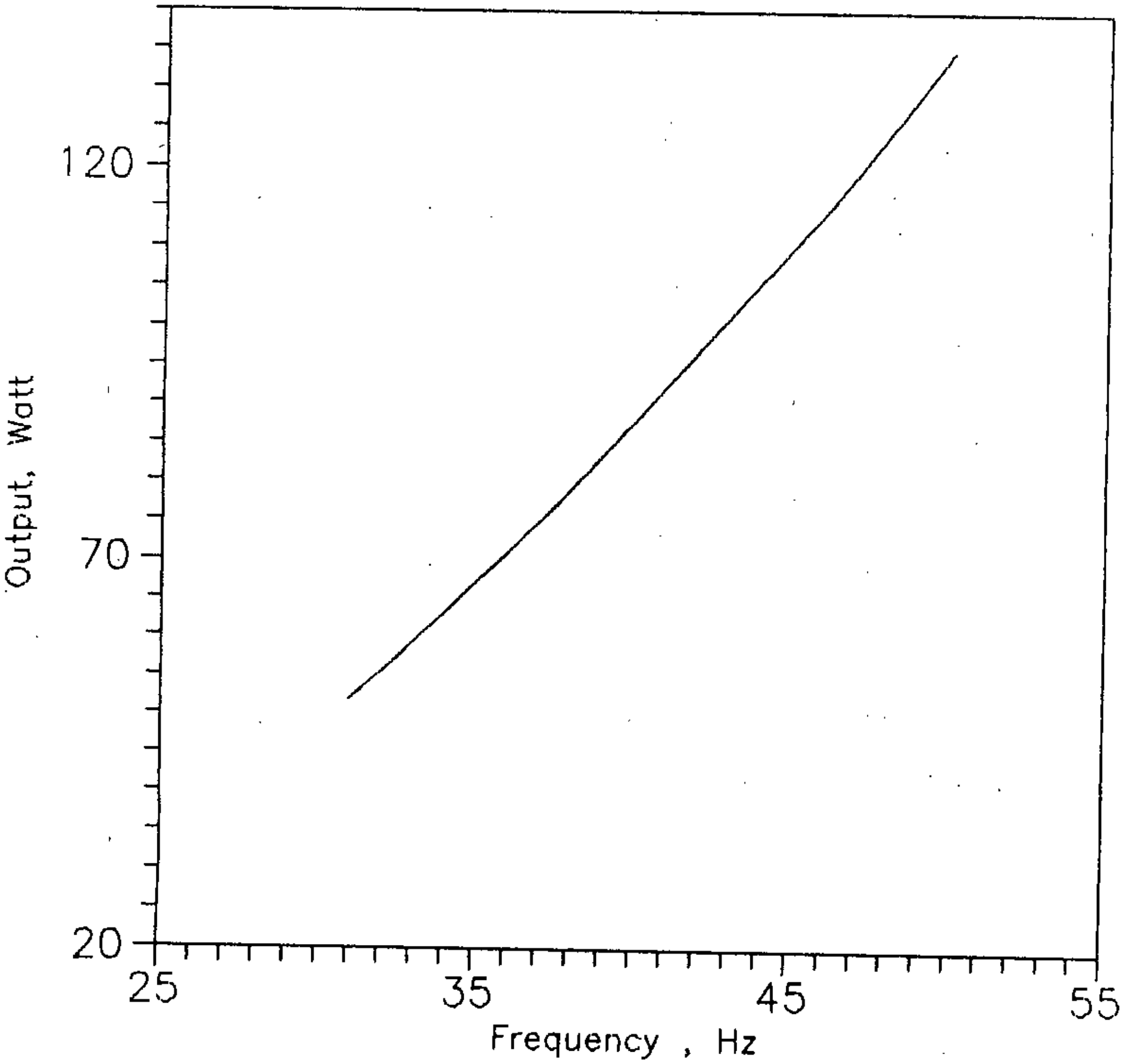


Figure 2.3 Output vs. Frequency for maximum efficiency of SPWM inverter-fed induction motor

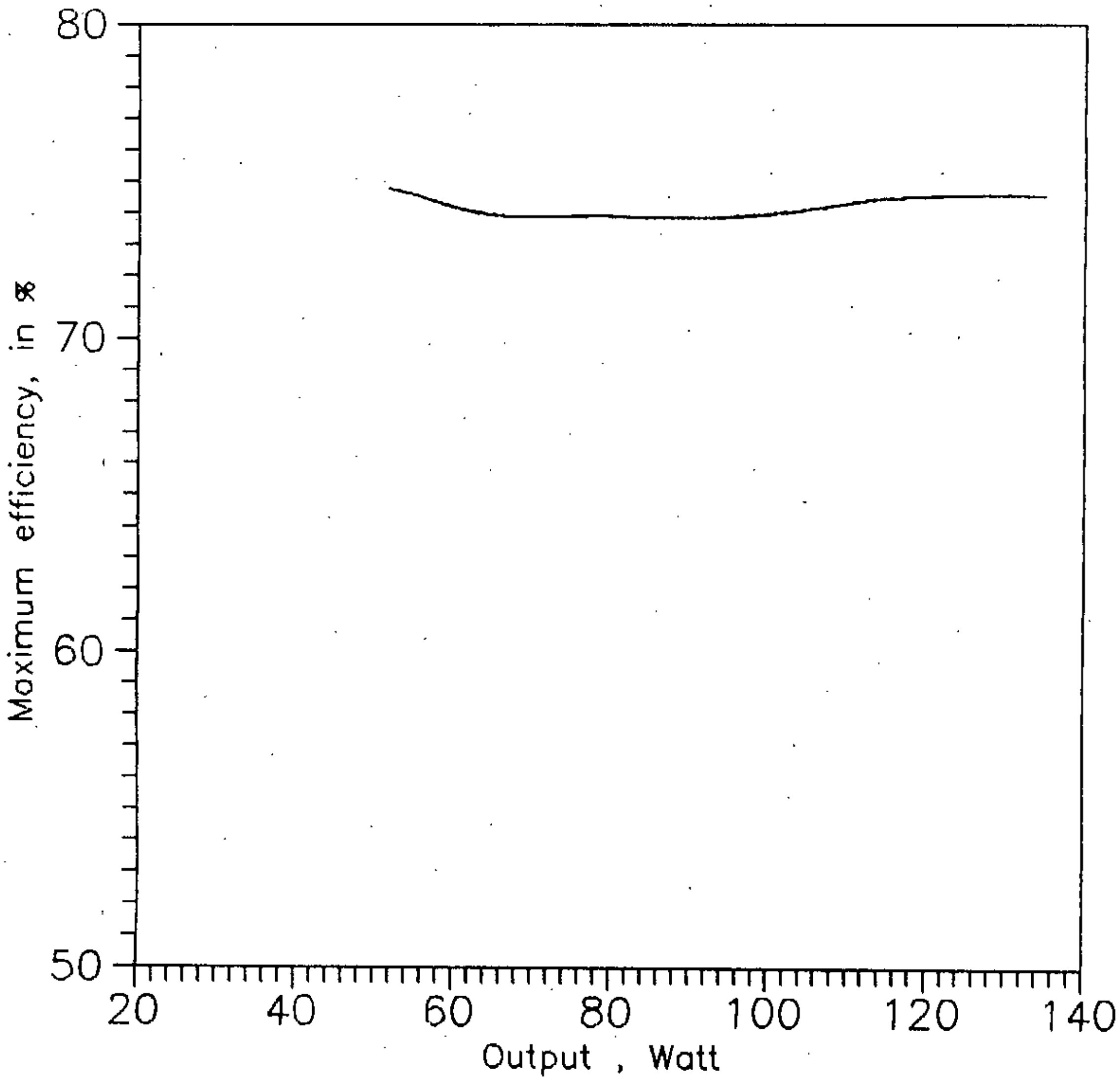


Figure 2.4 Maximum efficiency vs. output power of SPWM inverter-fed induction motor

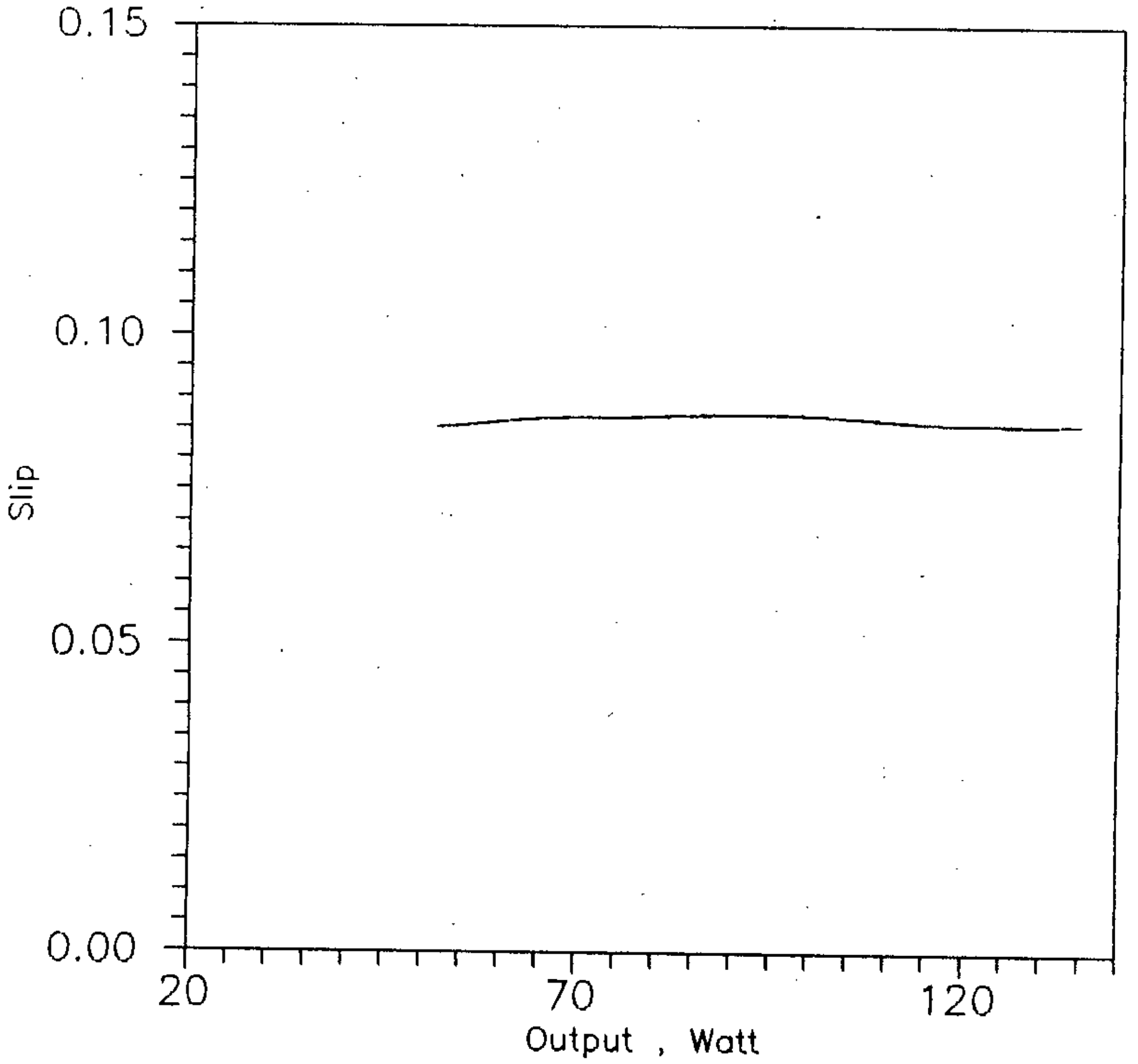


Figure 2.5 Slip vs. output power of SPWM inverter-fed induction motor at maximum efficiency operation

equations 2.2.6 to 2.2.14 are solved to determine the slip, output power and efficiency at maximum frequency for sinusoidal voltage fed induction motor. The results are presented in table 2.2. From table 2.2 we see that maximum efficiency is about 75% and the slip is about 0.085. From this table figures 2.6 to 2.8 are obtained. These plots are similar to figures 2.3 to 2.5. The induction machine equivalent circuit parameters required for the program was obtained from tests and are given in Appendix-I.

Alternative techniques were also developed for the verification of the result obtained and is provided in Appendix-III. The results of this are presented in table 2.3 and 2.4. From table 2.3 it is observed that for an output of 100 watt, maximum efficiency occurs at 43 Hz. Also for 80 watt output power maximum efficiency occurs at 38 Hz. These results are in close agreement with the results presented in table 2.2. The graphical plots of table 2.3 are presented in figures 2.9 and 2.10. It is seen that maximum efficiency for a particular output depends on the frequency of the supply voltage fed to the motor. The following conclusions from the theoretical results may be drawn. For motor output less than rated load the efficiency of the motor will be maximum at a particular frequency for a particular load. This frequency can be found from the characteristic curve of output vs. frequency. The optimum efficiency and slip for any load are almost constant and their values depend on the induction motor equivalent circuit parameters.

Table 2.2

Theoretical results of frequency and corresponding output, efficiency, and slip of sinusoidal voltage-fed induction motor at maximum efficiency condition

Frequency Hz	Output watt	Efficiency in %	Slip
31	51.74	74.92	.0893
32	55.12	74.91	.0849
33	58.60	74.91	.0849
34	62.18	74.91	.0848
35	65.87	74.91	.0848
36	69.67	74.90	.0849
37	73.56	74.90	.0849
38	77.56	74.90	.0848
39	81.67	74.89	.0848
40	85.88	74.89	.0848
41	90.19	74.89	.0848
42	94.61	74.89	.0847
43	99.12	74.88	.0847
44	103.74	74.88	.0847
45	108.46	74.88	.0847
46	113.29	74.87	.0847
47	118.21	74.87	.0847
48	123.24	74.87	.0847
49	128.36	74.86	.0846
50	133.60	74.86	.0846

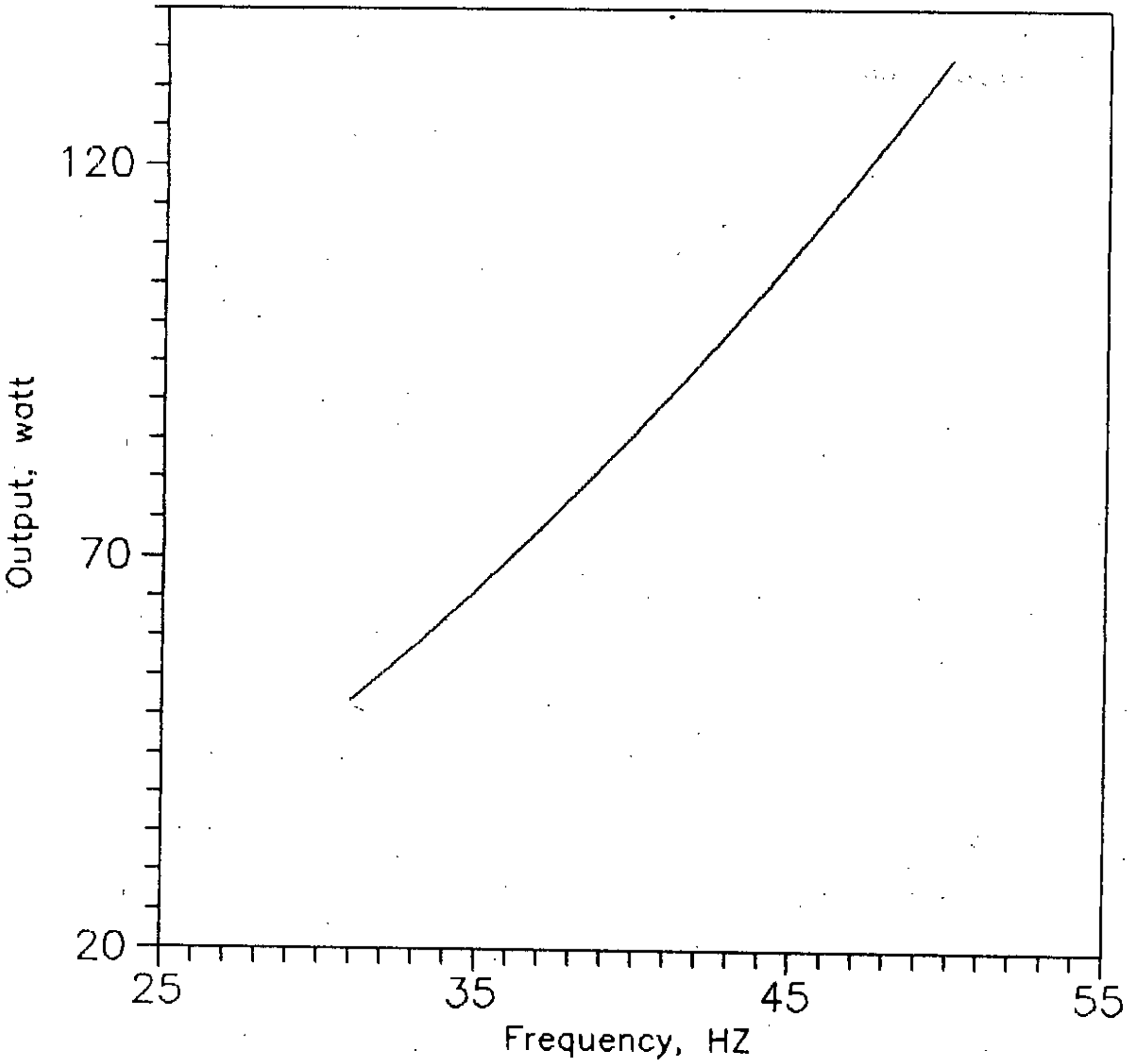


Figure 2.6 Output vs. frequency for maximum efficiency of sinusoidal voltage-fed induction motor

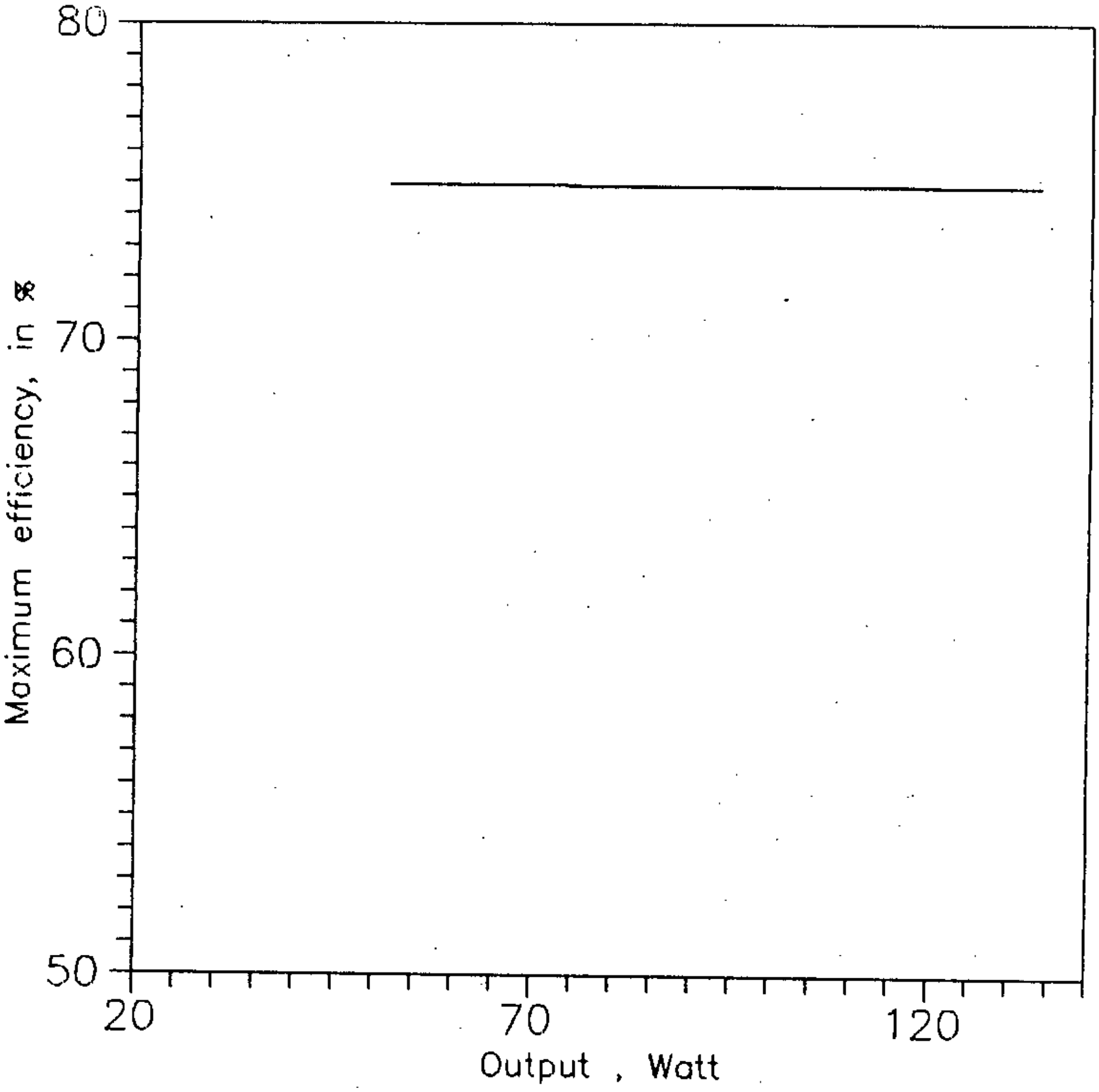


Figure 2.7 Maximum efficiency vs. output power of sinusoidal voltage-fed induction motor

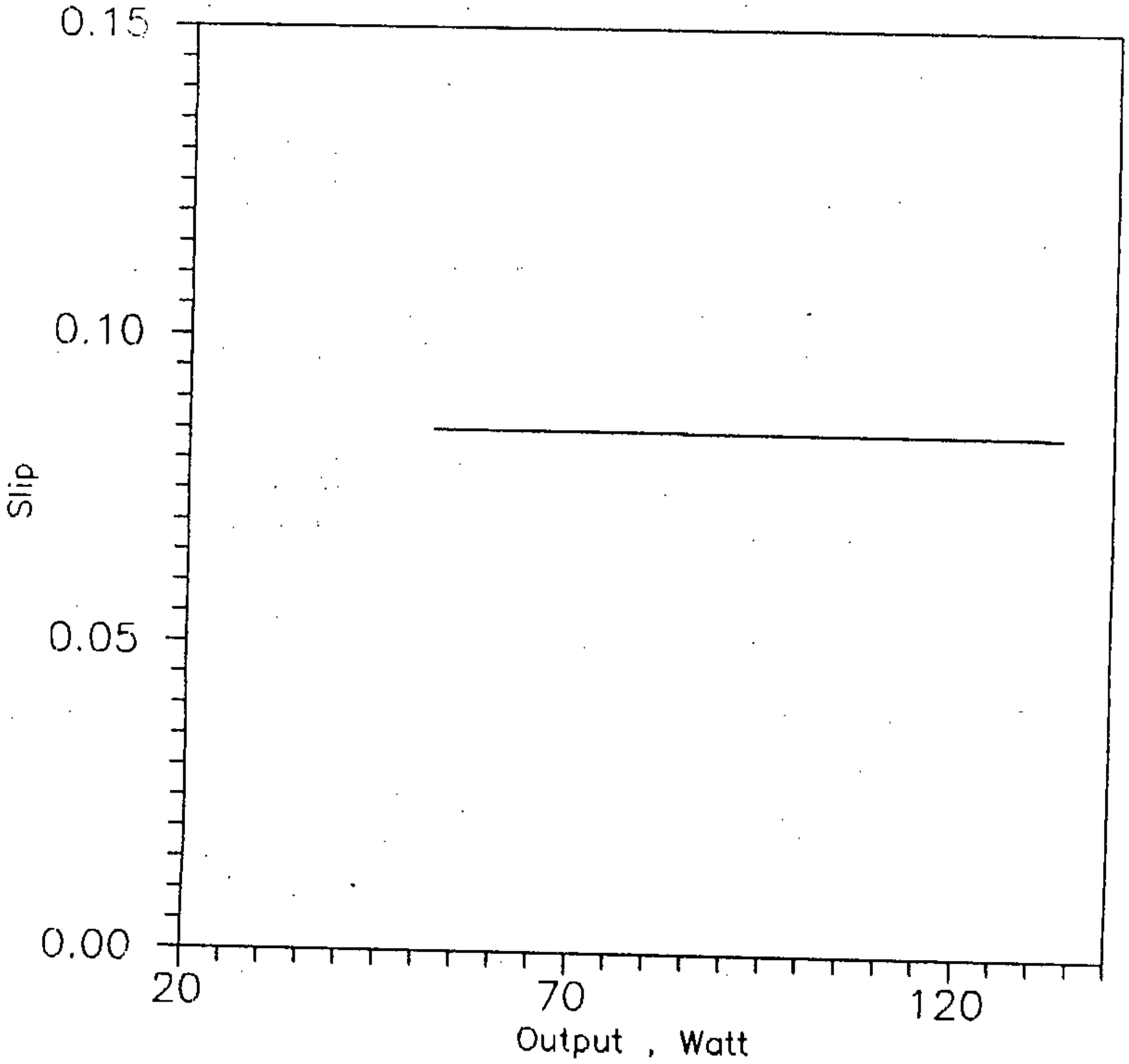


Figure 2.8 Slip vs. output power of sinusoidal voltage-fed induction motor at maximum efficiency operation

Table 2.3

Theoretical results of efficiencies of induction motor at different frequencies for P_{out} = 100 watt and P_{out} = 80 watt with sinusoidal input voltage

Pout = 100 watt		Pout = 80 watt	
Frequency Hz	Efficiency in %	Frequency Hz	Efficiency in %
31	64.33	31	71.32
32	66.99	32	72.40
33	68.95	33	73.22
34	70.45	34	73.84
35	71.62	35	74.29
36	72.53	36	74.60
37	73.25	37	74.79
38	73.80	38	74.88
39	74.22	39	74.82
40	74.52	40	74.68
41	74.72	41	74.49
42	74.84	42	74.24
43	74.88	43	73.96
44	74.86	44	73.63
45	74.78	45	73.26
46	74.65	46	72.87
47	74.47	47	72.44
48	74.26	48	72.00
49	74.00	49	71.52
50	73.72	50	71.03

Table 2.4

Theoretical results of minimum frequency levels for different output power of induction motor with sinusoidal input voltage

Output watt	Frequency Hz
175	45
165	44
160	43
150	42
145	41
140	40
130	39
125	38
120	37
110	36
105	35
100	34
95	33
90	32
80	31

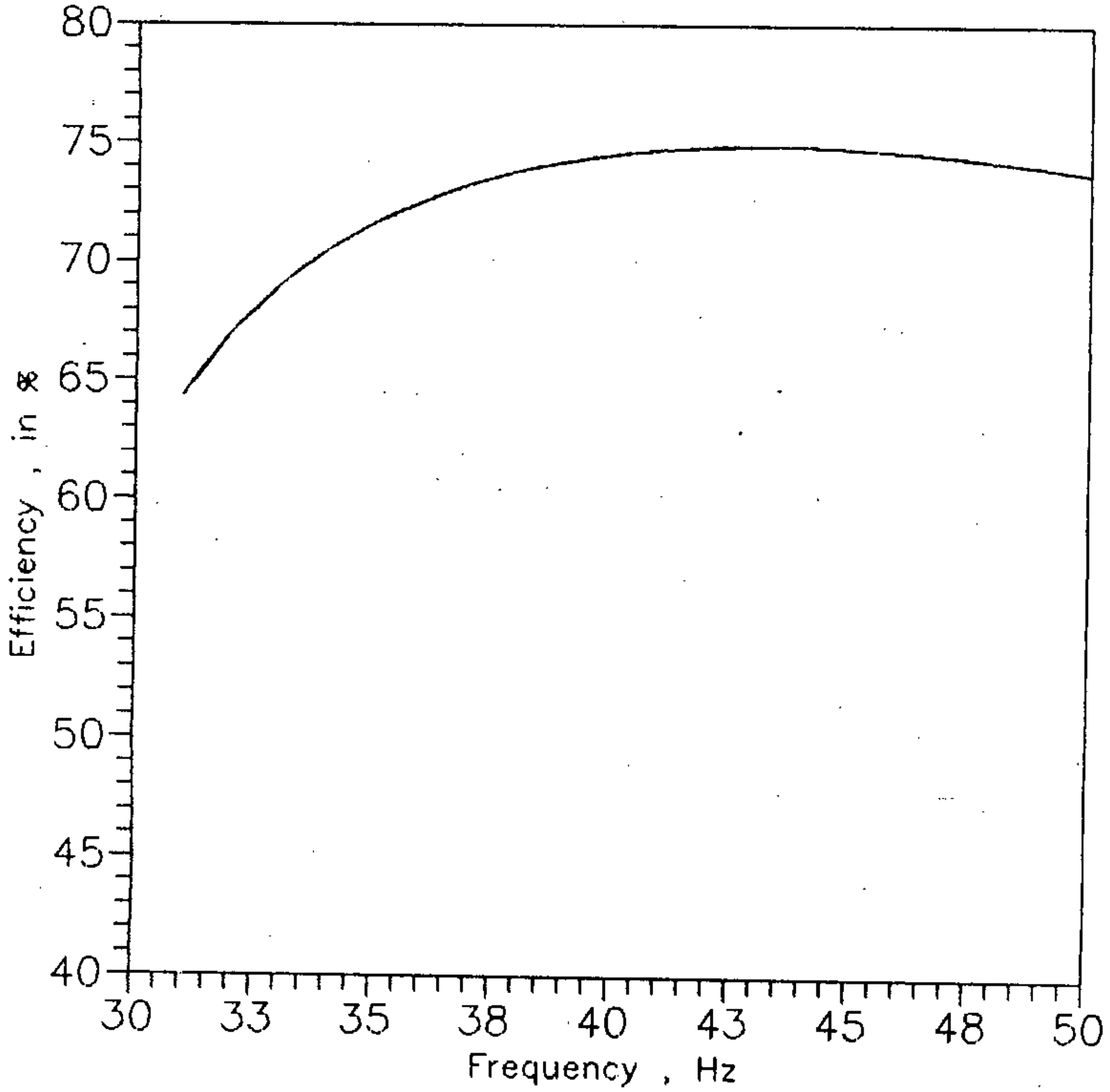


Figure 2.9 Efficiency vs. frequency of sinusoidal voltage-fed induction motor at Pout=100 watt

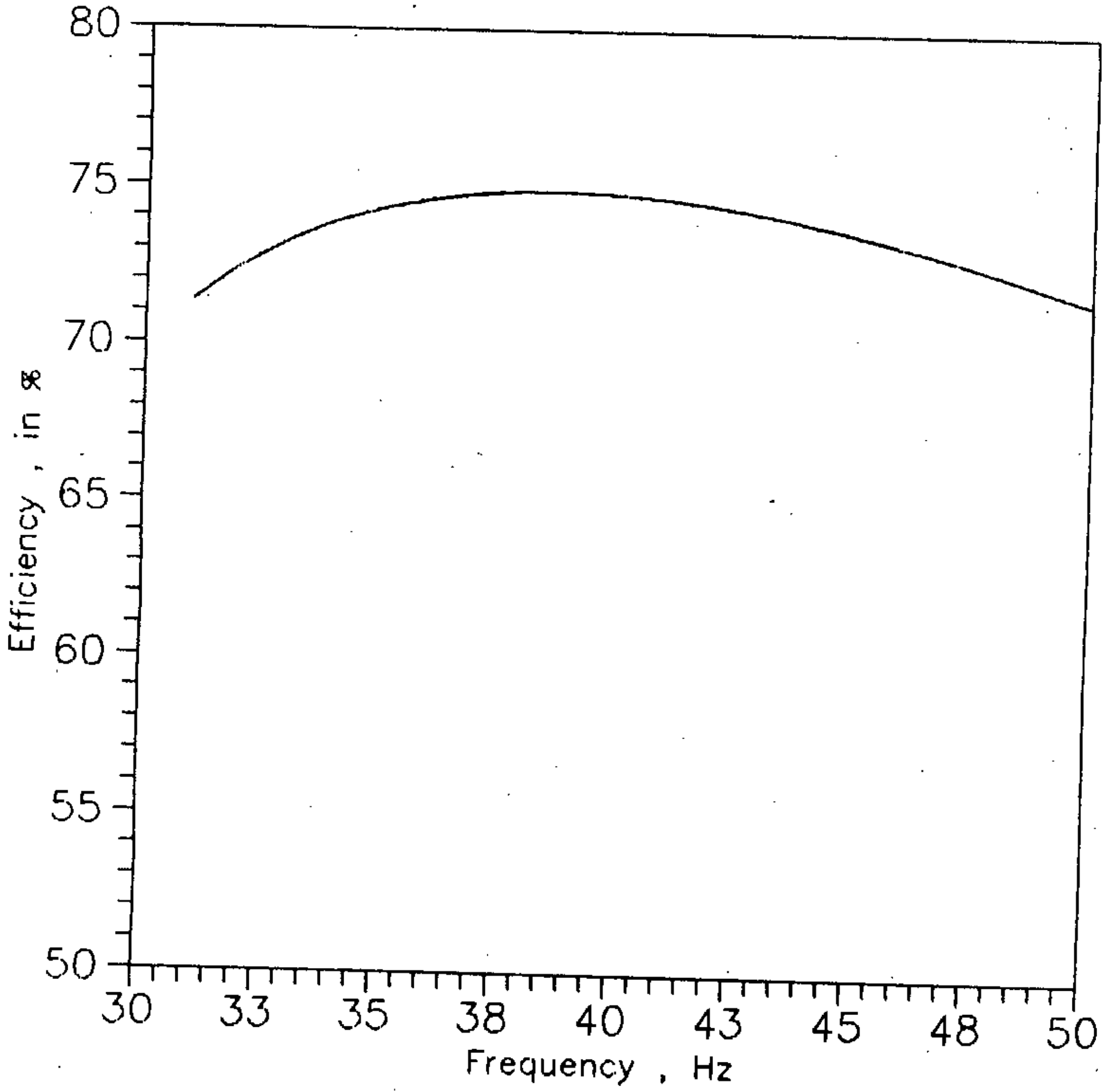


Figure 2.10 Efficiency vs. frequency of sinusoidal voltage-fed induction motor at Pout=80 watt

CHAPTER 3

EXPERIMENTAL RESULTS

3.1 INTRODUCTION

The objective of the present thesis was to develop a mathematical model for the most efficient operation of SPWM inverter-fed induction motor under varying load conditions and to verify the validity of the model by doing some experiments on a practical machine. The model developed is described in the previous chapter. The present chapter deals with the experimental set up procedure and results. Comparison of the experimental results with theoretical results are dealt in this chapter and limitations of the practical circuits used in the experiment are also listed.

3.2 EXPERIMENTAL SETUP WITH SPWM INVERTER SUPPLY

The practical circuit used for experimental verifications is shown in figure 3.1. The operation of this circuit is as follows : An unregulated full wave rectifier is used to supply dc power at the input of the center-tap transformer (24v/220v) – the secondary of which is connected to phase R1R2 of induction motor. The center-tap is connected to the positive terminal of dc supply. The drains D1 and D4

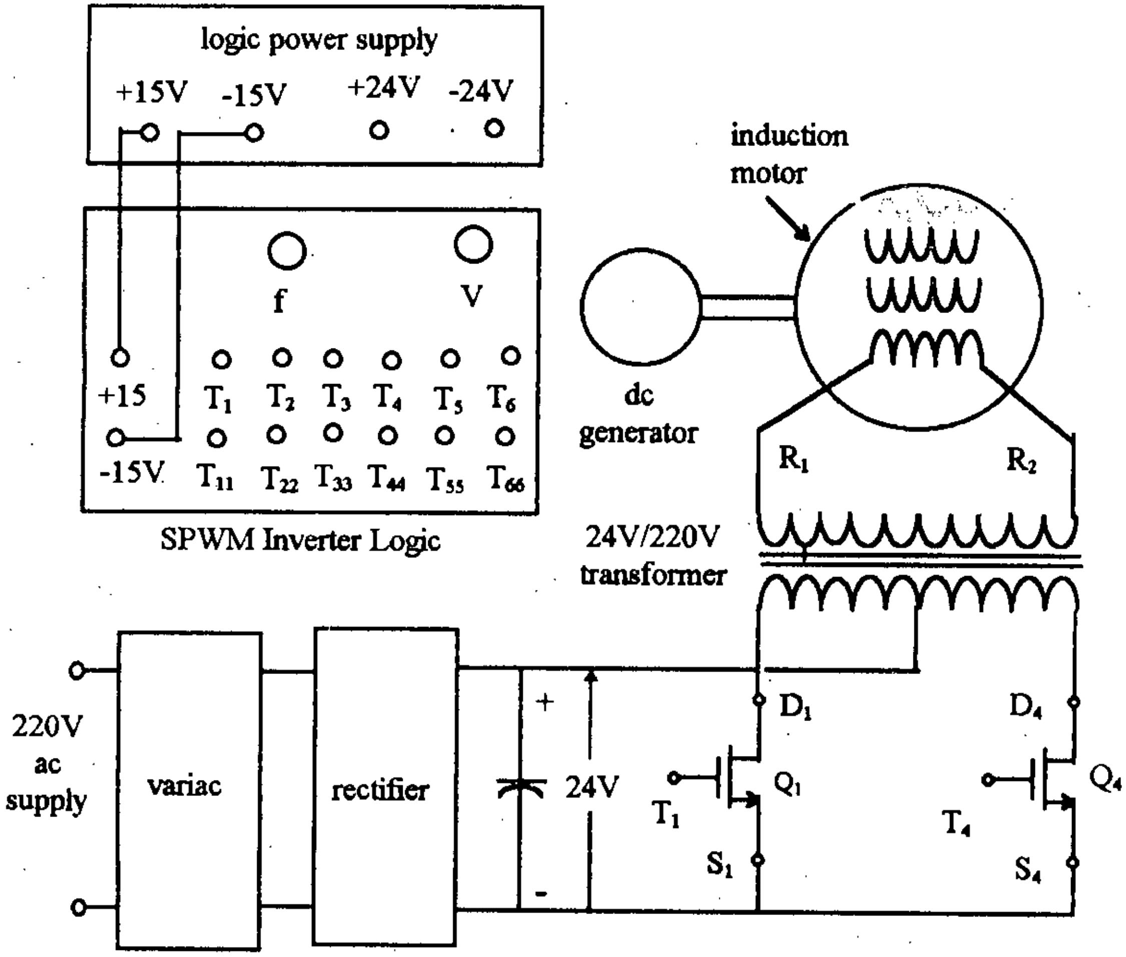


Figure 3.1 Experimental set-up using SPWM technique

of two MOSFETs are connected in series with the other two tappings. The sources of these two MOSFETs are connected to the negative terminal of the supply. The spwm inverter logic generates gate signals. Signals at T_1 and T_4 are 180° out of phase and are given to the trigger terminals G_1 and G_4 respectively. As a result sine pulse width modulated signal is generated at the secondary of the transformer. The voltage and frequency level can be controlled from spwm inverer logic. Similar arrangements were made for other two phases.

3.3 A BRIEF DESCRIPTION OF SPWM INVERTER LOGIC

The logic board in SPWM uses an LSI chip HEF4752. This chip is the major fundamental block of the logic circuit. The logic board has the following functional blocks (figure 3.2) :

1) Input frequency V.C.O.
2) Input voltage V.C.O.
3) Interlock delay period
4) Maximum chopping frequency
5) SPWM waveform generator
6) Stop/start control
7) Output gating

The input frequency V.C.O. block consists of two OP-AMPs, and a V.C.O.. This frequency is presented to the pin 12 of HEF4752. The output frequency of the SPWM waveform (observable at pin 23 of HEF4752) is equal to FCT (pin12 on HEF4752) devided by 3360. The input voltage V.C.O. block consists of two OP-AMPs and a V.C.O.. This frequency is presented to VCT, pin17on HEF4752. The

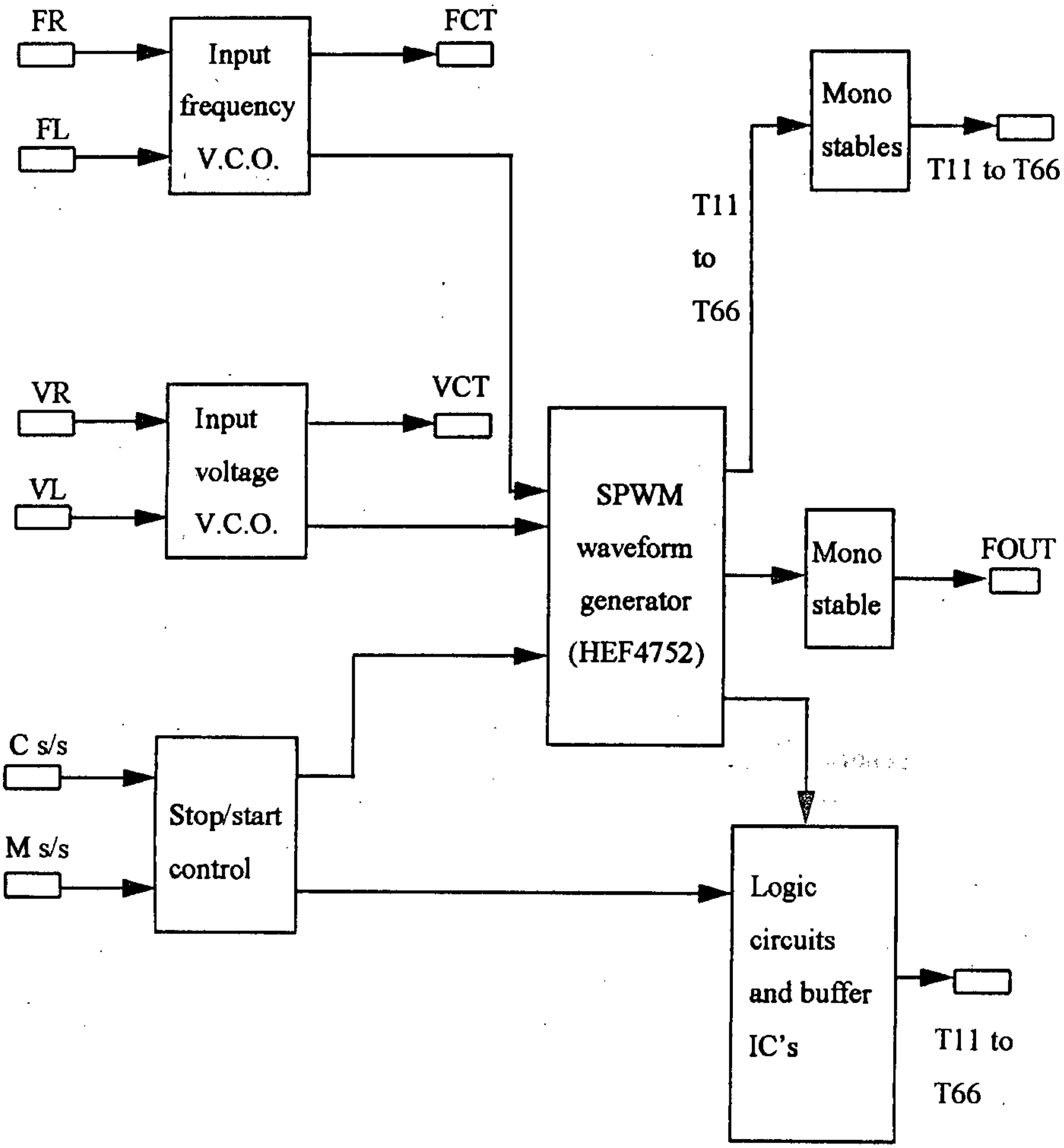


Figure 3.2 Schematic diagram of SPWM inverter logic

fundamental output voltage is inversely proportional to this frequency. Interlock delay period is the time when two complementary thyristors (T1 & T4, T3 & T6, T5 & T2) are not gated during the transition of one of the thyristors being commutated and the complementary thyristors being fired. A timer 555 creates a frequency Foct which is fed in HEF4752. The interlock delay period with 180° gating pulses is 53 μs. The maximum chopping frequency is set by another timer 555. This is fed into HEF4752 pin 4. The HEF4752 IC generates the gating waveforms required to drive three phase voltage source inverter employing the conventional circuits. The inputs C s/s(commutation start/stop) and M s/s (mains start/stop) allow stop/start control of the inverter logic. Due to the nature of power circuit, the commutation pulses must be turned on, prior to the main pulses being turned on and must be turned off, after the main pulses have been turned off. The logic incorporates a safety feature, which prevents incorrect sequencing. The main pulses are buffered through IC's. The commutation pulses are generated via monostables which are triggered on the rising edge of the interlocking delay period.

The frequency potentiometer controls the output frequency from 4 to 64 Hz. Voltage potentiometer controls the rms fundamental output voltage from 0 to $0.78V_{dc}$. Rotating the frequency potentiometer counterclockwise will decrease the fundamental voltage. Rotating the voltage potentiometer counterclockwise will increase the fundamental voltage.

3.4 EXPERIMENTAL SETUP WITH SINUSOIDAL SUPPLY

An schematic diagram of pure sinusoidal voltage-fed induction motor drive is shown in figure 3.3. The induction motor is fed from the synchronous generator,

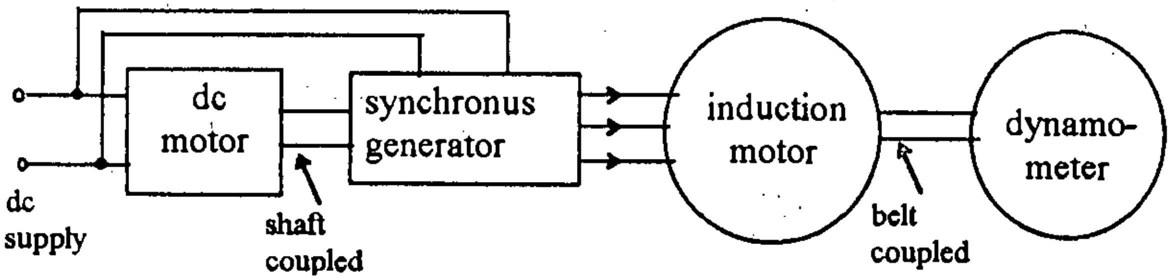


Figure 3.3 Schematic diagram of pure sinusoidal voltage-fed induction motor

the frequency of which depends on the dc motor speed and the excitation of alternator. At the beginning the voltage and frequency is set to the required value. Then the induction motor is loaded using dynamometer. The speed of the induction motor is measured using tachometer .The reading for torque is taken from dynamometer. The output power is the product of torque and speed of induction motor. Input power is measured using wattmeters at the input of the induction motor. The efficiency and slip are determined using these data.

3.5 EXPERIMENTAL RESULTS

The experimental results obtained for SPWM inverter-fed induction motor are presented in tables 3.1 and 3.2. Entry of each rows of table 3.1 are chosen from different sets of data. A particular set of data is obtained for a particular voltage and frequency of SPWM inverter output. The load on the motor is varied and input current I_i, output power P_{out}, input power P_{in}, efficiency η, slip s are determined for various loads. From these data a particular output power and slip were found for which efficiency was maximum. The data corresponding to maximum efficiency was chosen and recorded in table 3.1. Experimental data at rated voltage (220 volt) and frequency (50 hz) is presented in Appendix-V for illustration. Each row of table 3.2 is obtained for an output of 70 watt from each set of experimental data. The output power at rated voltage and frequency for maximum efficiency was found 102 watts. Efficiencies and slips are found almost constant. The efficiency is about 75% and the slip is about 0.16. Figures 3.4 to 3.6 are graphical representation of table 3.1. The characteristic obtained in figure 3.4 has similar trend to that obtained in figures 2.3 and 2.6. Figure 3.5 shows that efficiency is almost constant with variable outputs at frequencies corresponding to maximum

Table 3.1

Experimental results of frequency and corresponding output, efficiency, and slip of SPWM inverter-fed induction motor at maximum efficiency condition

Frequency Hz	Output watt	Efficiency in %	Slip
30	39	76.5	0.22
35	54	76.6	0.21
40	70	76.9	0.176
42	75	73.86	0.164
46	92	75.4	0.168
48	97	71.4	0.170
50	102	72.5	0.178

Table 3.2

Experimental results of efficiencies of induction motor at different frequencies for $P_{out} = 70$ watt with SPWM input voltage

Frequency Hz	Efficiency in %
35	67.10
40	76.90
42	71.75
46	65.20
48	60.10
50	59.00

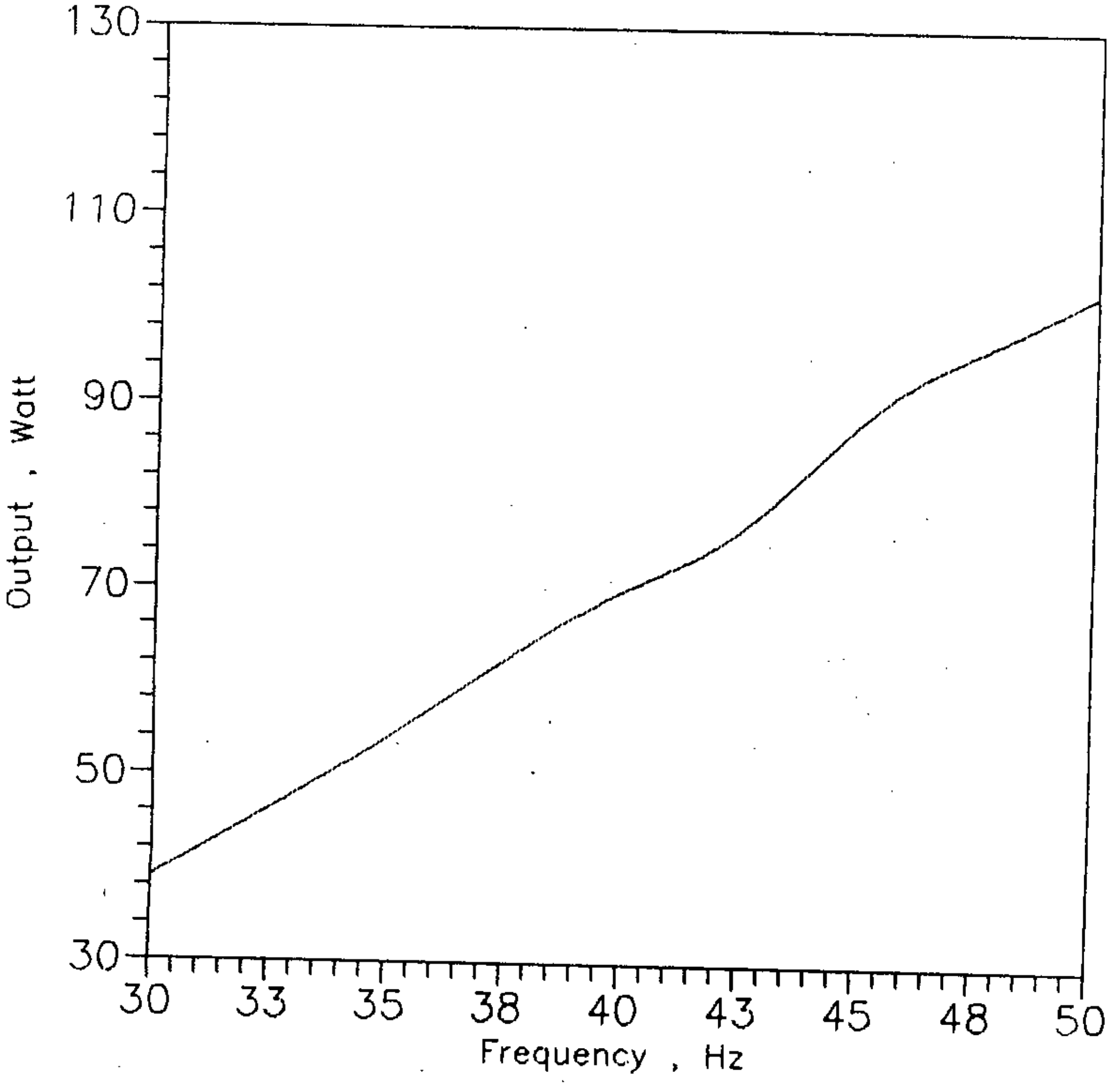


Figure 3.4 Output vs. frequency for maximum efficiency of SPWM inverter-fed induction motor

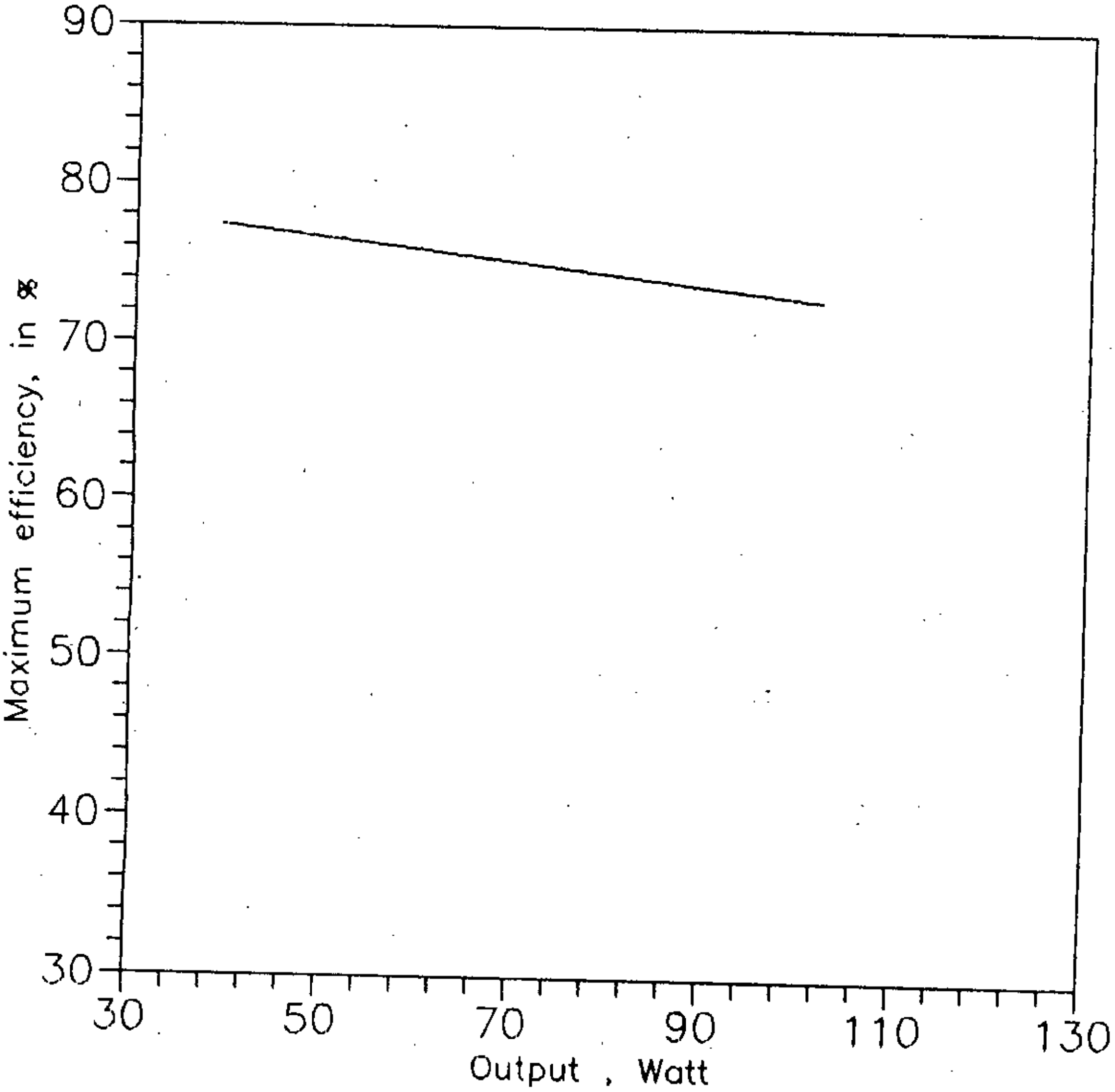


Figure 3.5 Maximum efficiency vs. output power of SPWM inverter-fed induction motor

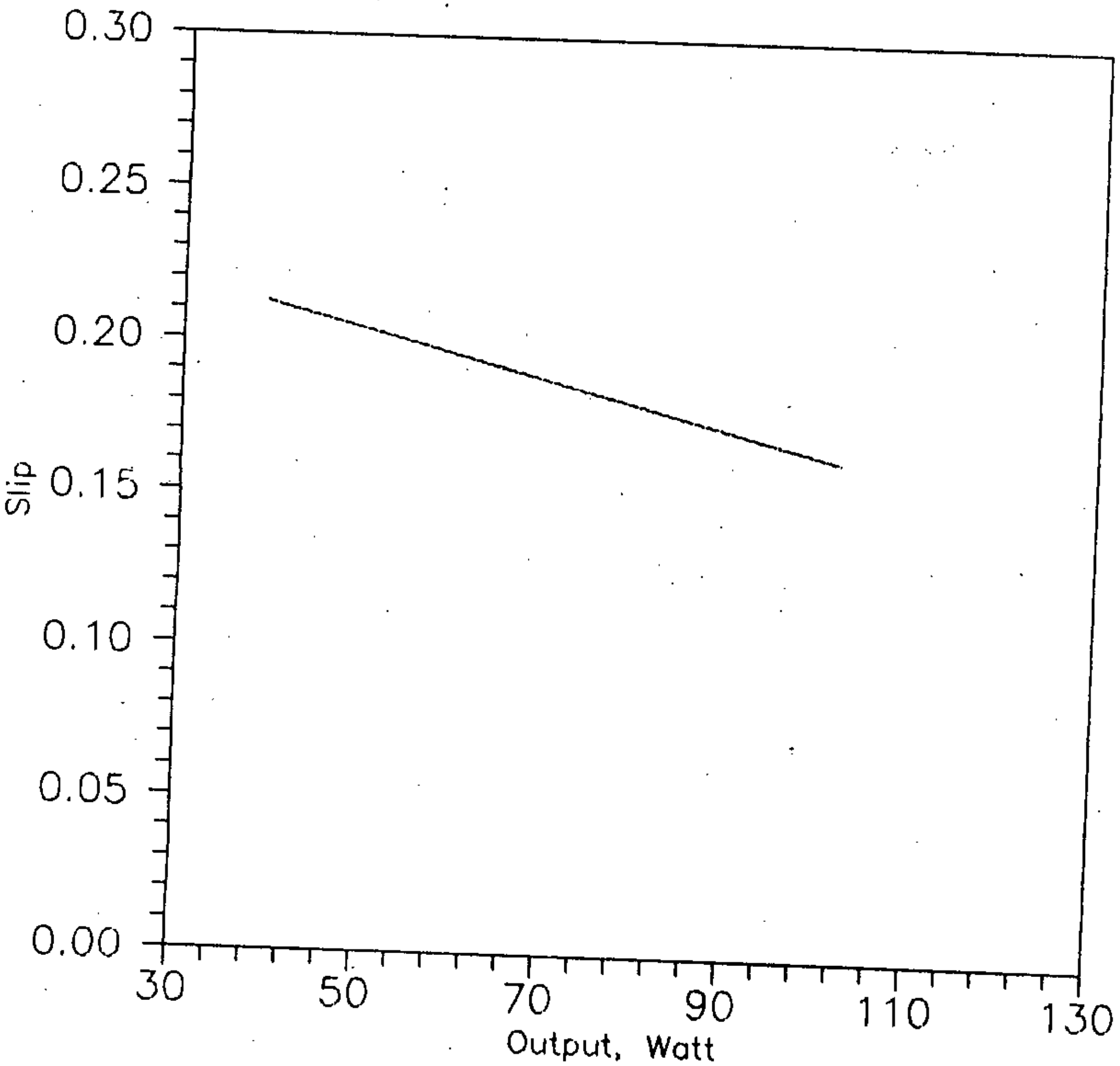


Figure 3.6 Slip vs. output power of SPWM inverter-fed induction motor at maximum efficiency operation

efficiency. Figure 3.6 shows that slip is almost constant at maximum efficiency irrespective of load. From table 3.2 it is seen that efficiency is maximum at 40 hz for 70 watt output. This table is represented graphically in figure 3.7.

Experimental results on induction motor with sinusoidal supply voltage are presented in tables 3.3 and 3.4 for maximum efficiency condition. Table 3.3 is obtained in the same way from different sets of experimental data as explained previously for SPWM inverter-fed motor. Experimentally obtained data at rated voltage and frequency is also presented in Appendix-V for illustration. Each row of table 3.4 is obtained for an output of 100 watt from each set of experimental data. The efficiency, as seen from table 3.3 , is 64% and the slip is 0.1 at maximum efficiency condition. Figures 3.8 to 3.10 are the graphical form of table 3.3. The nature of the curves are found identical as those of SPWM inverter fed induction motor. Table 3.4 shows that for 100 watt output, the efficiency is maximum at 44 hz which is the same as predicted by the theoretical model shown in table 2.2. The results of table 3.4 is shown graphically in figure 3.11.

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3.6 ANALYSIS AND COMPARISON OF RESULTS

The comparison of two practical results with the theoretical results gives following information :

1) From the theoretical results it is seen that the output power corresponding to maximum efficiency at rated frequency and voltage is 134 watts whereas, for sinusoidal and SPWM inverter fed supplies the output power obtained was 127 watts and 102 watts respectively. For sinusoidal voltage fed motor the result is closest to the theoretical ones. With SPWM inverter-fed motor the

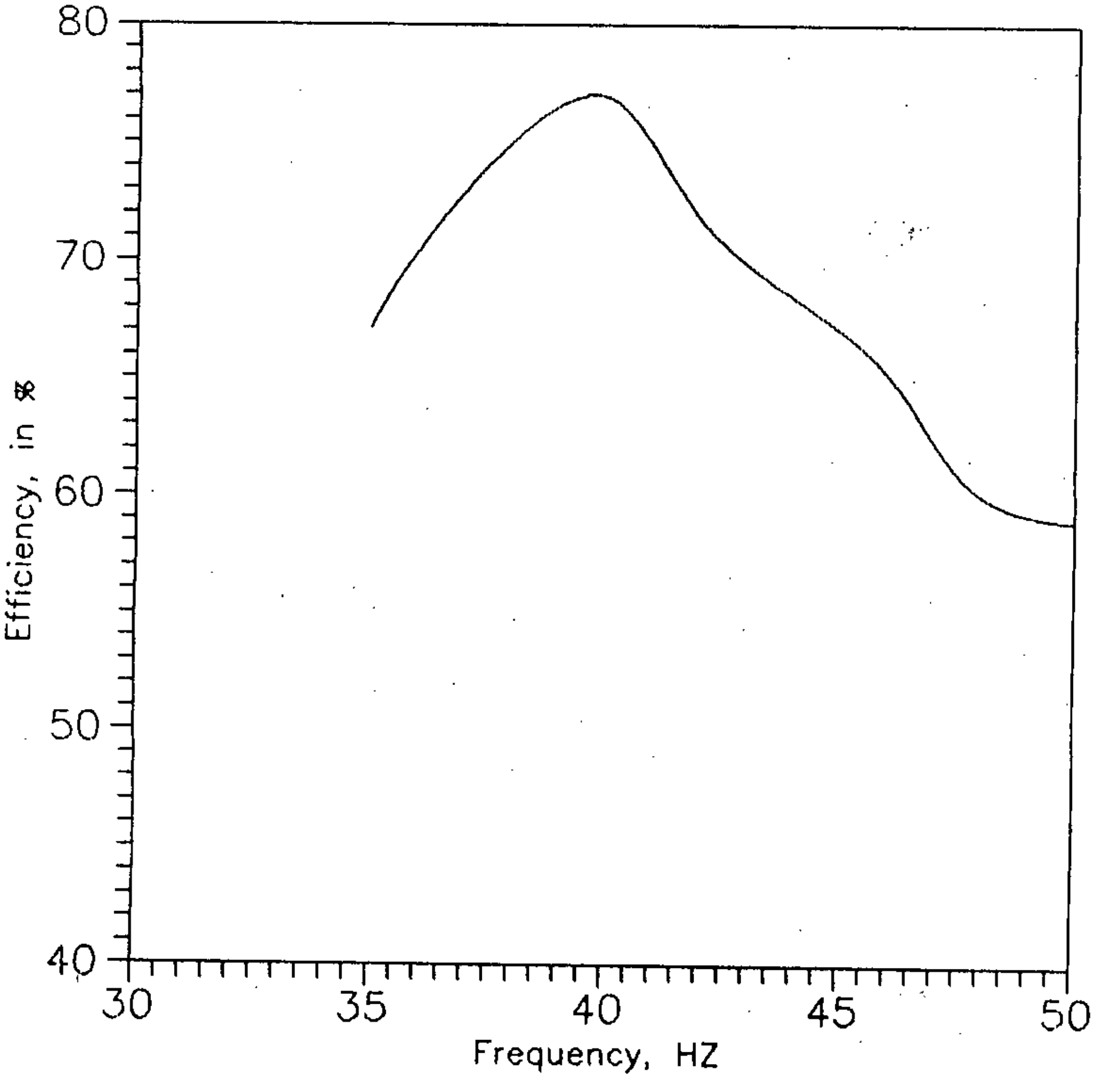

Figure 3.7 Efficiency vs. frequency of SPWM inverter-fed induction motor at P_{out} = 70 watt

Table 3.3

Experimental results of frequency and corresponding output, efficiency, and slip of sinusoidal voltage-fed induction motor at maximum efficiency condition

Frequency Hz	Output Watt	Efficiency in %	Slip
30	45.00	63.40	0.120
36	67.00	63.10	0.110
42	91.00	63.20	0.103
44	100.00	64.20	0.100
46	106.30	64.48	0.102
48	113.70	64.25	0.102
50	127.04	65.32	0.100

Table 3.4

Experimental results of efficiencies of induction motor at different frequencies for $P_{out} = 100$ watt with sinusoidal input voltage

Frequency Hz	Efficiency in %
38	54.2
40	62.5
42	63.18
44	64.2
46	63.85
48	62.11
50	61.5

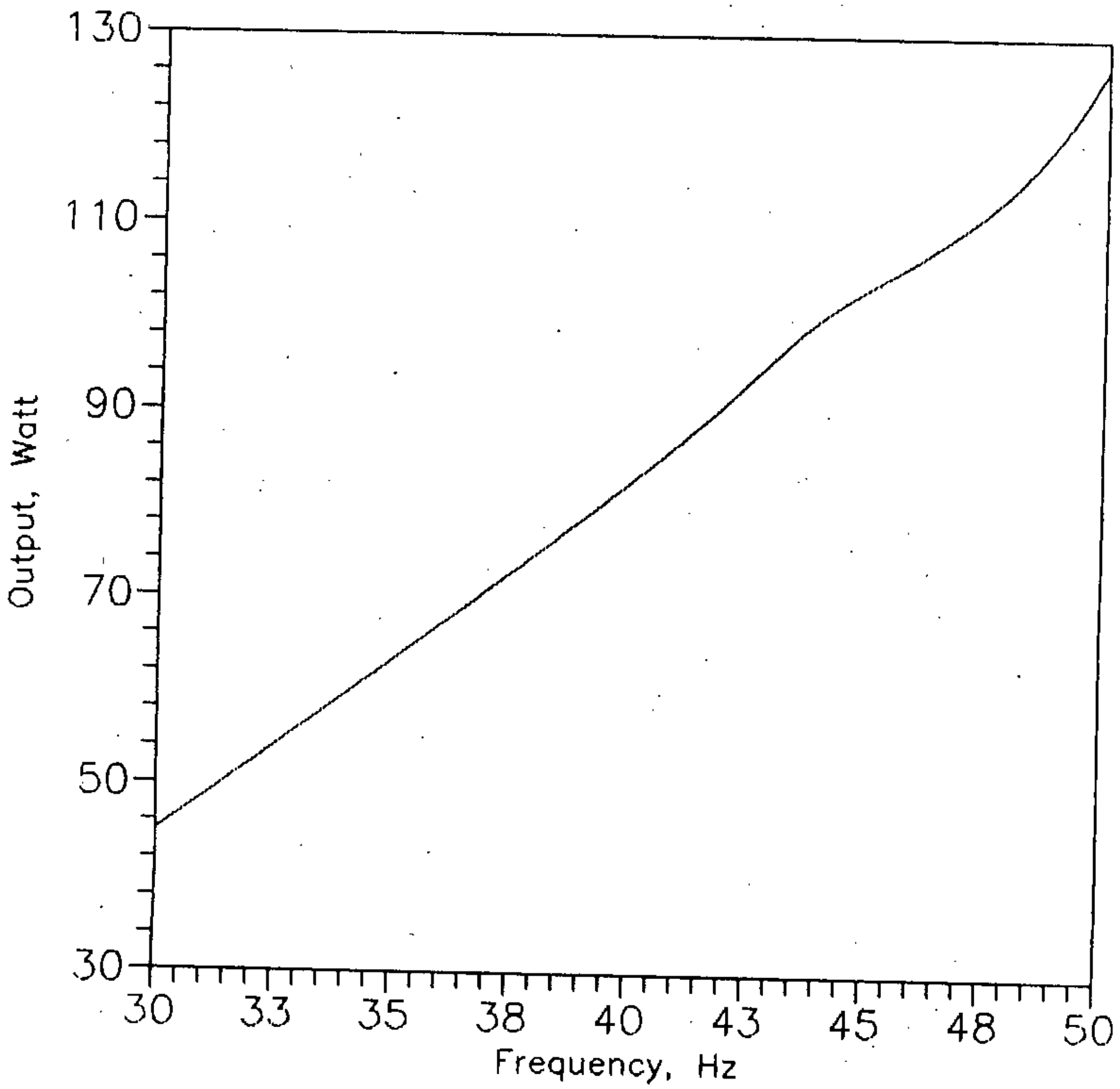

Figure 3.8 Output vs. frequency for maximum efficiency of sinusoidal voltage-fed induction motor

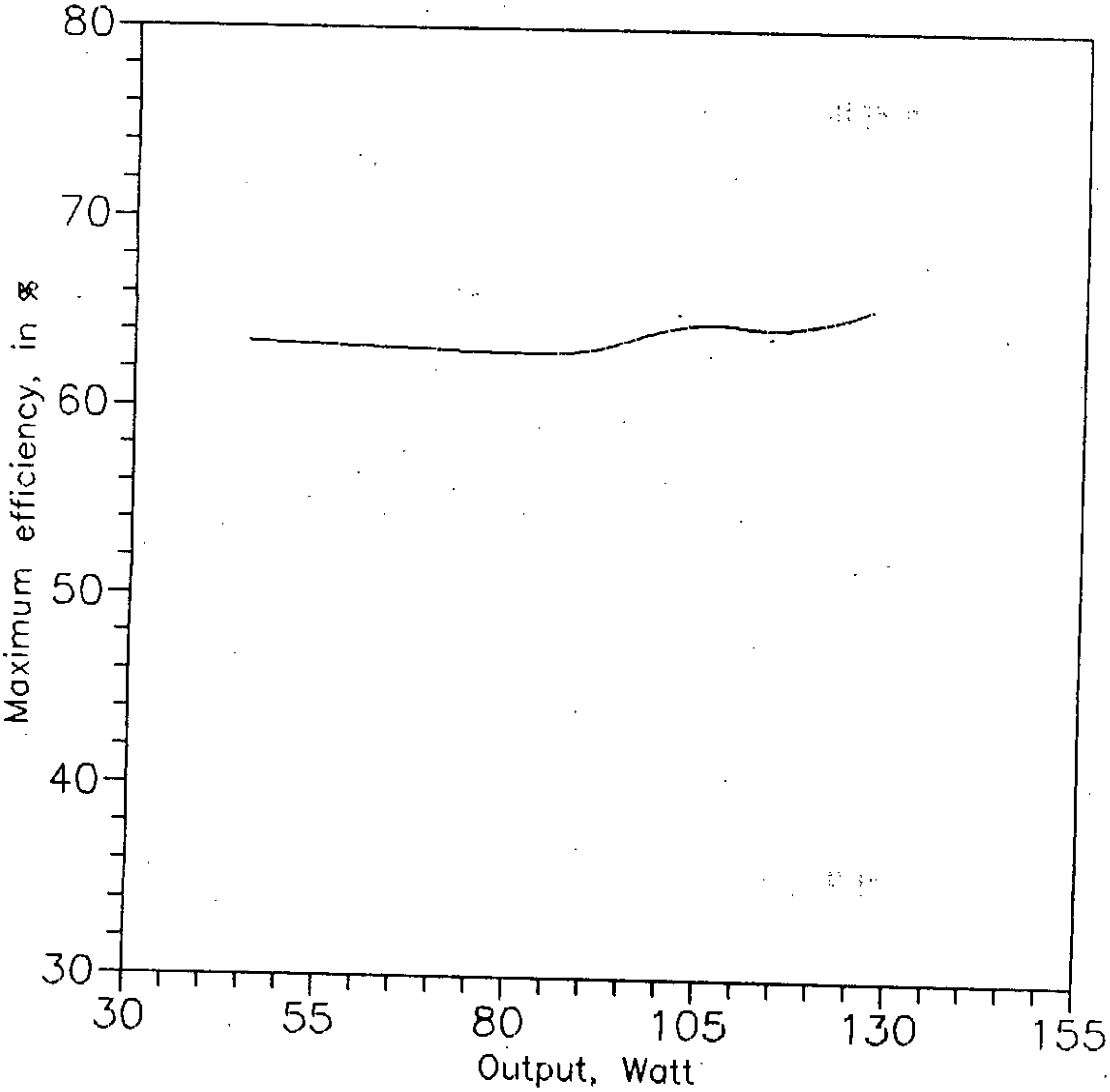

Figure 3.9 Maximum efficiency vs. output power of sinusoidal voltage-fed induction motor

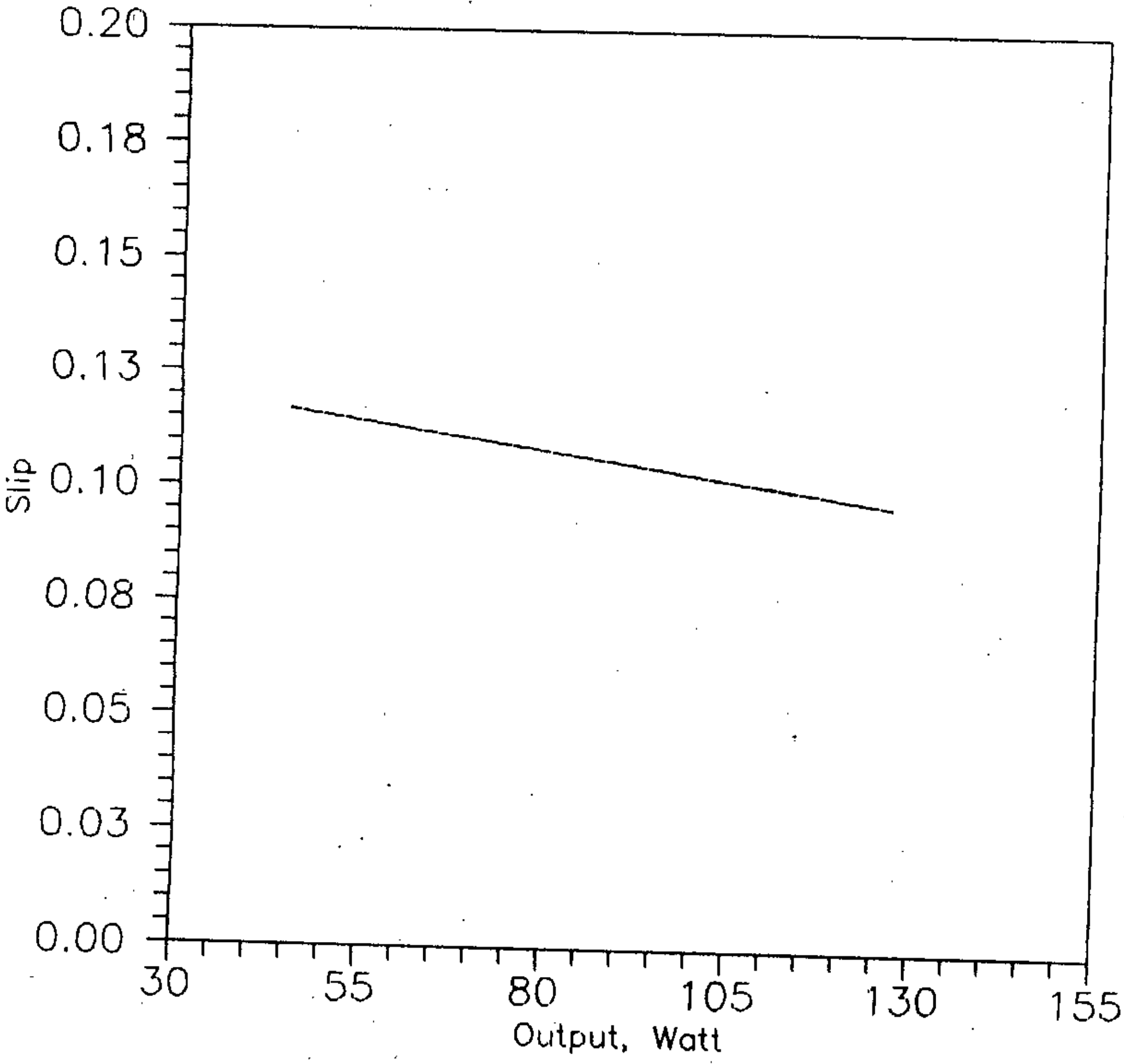

Figure 3.10 Slip vs. output power of sinusoidal voltage-fed induction motor at maximum efficiency operation

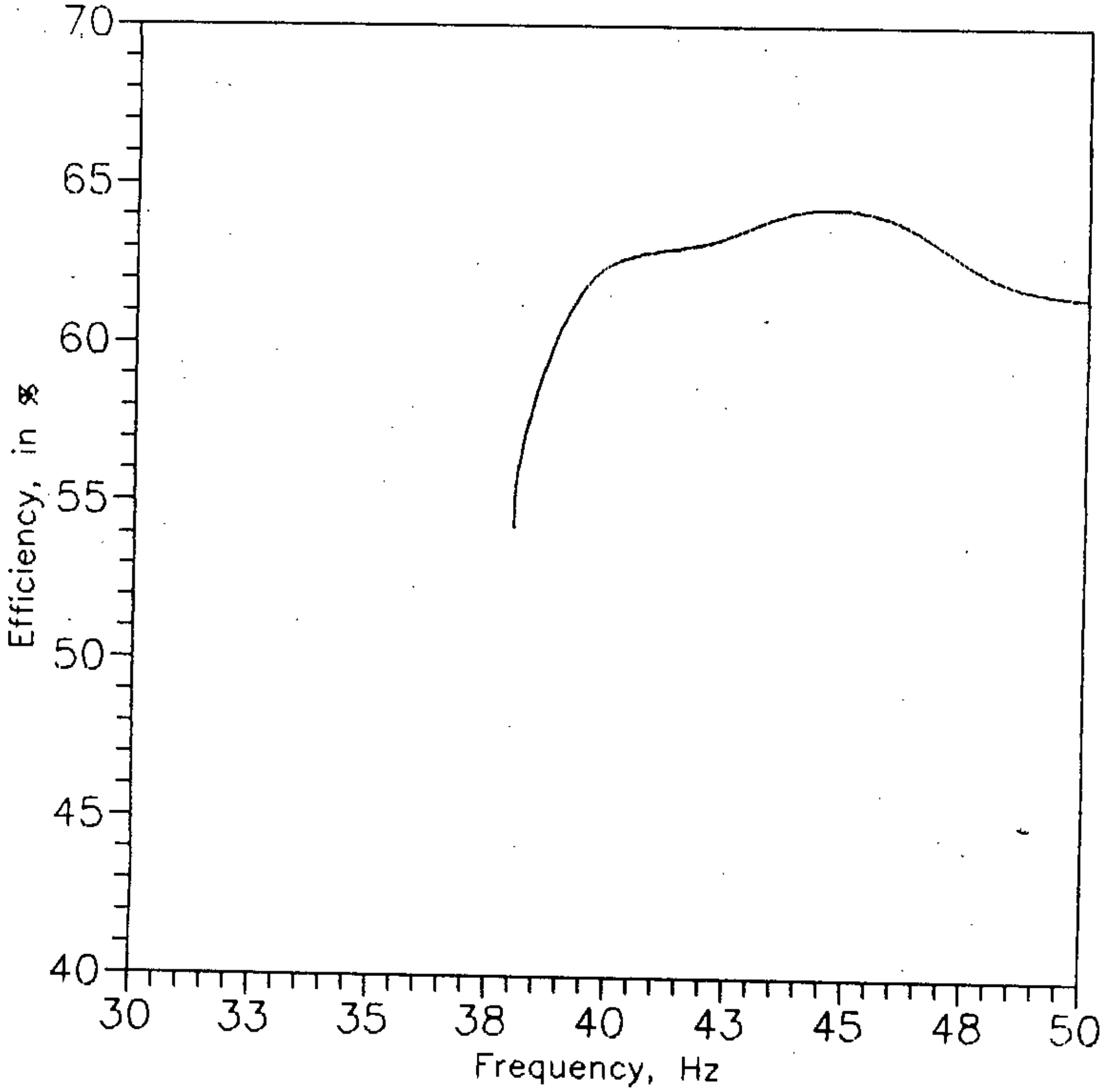

Figure 3.11 Efficiency vs. frequency of sinusoidal voltage-fed induction motor at Pout=100 watt

deviation of experimental result from that of the theoretical is greater. This is due to the fact that in the experiment of inverter fed induction motor the fundamental rms voltage was lower than the total rms voltage.

2) The maximum efficiency obtained theoretically was 74%. With sinusoidal voltage fed motor the efficiency obtained was 64% and for SPWM inverter fed motor the efficiency was 76%. The deviation was only 15.6% if the result of sinusoidal voltage fed motor is taken as a reference. The result is within the acceptable limit.

3) The slip at maximum efficiency obtained from the mathematical model is 0.0867, while the value of the same determined practically is 0.1 for sinusoidal voltage-fed motor, and 0.16 for SPWM inverter fed motor. However slip corresponding to maximum efficiency remains almost constant for both theoretical and practical cases. This result is acceptable.

4) Both the theoretical and practical curves for output power vs. frequency at optimum efficiency are of the same nature (figures 2.3, 2.6, 3.4 and 3.8). This verifies validity and accuracy of the developed mathematical model.

5) It is seen from figure 3.7 and 3.11 that for a particular output efficiency is maximum at a particular frequency. Theoretically the same results are obtained. For example, with sinusoidal input voltage, at P_{out}=100 watt, the experimentally obtained frequency at maximum efficiency is 44 hz. The theoretically obtained value under similar condition is also 44 hz. This proves and suggests that frequency may be used as a control variable to maximize efficiency of an induction motor under variable load conditions.

3.7 LIMITATIONS

The practical circuit used in the experiment had some limitations. These are as follows :

1) In the experiment of pure sinusoidal voltage fed induction motor, voltage of required frequency was obtained from a motor generator set. When the induction motor was loaded and the load was increased by dynamometer the dc motor had supplied the increased load. So, the speed of the motor decreased and it resulted in decrease in generator output voltage and frequency. To compensate this the speed of the motor was adjusted frequently. The adjustment was not very smooth. Hence the result was affected to some extent.

2) In SPWM inverter fed induction motor circuit, a substantial amount of losses occurred in transformer because the transformers were not designed for this particular operation. This loss was calculated using experimental data. A plot of transformer losses versus transformer primary current is shown in Appendix-IV.

Also there were core losses in the generator and losses due to coupling the motor with the generator. These losses were also found out experimentally.

3) The rated power of the motor is only 175 W . It is not that easy to handle such a small machine with accurate measurements of different experimental readings. Because, a slight variation or inaccuracy of any meter reading affects the overall result considerably. The motor parameters are determined using no load test and blocked rotor test. DC resistances are also measured using multimeter. There were some difference between the results obtained by two methods.

4) In the experiment with SPWM inverter-fed motor, total rms value of voltage was measured as there were no processes available to measure rms value of fundamental voltage. Hence the output power was found low compared to

theoretical value. The slip for maximum efficiency so found was also large for the same reason.

CHAPTER 4

CONCLUSIONS

4.1 CONCLUSIONS

From the theoretical and practical results presented in the previous two chapters following conclusions can be made :

1) A good agreement between the experimentally determined results and the results obtained from the theoretical model suggests that the developed mathematical model for determining the frequency for maximum efficiency of an SPWM inverter-fed induction motor under variable load conditions is accurate enough.

2) Efficiency improvement of induction motor under variable load operation would be possible by controlling voltage and frequency of the motor simultaneously using SPWM inverter supply.

3) Operation at maximum efficiency can always be maintained by operating the motor from variable frequency source.

4) The slip corresponding to maximum efficiency is constant at variable frequencies for any output power.

5) The maximum efficiency of an induction motor for any load condition is almost constant but it occurs at different supply frequency.

6) The assumption of negligible stray load loss and core loss due to harmonics is justified.

In the present thesis a technique is investigated for the control of an induction motor under variable load operation with a view to maximize its efficiency at all loads. SPWM inverter is used and constant voltage/frequency ratio is maintained at all frequencies. For a particular load a frequency can be determined for which the efficiency is maximum. It is seen from the theoretical and the experimental data that the maximum efficiency is almost constant for any load and slip is almost constant if the motor is operated at the optimum frequency. For the particular induction motor used in this thesis the efficiency is 75% at all optimum operating points. On the other hand if the motor is operated with conventional supply voltage and frequency the efficiency would be maximum near rated load. At other loads the efficiency would fall drastically. This results in increased power loss and the total expense of using the motor will be largely increased. In the proposed method the efficiency of the motor will be high and the expense of using the motor will be less. However, to ensure high efficiency the harmonic losses in the motor must be made low. The Sine Pulse Width Modulation ensures low harmonic losses as the modulated voltage is almost sinusoidal. To determine the optimum operating conditions for maximum efficiency the machine parameters must be determined accurately. This technique of controlling induction motor under variable load for maximum efficiency is suitable for large horsepower motors, because approximate equivalent circuit for such motors can be used suitably with vary little distortion in the results and the developed model also uses approximate equivalent circuit for simplified analysis. As this type of control ensures high efficiency it is recommended in opposition to the conventional system.

4.2 RECOMMENDATION FOR FUTURE WORKS

In this thesis the theory of operation of an induction motor from variable frequency source for maximizing its efficiency under variable load conditions is described. Here it is shown that how the supply frequency should be varied with variation in output power for achieving maximum efficiency. However, no attention is paid in the present scope of work about designing the control circuitry which could sense the output power and set the input frequency accordingly for optimum performance of the motor. In future a closed loop control system of induction motor under variable load may be designed. This design will sense output power and produce corresponding frequency and voltage signal for maximum efficiency operation. This signals will be fed externally to the SPWM Inverter logic to ensure optimum performance of the induction motor.

In the proposed technique of controlling induction motor using SPWM voltage of variable frequency, losses due to harmonics are introduced for obvious reasons. These losses may become significant and create problem if proper attention is not given for reducing the harmonic contents. Researchers all over the world are trying to find improved techniques to reduce losses due to harmonics and switching. Future research work may include development of a modulation technique for driving induction motor with variable frequency in order to attain most efficient performance of it under variable load.

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APPENDIX-I

MACHINE PARAMETERS

INDUCTION MOTOR DATA
(wound rotor)

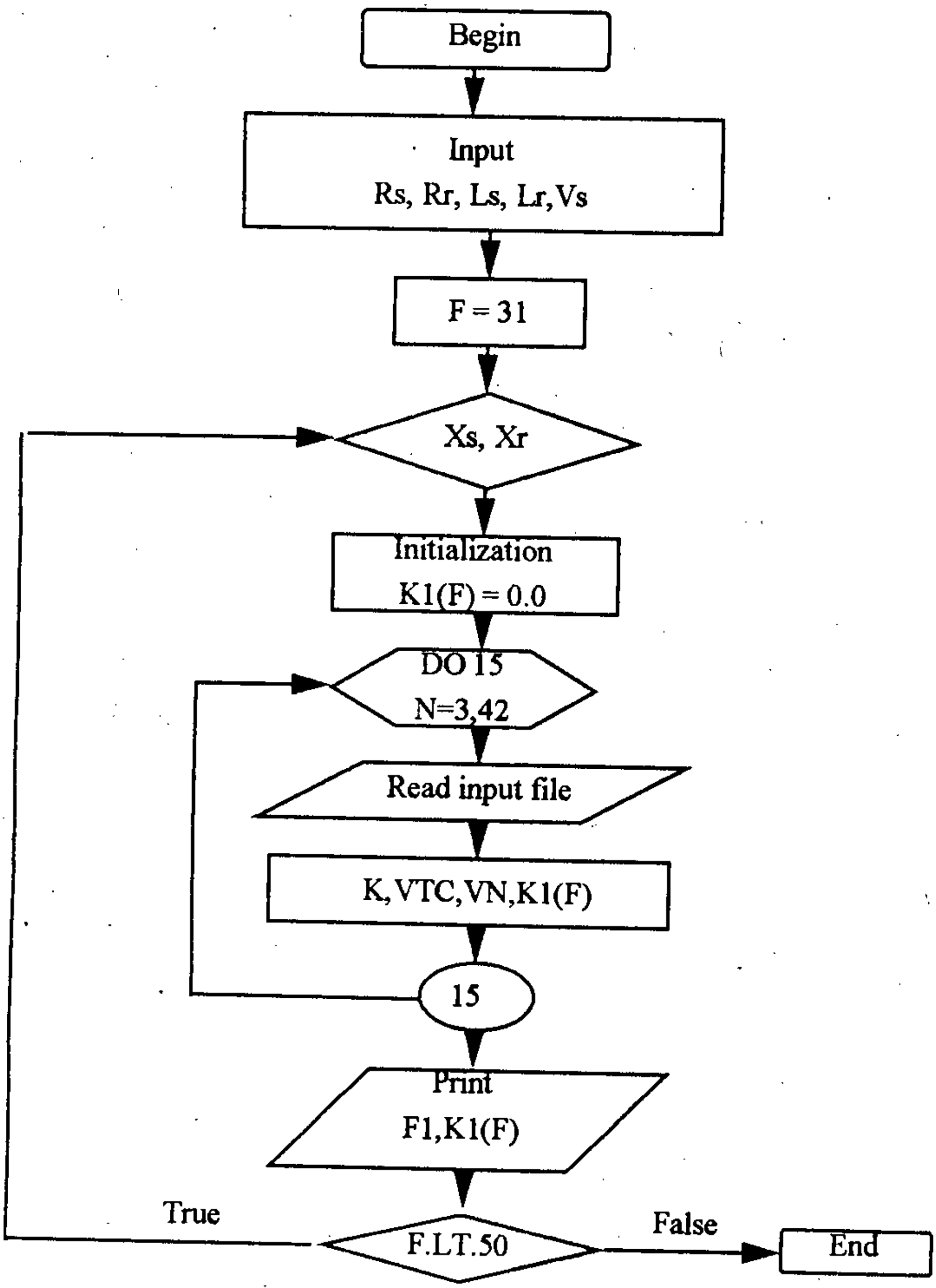
Rated voltage = 380 $V_{L\text{-}L}$
Rated current = 0.50 A
Rated power = 175 watt
rated frequency = 3 ~ -50 Hz

R_s = 41.2 Ω
R_r = 76.4 Ω
R_M = 7663 Ω
L_s = L_R = 0.13711 h
L_M = 1.8433 h

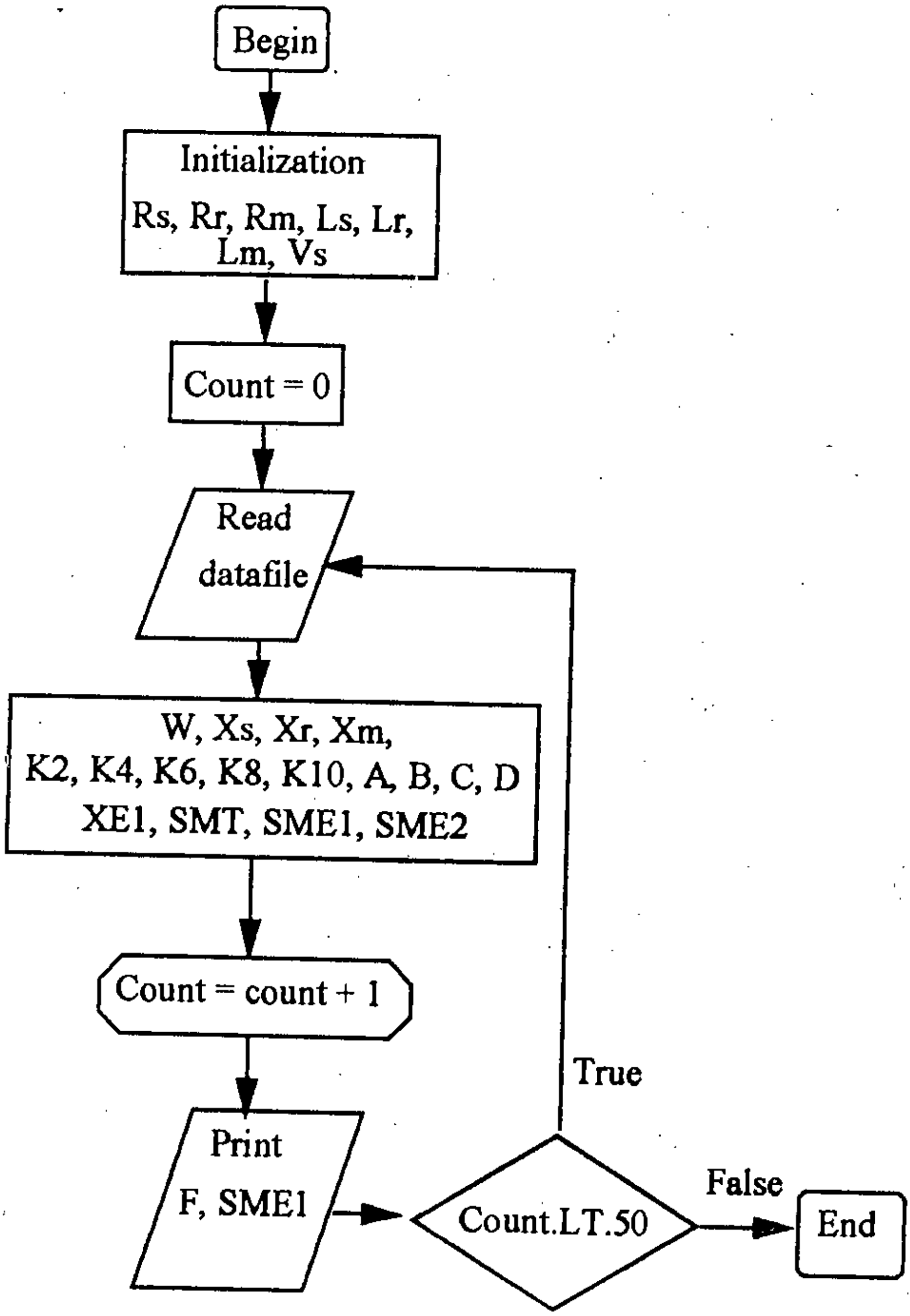
APPENDIX-II

FLOWCHARTS OF MAIN PROGRAM

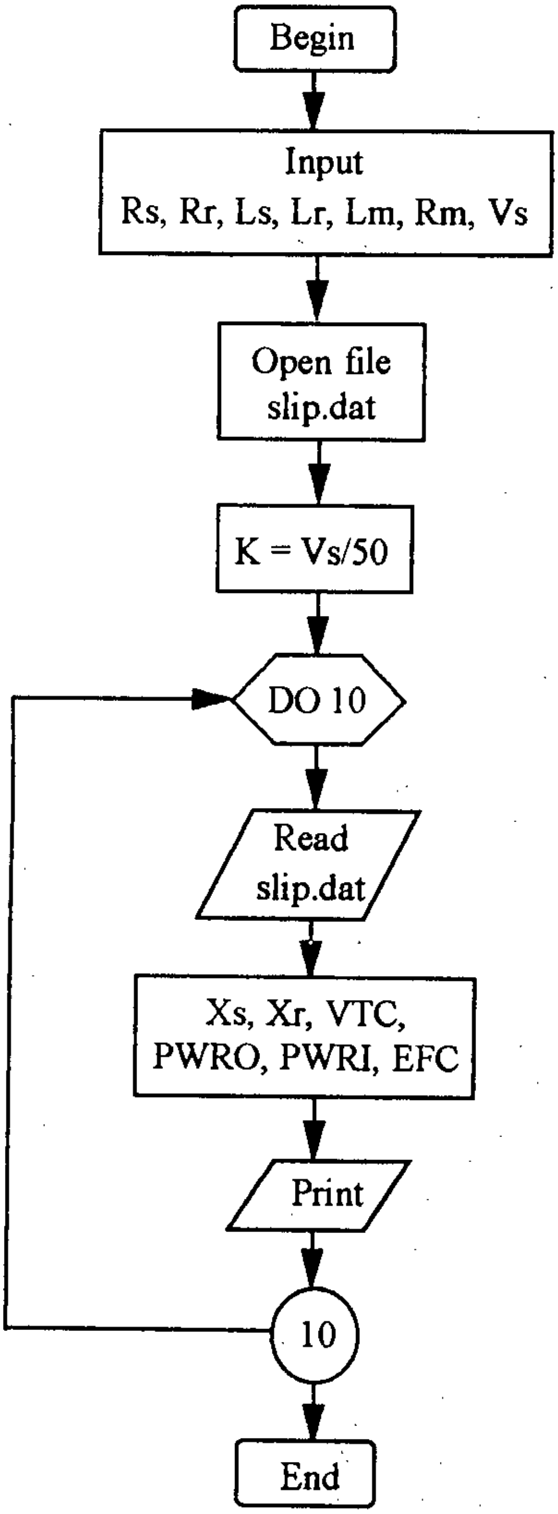
a) Flowchart of program K1.for for finding harmonic losses



b) Flowchart of program slip.for for finding slip corresponding to maximum efficiency



c) Flowchart of program pwro.for for finding output power at maximum efficiency



APPENDIX-III

ALTERNATIVE APPROACH OF FINDING EFFICIENCY AND FREQUENCY AT WHICH EFFICIENCY IS MAXIMUM

From expression (2.2.7) of chapter three the output power of an induction motor can be expressed as,

$$P_{out} = \frac{3V_S{}^2 R_r (1-s)/s}{\left[(R_S + R_r/s)^2 + (X_S + X_r)^2\right]}$$

$$\text{or, } P_{out} = \frac{3V_S{}^2 R_r (1-s)/s}{\left[(R_S + R_r/s)^2 + \{2\pi f(L_S + L_r)\}^2\right]}$$

$$\text{or, } P_{out} = \frac{3V_S{}^2 R_S (s - s^2)}{(R_S s + R_r)^2 + s^2 K_1{}^2 f^2}$$

.where, $K_1 = 2\pi\,(L_S + L_T)$

or, $P_{out}\,[R_S{}^2 s^2 + 2R_S R_r\, s + R_r{}^2 + s^2 K_1{}^2 f^2] = 3V_S{}^2 R_r (s - s^2)$

or, $P_{out}\,(R_S{}^2 + K_1{}^2 f^2)\, s^2 - (3V_s{}^2 R_r - 2R_S R_r P_{out})\, s + R_r{}^2 P_{out} + 3V_S{}^2 R_r\, s^2 = 0$

Let, $V_S / f = V_{rated} / f_{rated} = K_2$

so, $V_S = K_2 f$

or, $[P_{out}\,(R_S{}^2 + K_1{}^2 f^2) + 3K_2{}^2 f^2 R_r\,]\, s^2 - (3K_2{}^2 f^2 R_r - 2R_S R_r P_{out}\,)\, s - R_r{}^2 P_{out} = 0$

or, $As^2 - B\,s + C = 0$ (1)

where,

$A = P_{out}\,(R_S{}^2 + K_1{}^2 f^2\,) + 3K_2{}^2 f^2 R_r$ (2)

$B = 3K_2{}^2 f^2 R_r - 2R_S R_r P_{out}$ (3)

$C = R_r{}^2\, P_{out}$ (4)

$$K_1 = 2\pi\,(L_1 + L_2) \quad (5)$$

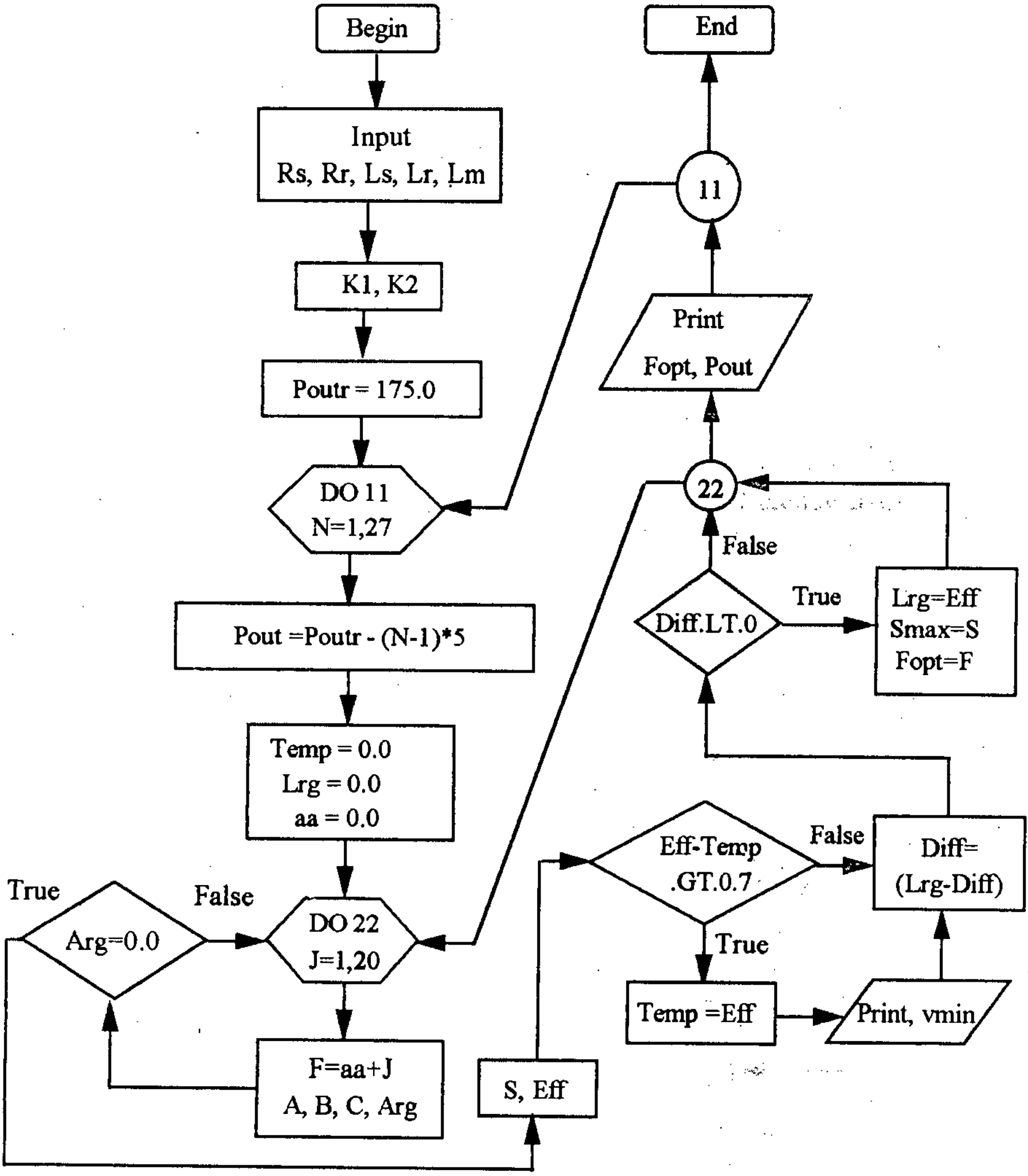
$$K_2 = V_{rated}/f_{rated} \quad (6)$$

$$\text{or, } s = \frac{B \pm \sqrt{B^2 - 4AC}}{2A} \quad (7)$$

$$\text{or, } \eta = \frac{-s^2 R_r R_m + s R_r R_m}{s^2\left[R_m R_S + R_S^2 + (X_S + X_r)^2\right] + s\left[R_m R_r + 2R_S R_r\right] + R_r^2} \quad (8)$$

From equation (7) we get slip corresponding to a particular load and frequency. Putting this value of slip in equation (8) we get the corresponding efficiency. Similarly for different frequencies we get other efficiencies. From these data maximum efficiency can be determined. A program is developed for this purpose the flowchart of which is given in the following page.

Flow chart of program alt.for for finding frequency,slip and output power corresponding to maximum efficiency using alternative technique



APPENDIX-IV

GRAPH REPRESENTING TRANSFORMER LOSSES

TRANSFORMER TEST DATA

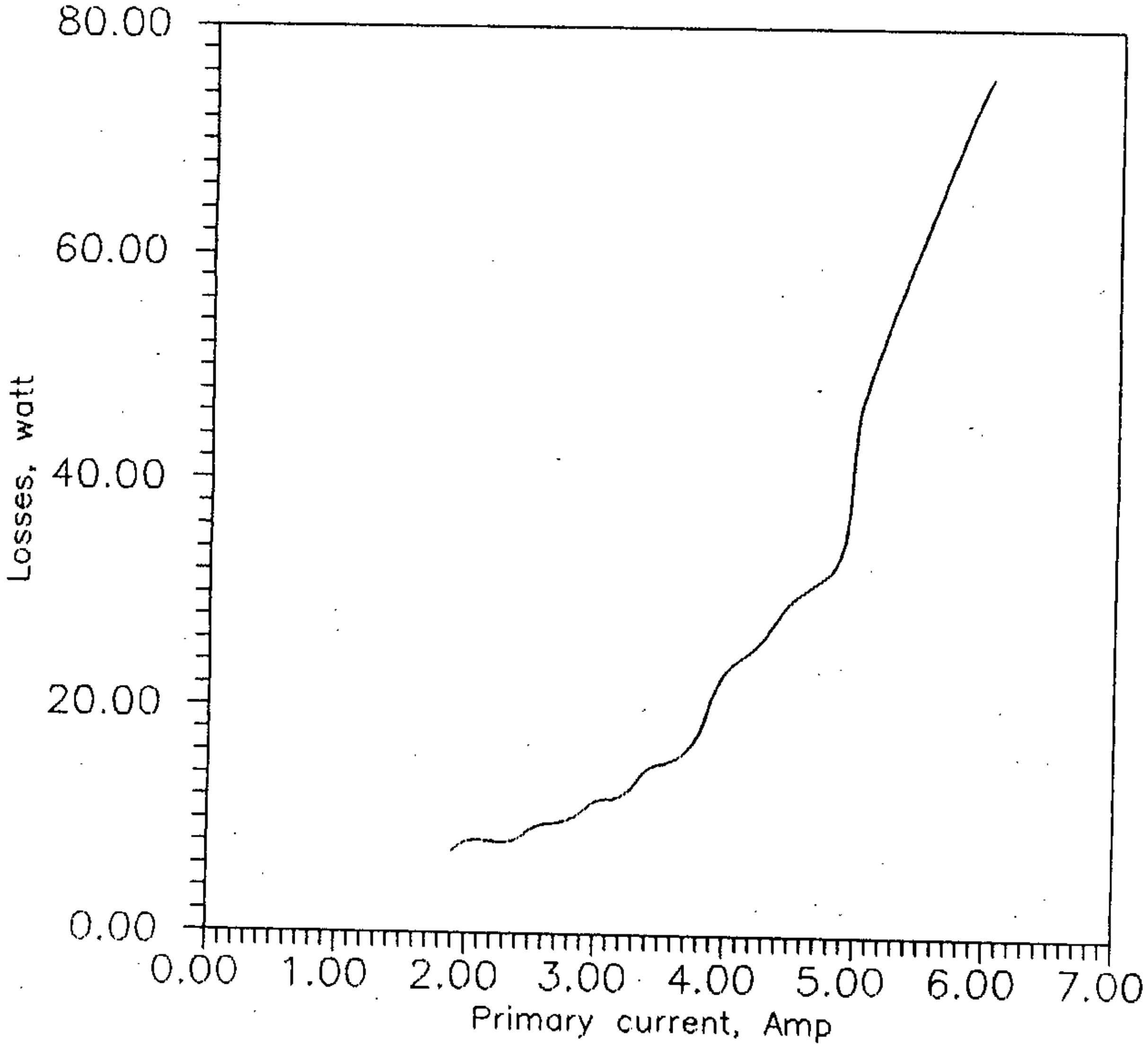


Figure : Transformer losses vs. current

APPENDIX-V

EXPERIMENTALLY OBTAINED DATA AT RATED VOLTAGE AND FREQUENCY

A) For SPWM inverter-fed induction motor

I_i amp	P_{Out} watt	P_{dc} watt	P_{loss} watt	P_{in} watt	η	s
7.55	63.33	184.97	66.0	118.97	53.22	0.110
8.00	66.78	192.00	75.0	117.00	57.07	0.129
8.15	75.91	199.675	78.0	121.67	62.38	0.136
8.60	76.54	215.00	87.0	128.00	59.80	0.142
10.00	93.8	250.00	120.0	130.00	72.15	0.170
10.50	102.28	273.00	132.0	141.00	72.53	0.178
11.00	109.58	297.00	145.5	151.50	72.33	0.184
11.50	112.68	316.25	158.0	158.25	71.2	0.198

B) For sinusoidal voltage-fed inverter

T nm	N rpm	P_{in} watt	P_{out} watt	η	s
0.1	1465	61.8	15.34	24.82	0.020
0.2	1452	78.6	30.41	38.69	0.032
0.3	1440	94.2	45.23	48.02	0.040
0.4	1426	112.2	59.73	53.23	0.049
0.5	1412	129.0	73.93	57.31	0.058
0.6	1398	145.5	87.84	60.37	0.068
0.7	1382	164.7	101.31	61.50	0.078
0.8	1366	181.8	114.44	62.94	0.089
0.9	1348	199.5	127.04	65.32	0.100
1.0	1330	217.5	134.28	64.03	0.113
1.1	1312	235.5	151.13	64.17	0.125
1.2	1294	255.3	162.61	63.69	0.137
1.3	1274	273.6	173.44	63.36	0.151

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