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POWER FACTOR CORRECTION OF INDUCTION MACHINE USING PWM INVERTER FED AUXILIARY STATOR WINDING

by

Indraman Tamrakar

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled, "Power Factor Correction Of Induction Machine Using PWM Inverter Fed Auxiliary Stator Winding" submitted by Indraman Tamrakar in partial fulfillment of the requirements for the degree of Master of Science.

Dr. O.P. Malik - Chairman
Department of Electrical and Computer Engineering

Prof. G.J. Berg
Department of Electrical and Computer Engineering

Dr. R.A. Heidemann
Department of Chemical and Petroleum Engineering

Date : 1992.04.20

ABSTRACT

This thesis deals with a scheme for power factor correction of an induction machine by using an auxiliary stator winding in conjuction with a PWM voltage inverter and a capacitor on the dc side of the inverter. The aim of this scheme is to use PWM technique as means to reduce the reactive components such as capacitor and filter circuits.

The basic principle of power factor correction has been elaborated by describing various methods of power factor correction for an induction motor.

The operating principle of the proposed scheme is explained with the help of an equivalent circuit and phasor diagram. Mathematical models are developed to simulate the proposed scheme. Mathematical analysis shows that the scheme does not give the best performance if the power factor is corrected to unity. A criterion has been developed to select the optimum value of power factor at which the scheme gives best performance. Fourier analysis of the PWM inverter output voltage waveform is performed and the effect of the harmonics on the performance of the scheme is investigated. The simulation and experimental results show that harmonic components in the PWM output voltage can be reduced by operating the PWM inverter with a higher frequency ratio and the distortion factor in the main input current can be reduced to get a nearly sinusoidal current waveform.

The proposed scheme is an alternative to the fixed capacitor thyristor controlled reactor scheme. The proposed scheme requires only a low cost dc capacitor rather than three units of ac capacitors and does not need any filter circuit. Hence the proposed scheme could be an economical scheme.

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To my parents

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LIST OF SYMBOLS

PWM	Pulse Width Modulation
FR	Frequency Ratio
MI	Modulation Index
TCR	Thyristor Controlled Reactor
I	Current
V,E	Voltage
P	Active power
Q	Reactive power
R	Resistance
X	Reactance
Z	Impedance
C	Capacitor
L	Inductor
f	Frequency
ω	Angular velocity in rad per sec
t	Time in second
ph,ϕ,θ,β,γ	Phase angle
α	Firing angle of thyristor
s	Slip of induction motor in p.u.
d.f.	Distortion factor

K_v	Ripple factor in dc voltage
p.f.	Power factor
CT	Current transformer
PT	Potential transformer
$(.)_{s1}$	Variable refered to main stator winding
$(.)_{s2}$	Variable refered to auxiliary stator winding
$(.)_c$, $(.)_{cap}$	Variables refered to capacitor
$(.)_L$, $(.)_{ind}$	Variables refered to inductor
$(.)_{f.l.}$	Variable refered to full load
$(.)_{n.l.}$	Variable refered to no-load

CHAPTER 1

INTRODUCTION

Induction machines contribute one of the major inductive loads in a power system. An induction motor normally draws a lagging current with a fairly low power factor. Poor power factor adversely affects the economics of the transmission and distribution system and a cost penalty is levied for excessive reactive power consumption.

Various methods to improve the power factor of induction motors are available. The simplest method is to install shunt capacitors across each phase of the stator windings. This method cannot fulfil the requirement of large induction machines with varying load. The availability of solid state switches has provided new directions in the area of reactive power compensation. Solid state reactive power compensators are becoming more popular because of their advantages over the conventional methods [1].

Several PWM techniques for voltage inverter have been investigated in the literature [2-5] to reduce harmonics, thereby minimizing harmonic losses. Use of a solid state Var compensator with a PWM inverter to compensate for reactive power at a utility load bus, has been explained in the literature [6][7], and the PWM technique has been used as a means of reducing the size of reactive components. The basic principle involved in the above PWM technique has been used to develop a scheme for power factor correction of an induction machine. This thesis deals with a detailed study of this new scheme for power factor correction of an induction machine. The scheme is particularly suitable for large induction machines with varying load.

1.1 OBJECTIVES OF THE THESIS

The objective of this thesis is to perform a detailed study of a new scheme for power factor correction of induction machines by employing a PWM voltage inverter. The detailed study includes an investigation of the operating principle of the scheme, development of a mathematical model of the proposed scheme, steady state analysis of the scheme in the presence of harmonics in the inverter output voltage, simulation of the scheme, experimental study to justify the simulation results.

1.2 THESIS OUTLINE

Various methods for power factor correction of an induction motor and limitations of each method are examined in Chapter 2. Mathematical equations for calculating the rating of various components used in each method are presented.

In Chapter 3 the proposed scheme for power factor correction of induction machines is described. The operating principle of the proposed scheme is explained and a mathematical model of the scheme is developed. A criterion is developed to determine the optimum value of the power factor at which the scheme gives the best performance. Mathematical analysis of a PWM inverter to calculate harmonics in the inverter output voltage is presented and circuit models are developed to study steady state performance of the scheme in the presence of these harmonics. A control system for the scheme is also investigated.

Chapter 4 describes the simulation studies of the proposed scheme. The mathematical models devceloped in Chapter 3 are used to simulate the proposed scheme. Simulation results are described for light load and full load conditions at different frequency ratios (FR) for the PWM inverter.

Experimental studies with the proposed scheme are described in Chapter 5. Experimental studies are performed in two stages. In the first stage, the basic principle of power factor correction involved in the proposed scheme is tested experimentally by replacing the PWM voltage inverter by a sinusoidal ac voltage source. In the next stage, experiments are conducted for light load with PWM inverter operated at different frequency ratios. The experimental results are described and compared with the simulation results.

In Chapter 6 the proposed scheme is compared with the fixed capacitor thyristor controlled reactor scheme. Application of the proposed scheme in an induction generator action is briefly disscused. A general review of the conclusions based on the studies presented in various Chapters is given in this Chapter. Some recommendations for further research are also outlined.

CHAPTER 2

POWER FACTOR CORRECTION OF AN INDUCTION MOTOR

In this chapter, various methods reported in the literature for power factor correction of an induction motor are described in brief and the limitations of each method are examined.

2.1 SINGLE CAPACITOR METHOD

The simplest method to improve the power factor of an induction motor is to install externally a capacitor of appropriate size in parallel with each phase of the stator winding. The basic configuration of this method is shown in Fig.2.1.

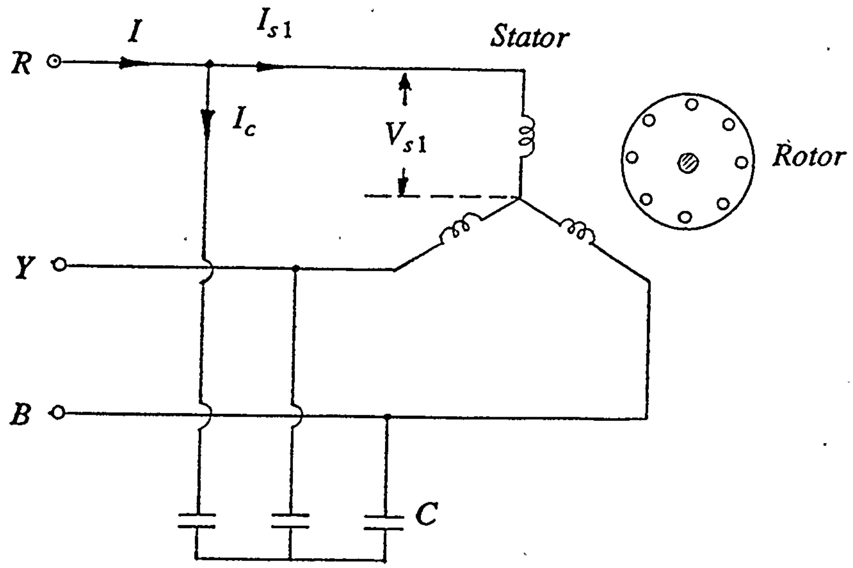
An induction motor normally draws a lagging current, I_{s1}, with a power factor, $\cos\phi$, which is fairly low. In order to improve the power factor, say to unity, the reactive component of I_{s1} (i.e. $I_{s1}\sin\phi$) has to be cancelled by some means. This is done by connecting a capacitor in parallel with each phase of the stator winding. The capacitor draws a leading current I_c so that it cancels the reactive component $I_{s1}\sin\phi$ and the main input current I is in phase with the supply voltage V_{s1} resulting in a unity power factor.

Rating of the required capacitor is

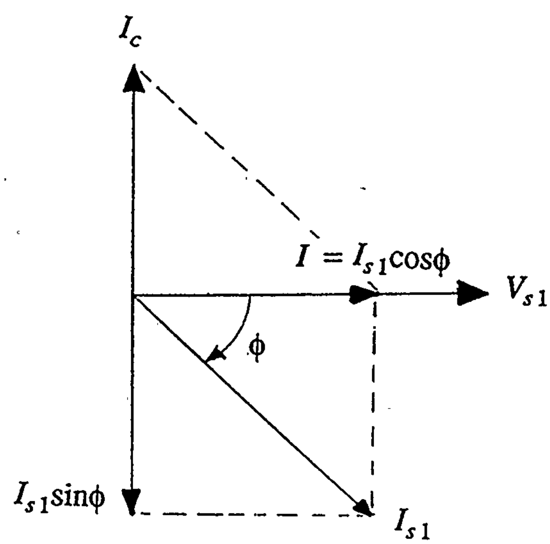
$$C = \frac{I_{s1}\sin\phi}{2\pi f V_{s1}} * 10^6 \ \ \mu F \qquad (2.1)$$

kVAr rating of the capacitor is

$$Q_{cap} = V_{s1} I_{s1} \sin\phi * 10^{-3} \quad kVAr \tag{2.2}$$



(a) Circuit diagram.



(b) Phasor diagram.

Fig.2.1 Single capacitor method for power factor improvement.

This method is useful only for small machines which generally operate at a fairly constant load. If the capacity of the machine is large and the machine operates at different values of load, the magnitude and phase of I_{s1} will change and the rating of the capacitor has to be changed accordingly to maintain the desired power factor. This can be done by building up the required capacity from banks of capacitors connected in parallel and, connecting and disconnecting the capacitors in parallel with the help of some switch. In earlier times, mechanical switchgear was used to connect and disconnect the capacitor banks. Now-a-days thyristors are used for this purpose as they have many advantages over the mechanical switchgear such as ease of maintenance,fast operation,automatic operation [1].

2.2 DISCRETE SWITCHING OF CAPACITORS

In this method, appropriately dimensioned capacitor banks are switched in and out in parallel with the stator winding with the help of static electronic switches. The electronic switch comprises of a pair of antiparallel connected thyristors. The basic arrangement of this method is shown in Fig.2.2 . The number of capacitor banks required is determined by the maximum allowed step change of reactive current. The input power factor can be sensed by some device and compared with the desired power factor. The error signal thus obtained can be used to operate the controller which switches in or out the capacitor to produce the required capacitance in the circuit. Inductance of an appropriate value is connected in series with each capacitor in order to limit the current in the thyristor due to possible potential difference between the line and the capacitor at the switching instant [1].

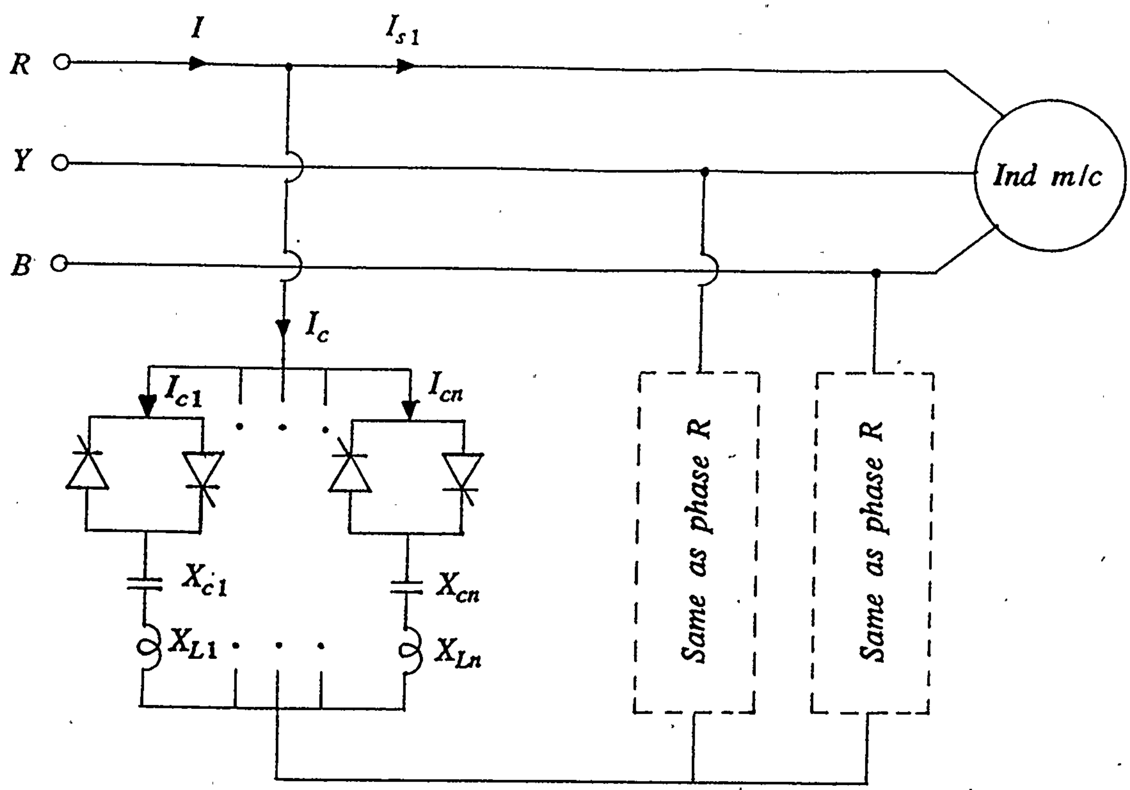


Fig.2.2 Discrete switching of capacitors

Total capacitance required at full load is given by

$$C = \frac{10^6}{2\pi f X_c} \quad \mu F \tag{2.3}$$

where

$$X_c = X_L + \frac{V_{s1}}{I_{s1}\sin\phi} \tag{2.4}$$

$$\frac{1}{X_L} = \frac{1}{X_{L1}} + \frac{1}{X_{L2}} + \dots\dots\dots + \frac{1}{X_{Ln}} \tag{2.5}$$

Capacitance of each capacitor is given by

$$C_1 = C_2 = \dots\dots\dots\dots = C_n = \frac{C}{n} \tag{2.6}$$

where, n = number of capacitor banks.

kVAr rating of each capacitor is

$$Q_{c1} = \frac{V_{s1} I_{s1} \sin\phi}{n} \tag{2.7}$$

This method is quite simple but it has the following disadvantages:

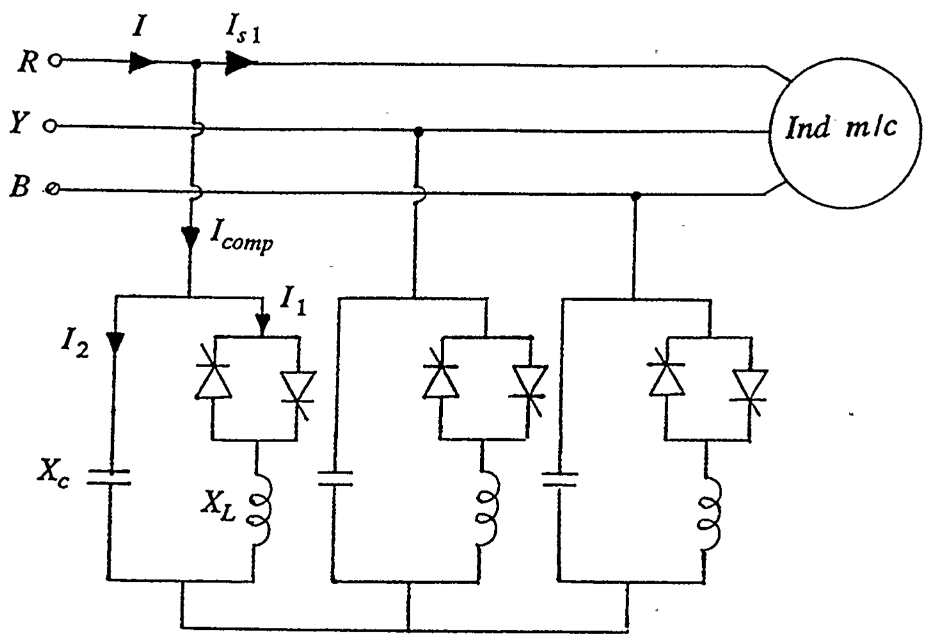
1) Compensation is not continuous.

2) Each capacitor bank requires separate thyristor switch pair.

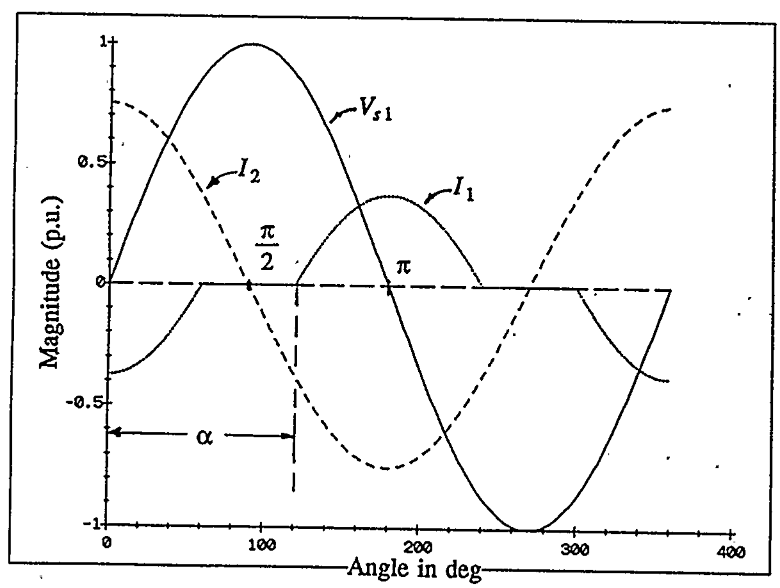
3) For smaller step control, larger number of capacitor banks and thyrister switch pairs are required.

2.3 FIXED CAPACITOR THYRISTOR CONTROLLED INDUCTOR SCHEME

The problems associated with discrete switching of capacitors have been greatly overcome by the use of solid state reactive power compensators such as the thyristor controlled reactor. The basic arrangement of a fixed capacitor thyristor controlled inductor scheme is shown in Fig.2.3(a). It consists of a fixed capacitor in parallel with a thyristor controlled inductor. With this arrangement a variable reactance ranging from purely capacitive to inductive can be realized by controlling the current flow through the inductor. The waveforms of currents I_1 and I_2 in relation to the waveform of supply voltage V_{s1} are shown in Fig.2.3(b). The firing angle α can be controlled from $\pi/2$ to π radians by thyristor switch pair. The magnitude and phase of the total compensator current I_{comp} is determined by phasor sum of I_1 and I_2.



(a) Basic circuit.



(b) Waveforms.

Fig.2.3 Fixed capacitor thyristor controlled inductor scheme.

At $\alpha = \pi$, the thyristor switch pair is open. Hence the total current $I_{comp} = I_2$ which is a pure sinusoid.

At $\alpha = \pi/2$, the thyristor switch pair is in full conduction. Hence the current I_1 is a pure sinusoid and the phasor sum of I_1 and I_2 (i.e. I_{comp}) is also purely sinusoidal.

Between these two extreme values of α, the current I_1 is not a pure sinusoid. It contains the fundamental as well as some harmonics. Fourier analysis of such a current waveform gives the following expressions for fundamental and harmonic components [8][9].

$$I_1(1) = [I_{\max}]\ \frac{1}{\pi}\ [2(\pi - \alpha) - sin\,2(\pi - \alpha)] \tag{2.8}$$

$$I_1(m) = [I_{\max}]\ [\frac{2}{m\pi}]\ [\frac{sin\,(m-1)(\pi-\alpha)}{(m-1)} - \frac{sin\,(m+1)(\pi-\alpha)}{(m+1)}] \tag{2.9}$$

where,

m = 2k + 1 , k = 1, 2, 3, ...etc.

$I_{\max} = V_{s1max} / 2\pi fL$.

$I_1(1)$ = Magnitude of the fundamental current component.

$I_1(m)$ = Magnitude of the odd harmonic current components.

f = Fundamental supply frequency (Hz).

L = Inductance of the inductor.

The main idea is to select X_c to give the desired power factor at full load and to operate the compensator at $\alpha = \pi$. Operation at full load and unity power factor with $\alpha = \pi$ is illustrated in Fig.2.4(a). At lower loads, firing angle α has to be selected in the range of $\pi/2 < \alpha < \pi$ to produce the desired power factor.

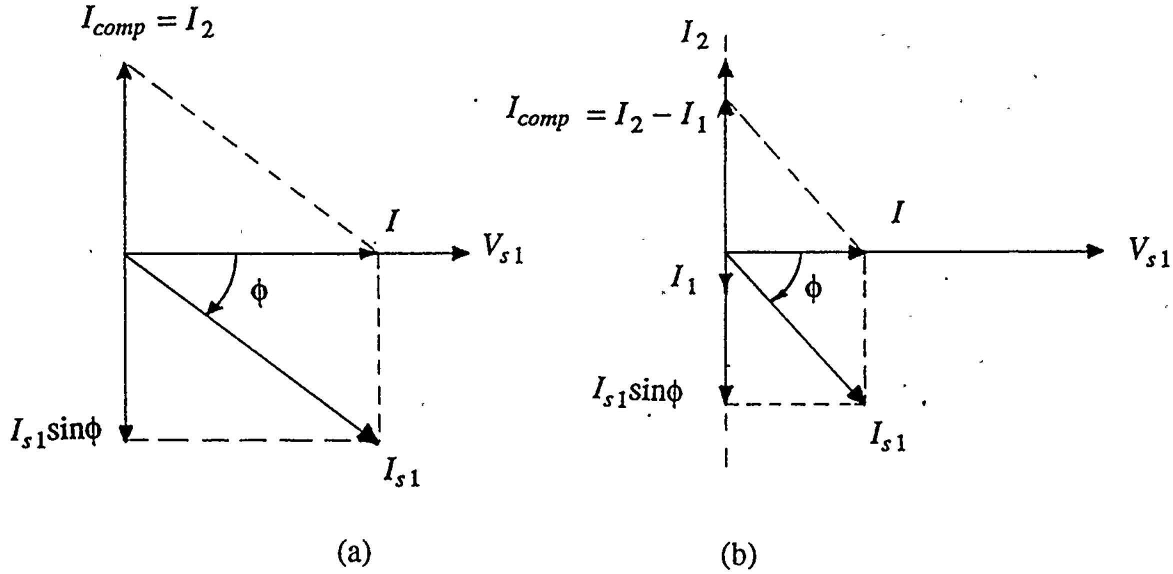
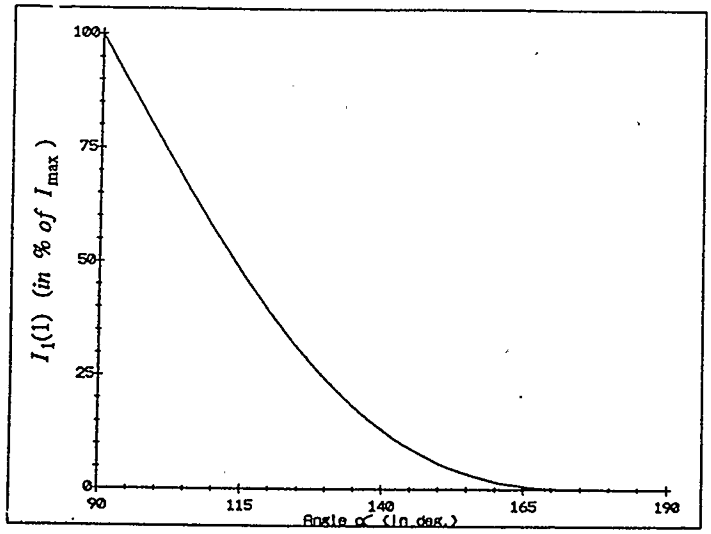
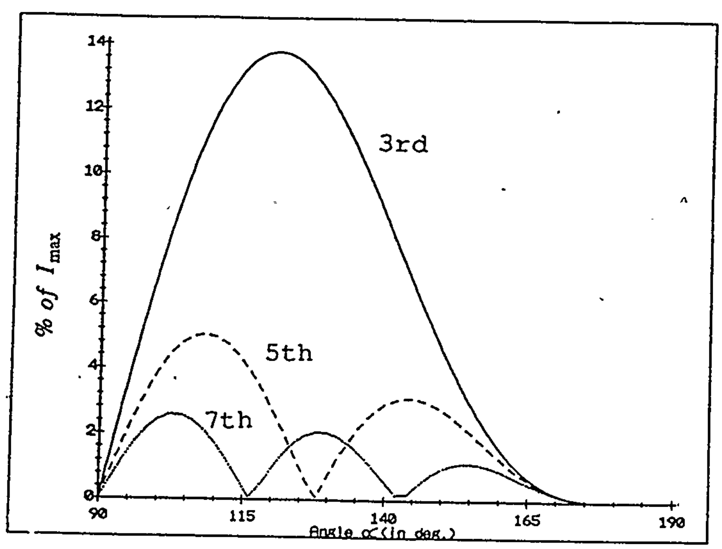


Fig.2.4 Phasor diagram (a) for $\alpha = \pi$ (b) for $\pi/2 < \alpha < \pi$.

Operation at less than full load and unity power factor with $\pi/2 < \alpha < \pi$ is illustrated in Fig.2.4(b). With this method, continuous variation of reactance can be realized by changing the firing angle α. However, this compensator generates harmonic currents due to switching of the thyristor switch pair. The fundamental and harmonic components of current through the inductor as a function of firing angle α are shown in Fig.2.5. The presence of harmonics requires that some filter shall be provided to reduce the harmonic components of the current. Hence an actual compensator with filter looks like that shown in Fig.2.6 [8][9].



(a) Fundamental component Vs α



(b) Harmonic components Vs α

Fig. 2.5 Magnitude of fundamental and harmonic components as a function of the firing angle.

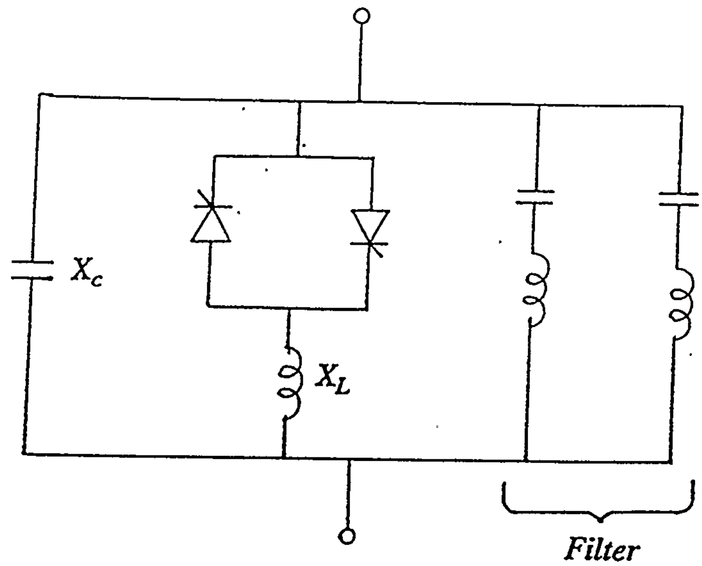


Fig.2.6 Fixed capacitor thyristor controled inductor with filter.

The rating of the required capacitor is

$$C = \frac{10^6}{2\pi f X_c} \quad \mu F \tag{2.10}$$

where,

$$X_c = \frac{V_{s1}}{(I_{s1}\sin\phi)f.l.} \tag{2.11}$$

The kVAr rating of the required capacitor is

$$Q_{cap} = V_{s1}(I_{s1}\sin\phi)f.l. \ * \ 10^{-3} \ kVAr \ per \ phase \tag{2.12}$$

The net leading compensator current required at no-load is

$$I_{comp}(n.l.) = I_{s1}\sin\phi_{s1}(n.l.) \tag{2.13}$$

Current through the inductor at no-load is

$$I_1(n.l.) = I_{s1}\sin\phi_{s1}(f.l.) - I_{comp}(n.l.) \tag{2.14}$$

then,

$$X_L\ (required) = \frac{V_{s1}}{I_1(n.l.)} \tag{2.15}$$

and,

$$L = \frac{X_L}{2\pi f}\ H \tag{2.16}$$

Current rating of the inductor is

$$I_{ind} = I_1(n.l.)\quad A \tag{2.17}$$

SUMMARY

Basic principles of power factor correction have been discussed. Three methods of power factor correction proposed in the literature have been described briefly and equations to calculate the rating of different components have been presented. It provides a basis for comparing the various methods with the proposed method discussed in the next Chapter.

CHAPTER 3

PROPOSED METHOD FOR POWER FACTOR CORRECTION

In this Chapter, the proposed method for power factor correction of an induction motor is described. In this method, an additional set of stator windings is used in conjuction with a Pulse Width Modulated (PWM) voltage inverter. Equivalent circuit model of the scheme is developed and a detailed mathematical analysis of the scheme is presented so that it can be simulate. Simulation results for the scheme are presented in Chapter 4. A tentative control strategy for the scheme is also described.

3.1 THE PROPOSED SCHEME

The proposed scheme employs an induction machine having two sets of stator windings. These two sets of stator windings are wound in the same slots but are electrically isolated from each other. One set (the main winding) is connected to the utility supply, while the other set (the auxiliary winding) is supplied by a PWM voltage inverter as shown in Fig.3.1. The main idea is to control the magnitude and phase of the PWM inverter output voltage with respect to the main winding supply voltage so that the main winding will carry mainly the active power and the auxiliary winding will carry mainly the reactive power. Since the auxiliary winding carries mainly the reactive power, the dc voltage of the PWM voltage inverter can be supported by a dc capacitor and need not be connected to a power source [7]. The main attractions of this scheme are that the PWM inverter can be operated at higher chopping frequency to reduce volage harmonics and the machine inductance itself acts as the filter to reduce harmonics in the line current [10-12]. Hence it does not need any additional filter. Also, the inverter requires only a single low cost dc capacitor rather than three ac capacitors.

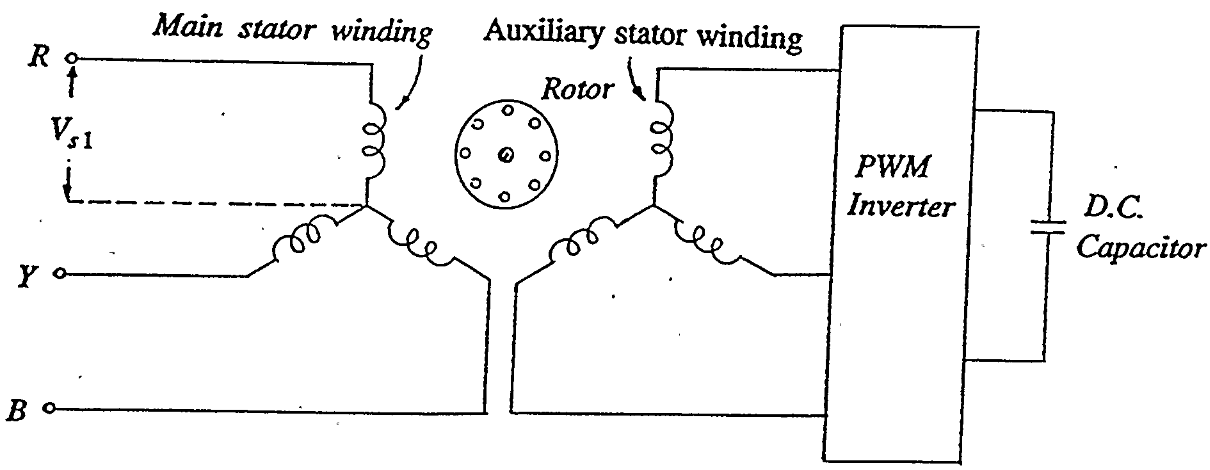


Fig 3.1 Schematic diagram of the proposed scheme.

3.2 EQUIVALENT CIRCUIT OF THE PROPOSED SCHEME

The per phase equivalent circuit of the scheme with the induction machine having a double stator winding can be realized as shown in Fig.3.2 based on the equivalent circuit of a three winding transformer [13][14]. The two sets of stator windings can be represented effectively by two branches, each having separate resistance and leakage reactance together with a common mutual leakage reactance X_{lm} which occurs due to the fact that the two sets of stator windings occupy the same slots and are therefore mutually coupled by a component of leakage flux (i.e. non airgap component of stator flux). The effect of the PWM voltage inverter is represented by an ac voltage source V_{s2}(m) in the equivalent circuit. Note that the voltage V_{s2}(m) will have fundamental as well as some harmonic components.

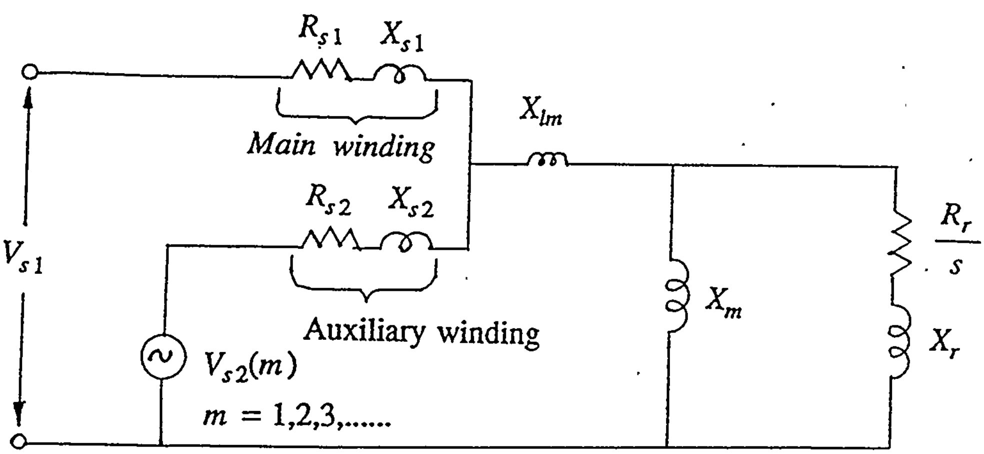


Fig 3.2 Equivalent circuit of the proposed scheme.

R_{s1} = Resistance of the main stator winding per phase.

X_{s1} = Leakage reactance of the main stator winding per phase.

R_{s2} = Resistance of the auxiliary stator winding per phase.

X_{s2} = Leakage reactance of the auxiliary stator winding per phase.

X_{lm} = Mutual reactance between the main and auxiliary windings.

X_m = Magnitizing reactance per phase.

R_r = Resistance of rotor winding per phase.

X_r = Rotor leakage reactance at standstill per phase.

s = Slip of the motor.

3.3 OPERATING PRINCIPLE

The operating principle of the proposed scheme can be explained with the help of a modified equivalent circuit shown in Fig.3.3 in which the PWM inverter has been replaced by a fictitious variable capacitor having reactance X_{c2}. It is possible to make the imaginary part of the total impedance as seen from the main terminals equal to zero at some particular value of X_{c2} and thus achieve unity power factor. This value of X_{c2} can be obtained by analyzing the equivalent circuit.

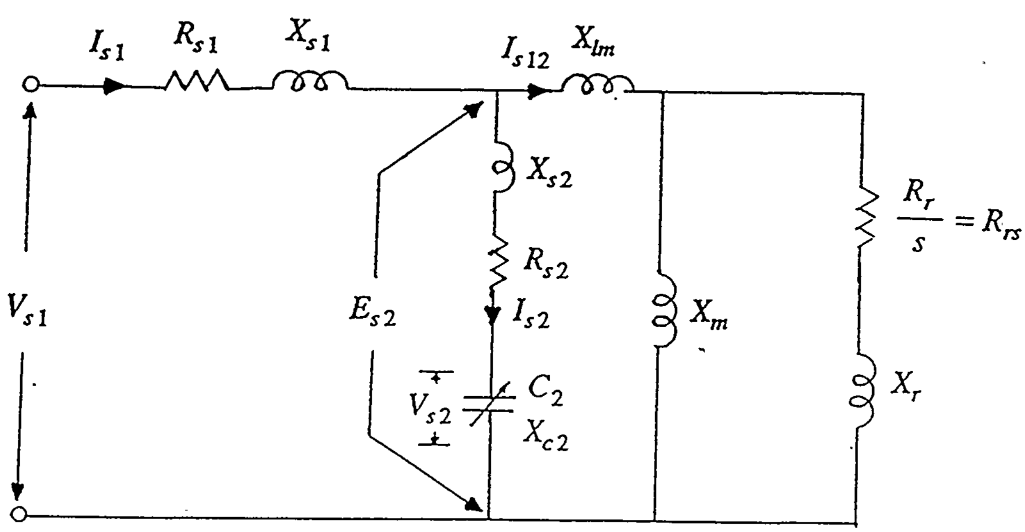


Fig. 3.3 Modified equivalent circuit of the proposed scheme.

The equivalent circuit shown in Fig.3.3 can be further simplified to that shown in Fig.3.4.

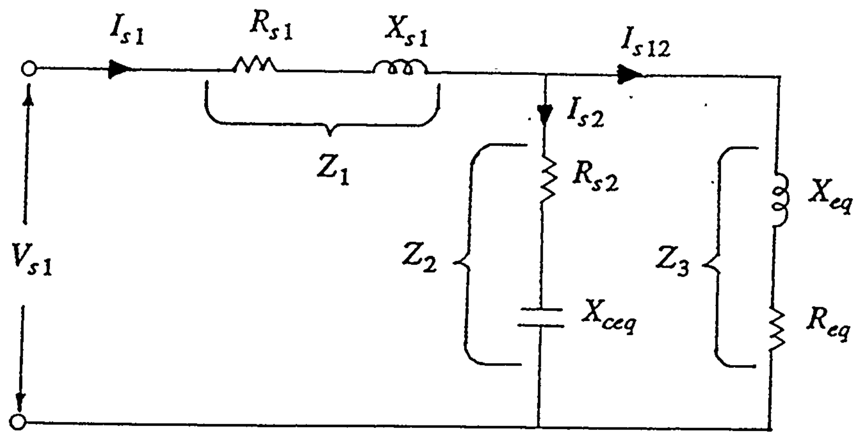


Fig. 3.4 Simplified equivalent circuit of the proposed scheme.

In this figure,

$$X_{ceq} = X_{c2} - X_{s2} \tag{3.1}$$

$$R_{eq} = \textit{Real part of } [\, jX_{lm} + (\frac{R_r}{s} + jX_r)//jX_m \,] \tag{3.2}$$

$$X_{eq} = \textit{Imaginary part of } [\, jX_{lm} + (\frac{R_r}{s} + jX_r)//jX_m \,] \tag{3.3}$$

Mathematical simplification gives :

$$R_{eq} = \frac{X_m R_{rs} (X_m + X_r) - X_m X_r R_{rs}}{R_{rs}^{\,2} + (X_m + X_r)^2} \tag{3.4}$$

$$X_{eq} = X_{lm} + \frac{X_m X_r (X_m + X_r) + X_m R_{rs}^2}{R_{rs}^2 + (X_m + X_r)^2} \tag{3.5}$$

The condition for unity power factor is

$$Imaginary\ part\ of\ [\ Z_1 + Z_2 // Z_3\ ] = 0 \tag{3.6}$$

Mathematical manipulation of eqn.(3.6) gives the condition of unity power factor as follows :

$$A (X_{ceq})^2 + B (X_{ceq}) + C = 0 \tag{3.7}$$

where,

$$A = X_{eq} + X_{s1}$$
$$B = R_{eq} (R_{s2} + R_{eq}) - R_{s2} R_{eq} + X_{eq}^2 + 2 X_{s1} X_{eq} \tag{3.8}$$
$$C = X_{s1} [(R_{s2} + R_{eq})^2 + X_{eq}^2] - X_{eq} [R_{s2} R_{eq} - R_{s2} (R_{s2} + R_{eq})]$$

hence,

$$X_{ceq} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{3.9}$$

provided,

$$B^2 - 4AC \geq 0$$

and

$$X_{c2} = X_{ceq} + X_{s2} \tag{3.10}$$

The above analysis shows that unity power factor can be obtained at two different values of X_{c2} for a particular value of slip. When the circuit is operated at one of these two values of X_{c2}, the fictitious capacitor C_2 will have some voltage V_{s2} across it with a phase angle θ with respect to the main supply voltage V_{s1}. If the

PWM voltage inverter can be controlled to produce the same output voltage V_{s2} with phase angle θ. Unity power factor can be obtained at the input terminals. Hence the effect of the PWM inverter can be represented by a variable capacitor C_2 in the equivalent circuit as shown in Fig.3.3.

A phasor diagram of the proposed scheme for unity power factor operation is shown in Fig.3.5. Phasor I_{s12} is the current drawn by the motor in the absence of the auxiliary stator winding. This current has a significant reactive component $I_{s12}\sin\phi$ with power factor $\cos\phi$, which is fairly low. The function of the PWM inverter is to produce a voltage V_{s2} with an appropriate phase angle θ so that the current through the auxiliary stator winding I_{s2} has a leading reactive component $I_{s2}\cos\theta$ which cancels the reactive component of I_{s2} (i.e.$I_{s2}\sin\phi$).

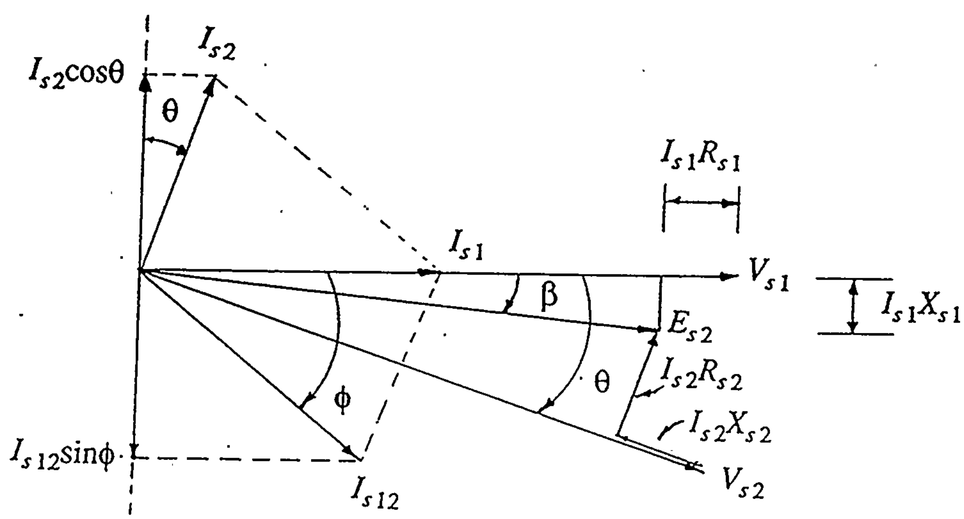


Fig.3.5 Phasor diagram for unity power factor operation.

Current through the auxiliary stator winding is

$$\vec{I}_{s2} = \frac{\vec{E}_{s2} - \vec{V}_{s2}}{R_{s2} + jX_{s2}} \tag{3.11}$$

or in terms of the fictitious capacitor's reactance

$$\vec{I}_{s2} = \frac{\vec{E}_{s2}}{R_{s2} + j\,(X_{s2} - X_{c2})} \tag{3.12}$$

where,

$$\vec{E}_{s2} = \vec{V}_{s1} - \vec{I}_{s1}\,(R_{s1} + jX_{s1}) \tag{3.13}$$

The reactance X_{c2} depends on the PWM output voltage V_{s2} and the current through the auxiliary winding I_{s2} and is given by:

$$X_{c2} = \frac{V_{s2}}{I_{s2}} \tag{3.14}$$

Here it is important to note that V_{s2} is the fundamental component of the PWM output voltage. In practice, the PWM inverter output voltage has a fundamental as well as harmonic components. The performance of the scheme under this condition will be discussed in section 3.7.

Variation of the imaginary component of the total impedance with X_{ceq} for different values of slip for a typical induction machine whose parameters are given in Appendix 'A' [15] is shown in Fig.3.6. It is clear from the figure that unity power factor can be obtained at different values of slip (load). For a particular value of slip, power factor becomes unity at two different values of X_{ceq}. The higher value of X_{ceq} corresponds to higher value of V_{s2} which results in a lower value of current through the auxiliary winding. On the other hand, the lower value of X_{ceq} corresponds to lower value of V_{s2} which results in higher current through the auxiliary winding. Hence PWM inverter should be controlled to obtain a higher value of X_{ceq} so that the power loss in the auxiliary winding can be kept small.

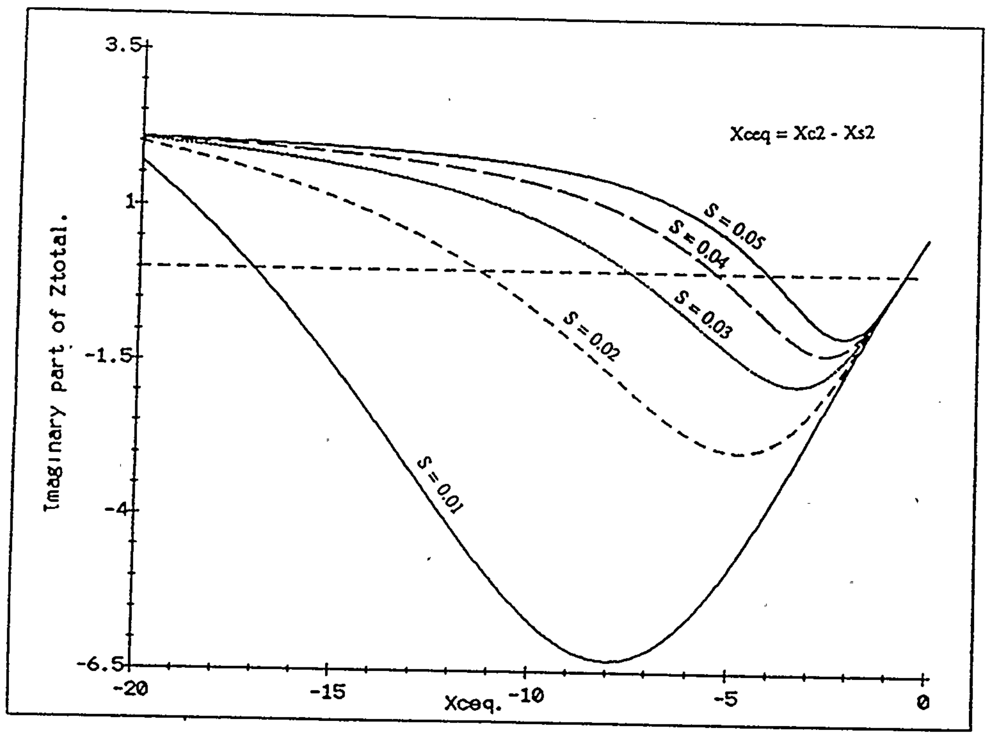


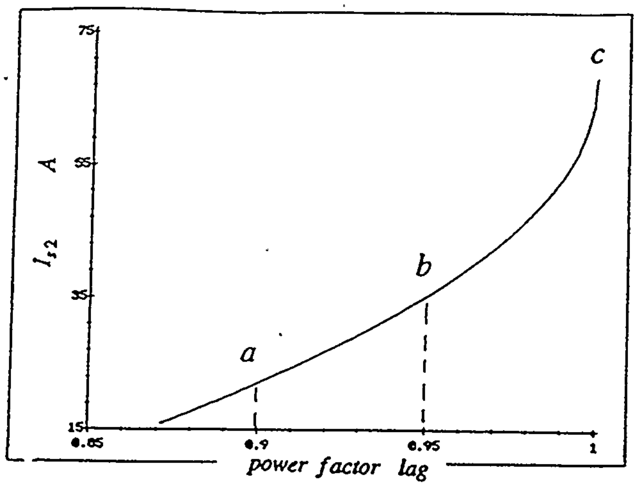
Fig.3.6 Imaginary part of total impedance versus X_{ceq} for various values of slips in p.u.

It is seen from Fig.3.6 that the value of X_{ceq} required to produce unity power factor at higher load is comparatively smaller than that required at light load. Therefore at higher load, high current will flow through the auxiliary winding for unity power factor operation. This high current will produce high copper losses in the auxiliary stator winding resulting in poor efficiency of the system. Hence, operating the machine at unity power factor may not give the most desired performance. The optimum value of power factor, at which the machine shall be operated, has to be determined by some criterion and the PWM inverter output voltage has to be controlled to produce the desired power factor.

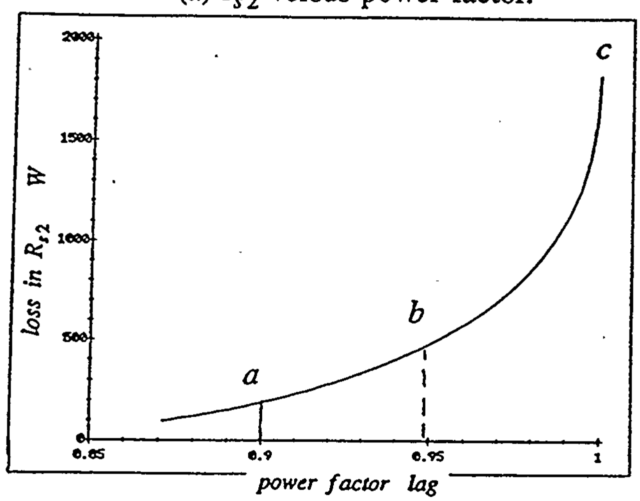
3.4 DETERMINATION OF THE OPTIMUM VALUE OF POWER FACTOR

As explained above, unity power factor operation requires high current through the auxiliary stator winding and results in poor efficiency. On the other hand, if the machine is operated at a low power factor, more line current will be required to develop a particular output power and again may result in poor efficiency. The optimum value of the power factor, at which the machine shall be operated, can be determined by analyzing the performance of the machine.

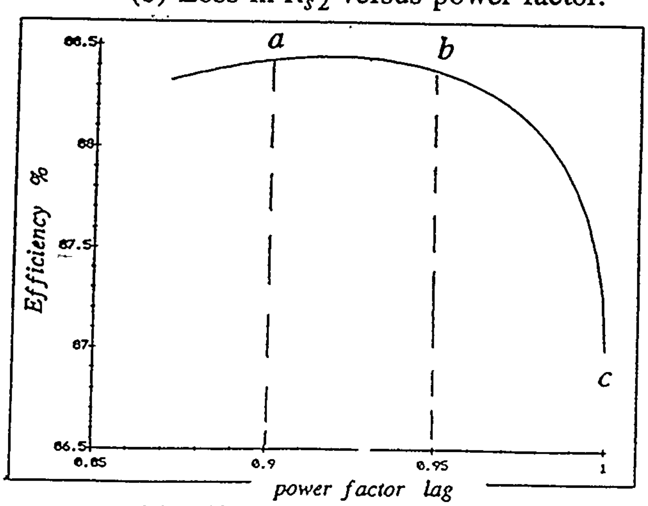
Characteristics, such as I_{s2} versus power factor, loss in R_{s2} versus power factor and efficiency versus power factor at a particular value of slip (s = 0.04 p.u.), for the machine whose parameters are given in Appendix 'A', are shown in Fig.3.7. These characteristics show that I_{s2} and power loss in R_{s2} are very high at unity power factor and they decrease rapidly within a small range of power factor from c to b. After that there is only a small decrease in I_{s2} and power loss in R_{s2} with decrease in power factor. By inspection it seems that power factor has to be selected within the range of a-b. The efficiency characteristic shows that the machine has maximum efficiency at a power factor which also lies between a and b. Hence the criterion for maximum efficiency can be used to select the optimum value of power factor for a particular value of slip.



(a) I_{s2} versus power factor.

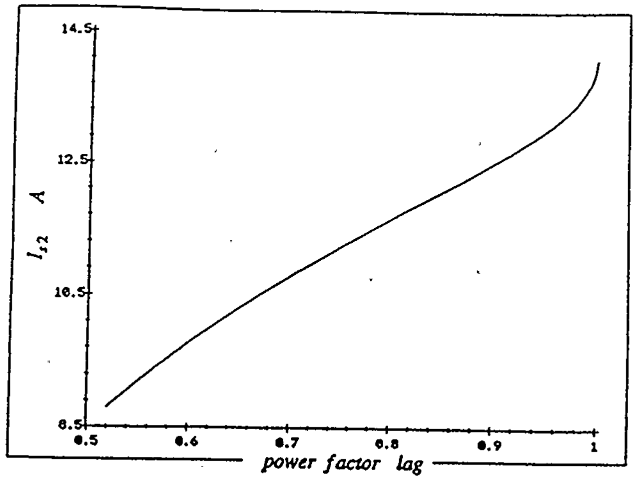


(b) Loss in R_{s2} versus power factor.

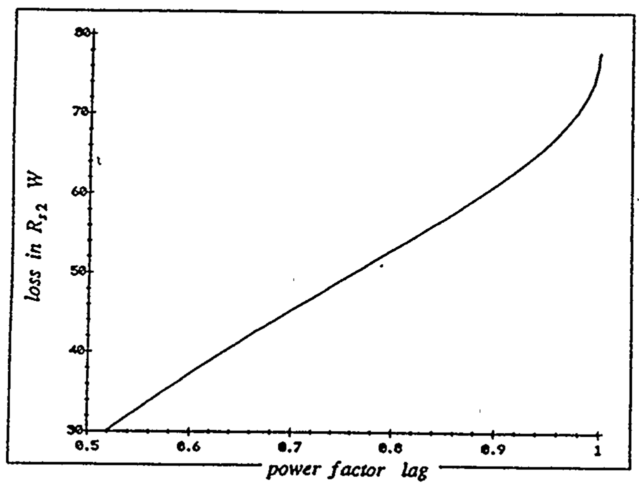


(c) Efficiency versus power factor.

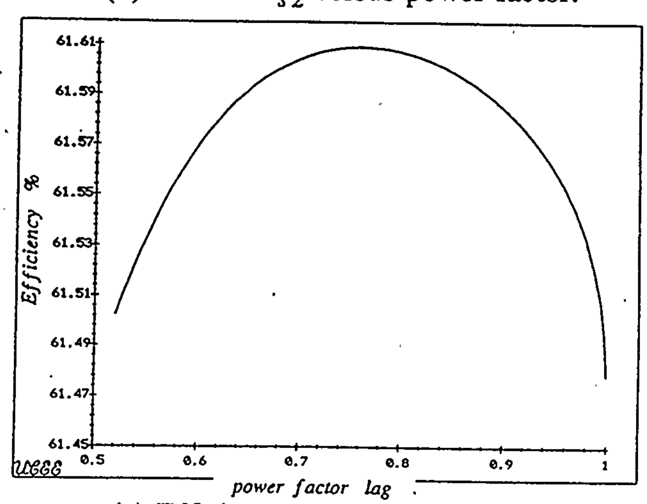
Fig.3.7 Induction motor characteristics at 0.04 p.u. slip.



(a) I_{s2} versus power factor.



(b) Loss in R_{s2} versus power factor.



(c) Efficiency versus power factor.

Fig.3.8 Induction motor characteristics at 0.0015 p.u. slip.

Comparing the results given in Figs. 3.7 and 3.8 it is seen that the power factor at which the maximum efficiency occurs varies with load. The characteristics given in Fig.3.8 for s=0.0015 p.u. show that if the criterion of maximum efficiency is used to select the power factor, the machine will operate at a fairly low power factor at light loads. To avoid operation at low power factor, it is better to put a lower limit on the power factor, say 0.85, for the operation of the machine. Because of the narrow range over which the efficiency of the machine varies with power factor, at light load, [Fig.3.8(c)], the machine will still operate close to maximum efficiency.

3.5 PWM VOLTAGE INVERTER

Basic configuration of a three phase voltage inverter is shown in Fig.3.9. In an ordinary quasi-square wave three phase voltage inverter (i.e. without PWM technique), the solid state switches are turned on and off to produce voltage waveform as shown in Fig.3.10 [12][16][17]. The waveforms are drawn for a dc supply of ±300 volts. V_r, V_y and V_b are voltages at points 'R','Y' and 'B' respectively with respect to the mid point of the dc supply. V_{ry}, V_{yb} and V_{br} are the three phase line to line voltages. V_{rn}, V_{yn} and V_{bn} are the phase voltages across the R, Y and B phases respectively. V_n is the potential of the load neutral point with respect to the mid point of the dc supply. The switching pattern determines the waveforms of V_r, V_y and V_b and the waveforms of other voltages can be determined by the following equations [16][18].

$$V_n = \frac{1}{3}\,(V_r + V_y + V_b) \tag{3.15}$$

$$V_{rn} = V_r - V_n \tag{3.16}$$

$$V_{ry} = V_r - V_y \tag{3.17}$$

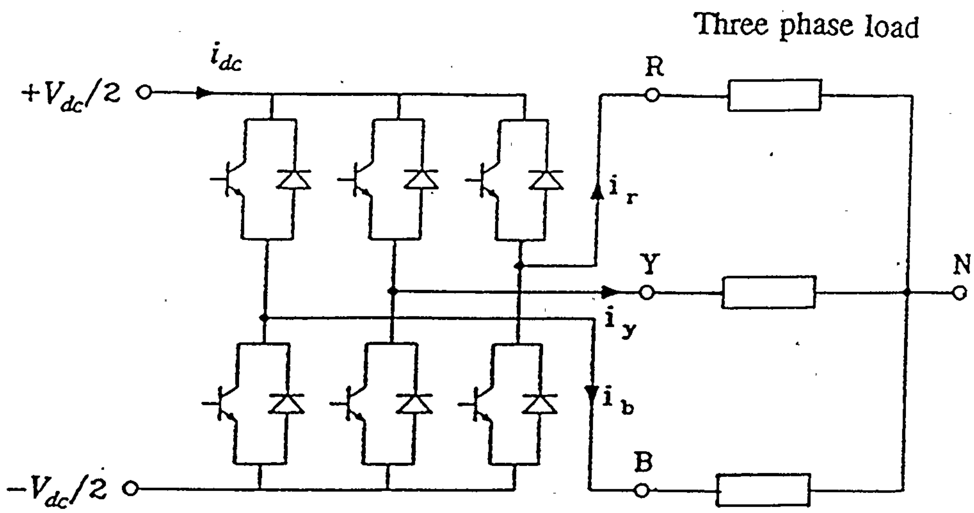


Fig.3.9 Three phase voltage inverter.

Fourier components of V_r, V_y and V_b are given by :

$$V_r(m) = \frac{4}{\pi}\frac{V_{dc}}{2}\sum_{m=1}^{\infty}\frac{1}{m}sin\,(m\theta) \tag{3.18}$$

$$V_y(m) = \frac{4}{\pi}\frac{V_{dc}}{2}\sum_{m=1}^{\infty}\frac{1}{m}\sin\,m\,(\theta-\frac{2\pi}{3}) \tag{3.19}$$

$$V_b(m) = \frac{4}{\pi}\frac{V_{dc}}{2}\sum_{m=1}^{\infty}\frac{1}{m}\sin\,m\,(\theta-\frac{4\pi}{3}) \tag{3.20}$$

where m has only odd integer values.

Fourier components of load neutral voltage V_n are given by :

$$V_n(m) = \frac{4}{\pi}\frac{V_{dc}}{2}\sum_{m=3}^{\infty}\frac{1}{m}\sin\,m\,(\theta) \tag{3.21}$$

where m = 3,9,15,.....

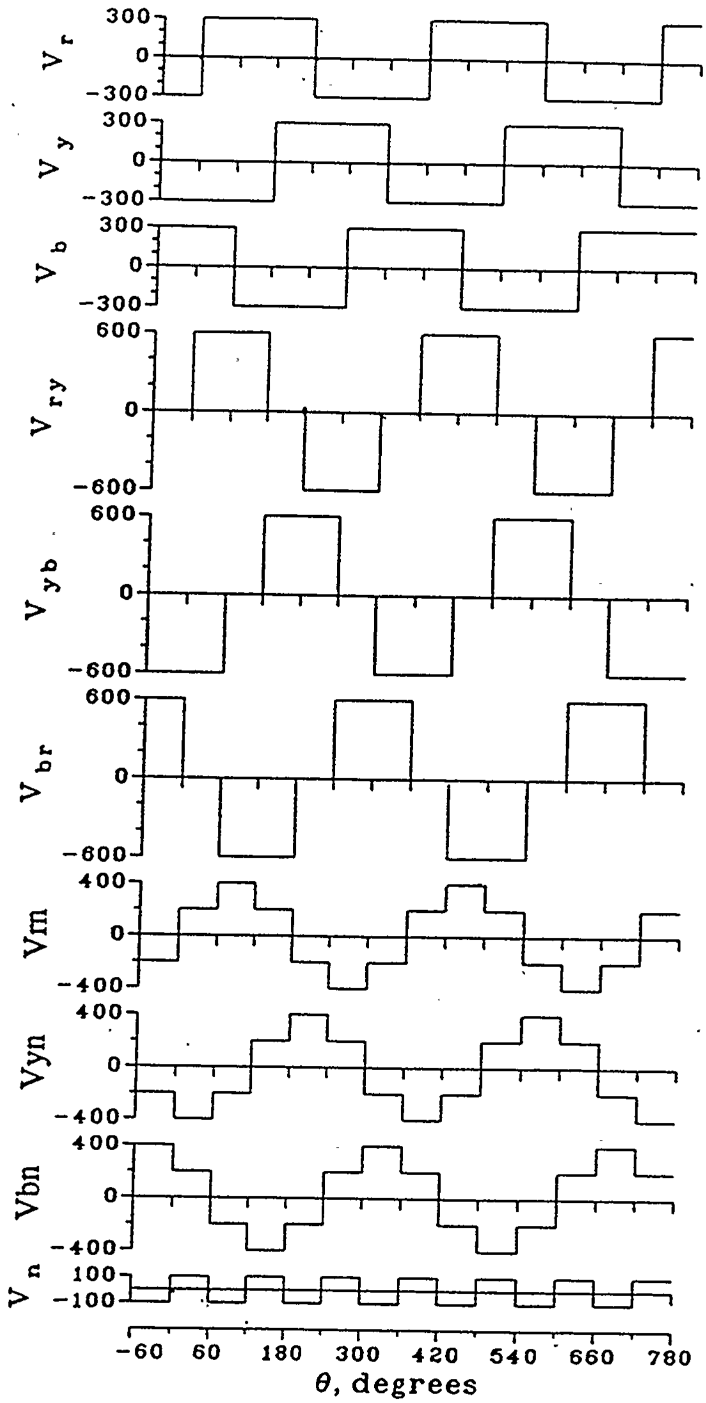


Fig.3.10 Waveforms of quasi-square wave three phase voltage inverter.

Fourier components of phase voltage V_{rn} are given by :

$$V_{rn}(m) = \frac{4}{\pi}\frac{V_{dc}}{2}\sum_{m=1}^{\infty}\frac{1}{m}sin(m\theta) \tag{3.22}$$

where m has only odd integer values without 3 and its integer multiples.

The first fourteen Fourier components of V_{rn} are shown in table 3.1.

Table 3.1 First fourteen Fourier components of V_{rn} for $V_{dc} = \pm 300$ volts.

Order	Magnitude (Peak) (Volts)
1.	381.97
2.	0.0
3.	0.0
4.	0.0
5.	76.39
6.	0.0
7.	54.56
8.	0.0
9.	0.0
10.	0.0
11.	34.72
12.	0.0
13	29.38
14	0.0

Basic principle of the PWM voltage inverter is the same as that of an ordinary three phase voltage inverter. However, in the PWM voltage inverter, the solid state switches are turned on and off to produce several positive and negative square wave outputs per cycle. Switching pattern for a cycle is dertermined by comparing the high frequency triangular carrier wave with the sinusoidal modulating signal. A sinusoidal modulating signal and a triangular carrier wave with frequency ratio (FR) of 6 and modulation index (MI) of 0.6 are shown in Fig.3.11. Frequency ratio is defined as the ratio of the frequency of the triangular carrier to the frequency of the modulating signal. The frequency of the modulating signal is equal to the fundamental frequency of the inverter output voltage. Modulation index is the ratio of the peak value of the modulating signal to peak value of the triangular carrier. The switching pattern follows the following rules :

If modulating signal > carrier signal, then $V_r = +V_{dc}/2$

If modulating signal < carrier signal, then $V_r = -V_{dc}/2$

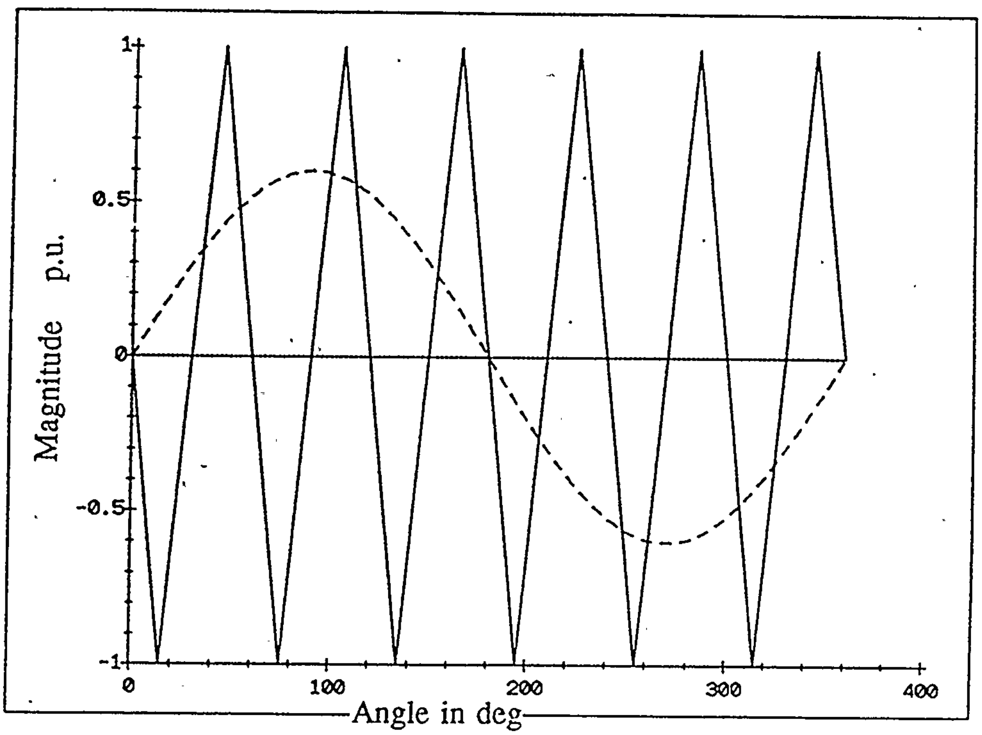
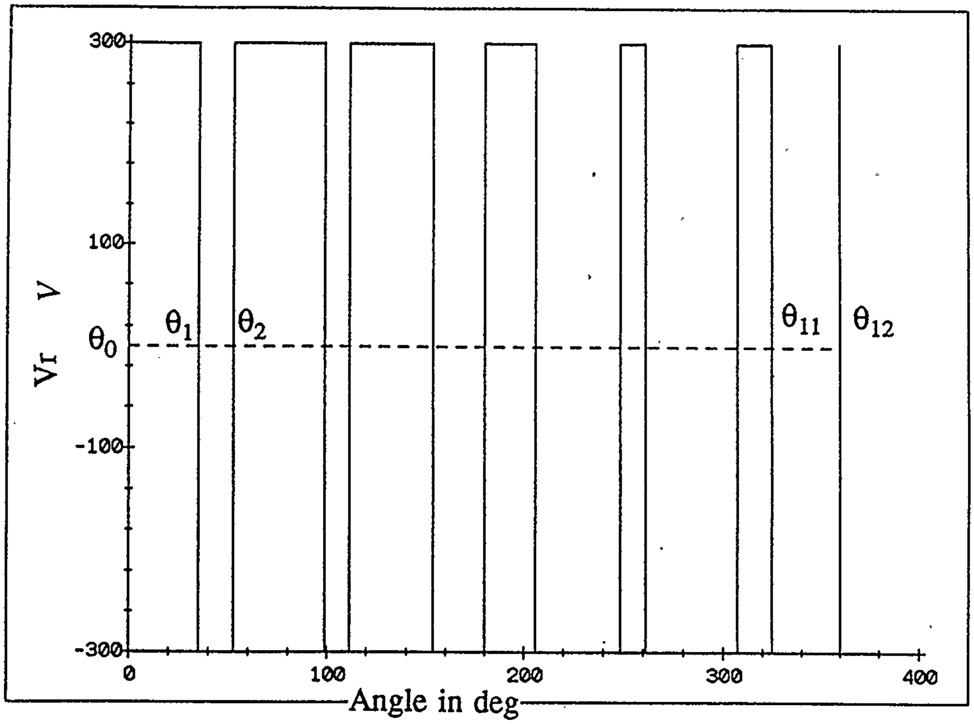
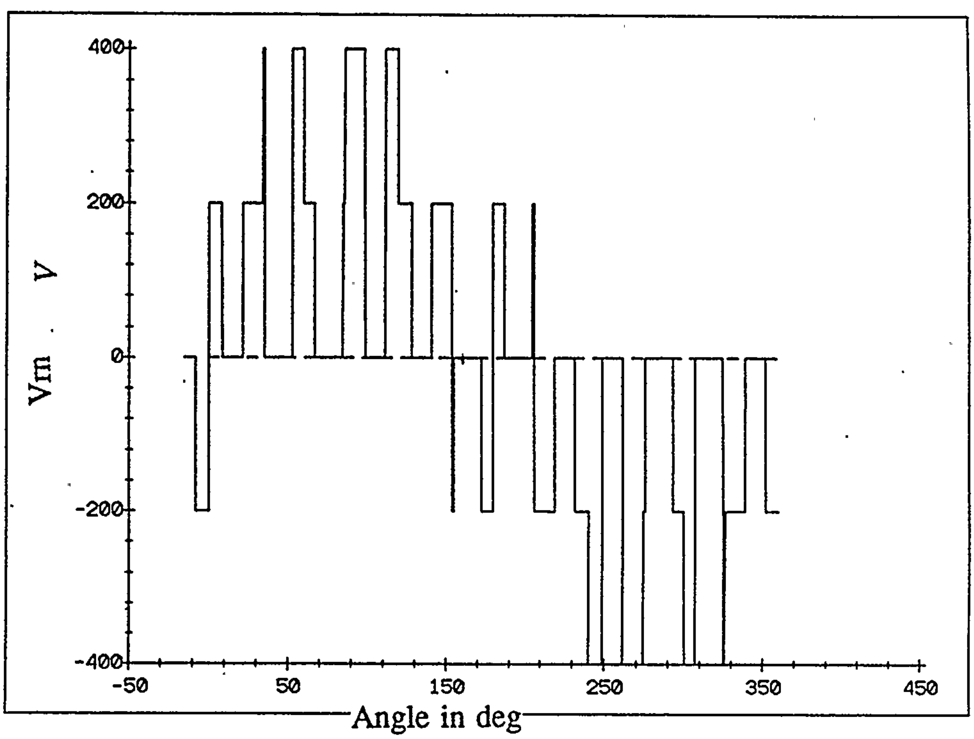


Fig.3.11 Modulating sinewave and triangular carrier for MI = 0.6, FR = 6.

Waveforms of V_r and V_{rn} are shown in Fig.3.12(a) and Fig.3.12(b) respectively.



(a) Waveform of V_r.



(b) Waveform of V_m.

Fig.3.12 Waveforms of V_r and V_m for MI = 0.6, FR = 6, V_{dc} = ±300 volts.

Fourier components of V_r are given by :

$$\textit{Magnitude} : \quad V_r(m) = \sqrt{A_{cr}(m)^2 + B_{sr}(m)^2} \tag{3.23}$$

$$\textit{Phase} : \quad Phr(m) = \tan^{-1}\left[\frac{A_{cr}(m)}{B_{sr}(m)}\right] \tag{3.24}$$

where,

A_{cr}(m) = Cosine component of V_m(m).

B_{sr}(m) = Sine component of V_m(m).

and

$$A_{cr}(m) = \frac{V_{dc}}{2\pi m}\,[\,(sin\ m\theta_1 - \sin m\theta_0) - (sin\ m\theta_2 - \sin m\theta_1)$$

$$+ (sin\ m\theta_3 - \sin m\theta_2) - ....] \tag{3.25}$$

$$B_{sr}(m) = \frac{V_{dc}}{2\pi m}\,[\,-(cos\ m\theta_1 - \cos m\theta_0) + (cos\ m\theta_2 - \cos m\theta_1)$$

$$- (cos\ m\theta_3 - \cos m\theta_2) + ...] \tag{3.26}$$

Fourier components of load neutral voltage V_n are given by :

$$\textit{Magnitude} : \quad V_n(m) = \sqrt{A_{cn}(m)^2 + B_{sn}(m)^2} \tag{3.27}$$

where,

A_{cn}(m) = Cosine component of V_n(m).

B_{sn}(m) = Sine component of V_n(m).

and

$$A_{cn}(m) = \frac{1}{3}\,[\,A_{cr}(m) + A_{cy}(m) + A_{cb}(m)\,] \tag{3.28}$$

$$B_{sn}(m) = \frac{1}{3} [\, B_{sr}(m) + B_{sy}(m) + B_{sb}(m) \,] \tag{3.29}$$

and,

$$A_{cy}(m) = V_r(m)\, sin(\, phr(m) - m\frac{2\pi}{3}) \tag{3.30}$$

$$A_{cb}(m) = V_r(m)\, sin(\, phr(m) - m\frac{4\pi}{3}) \tag{3.31}$$

$$B_{sy}(m) = V_r(m)\, cos(\, phr(m) - m\frac{2\pi}{3}) \tag{3.32}$$

$$B_{sb}(m) = V_r(m)\, cos(\, phr(m) - m\frac{4\pi}{3}) \tag{3.33}$$

Fourier components of V_{rn} are given by :

$$\textit{Magnitude} : \quad V_{rn}(m) = \sqrt{A_{crn}(m)^2 + B_{srn}(m)^2} \tag{3.34}$$

$$\textit{Phase} : \quad Ph_{rn}(m) = \tan^{-1} [\frac{A_{crn}(m)}{B_{srn}(m)}] \tag{3.35}$$

where,

A_{crn}(m) = Cosine component of V_{rn}(m).

B_{srn}(m) = Sine component of V_{rn}(m).

and,

$$A_{crn}(m) = A_{cr}(m) - A_{cn}(m). \tag{3.36}$$

$$B_{srn}(m) = B_{sr}(m) - B_{sn}(m). \tag{3.37}$$

The first fourteen Fourier components of V_{rn}, for V_{dc} of ±300 volts, modulation index of 0.6 and frequency ratio of 6, are shown in Table 3.2, and Table 3.3 shows the same but with a modulation index of 0.8.

Table 3.2 First fourteen Fourier components of V_{rn}

for MI = 0.6, FR = 6 and V_{dc} = ±300 volts.

order	Amplitude(Peak)	phase(rad)
1.	180.0406188965	0.00000
2.	0.7365460992	0.03555
3.	0.0000000028	1.57080
4.	39.3769187927	-0.00058
5.	0.0199498292	1.33701
6.	0.0000368382	1.57080
7.	1.0341843367	-3.12262
8.	39.3990707397	-0.00032
9.	0.0000074208	1.57080
10.	0.7566280365	0.00011
11.	111.0484313965	-3.14144
12.	0.0000004629	1.57080
13.	111.0347137451	0.00009
14.	13.9729642868	-0.00093

Table 3.3 First fourteen Fourier components of V_{rn}

for MI = 0.8, FR = 6 and V_{dc} = ±300 volts.

order	Amplitude	phase(rad)
1.	240.0590515137	0.00003
2.	2.3274059296	-0.00800
3.	0.0000000042	-1.10715
4.	65.9824371338	-0.00002
5.	0.1689024419	-2.92498
6.	0.0000647027	1.57080
7.	3.8445022106	3.13753
8.	65.9668960571	-0.00003
9.	0.0000005481	-1.57080
10.	2.6364221573	0.01105
11.	94.2673797607	3.14134
12.	0.0000015907	1.57080
13.	94.2691879272	-0.00014
14.	31.3481235504	-0.00013

From Tables 3.2 and 3.3 it is clear that the magnitude of the fundamental component of V_{rn} can be changed by changing the modulation index.

The first fourteen Fourier components of V_{rn}, for V_{dc} of ±300 volts, modulation index of 0.6 and frequency ratio of 12, are shown in Table 3.4. Here the magnitude of the harmonic components in V_{rn} is comparatively less than that given in Table 3.2. Hence the harmonic components in V_{rn} can be reduced by operating the PWM inverter with higher carrier frequency (or frequency ratio). However, very high chopping frequency requires that the switching device have a very short recovery time which may cause practical problems. Also such a switching device will be more expensive.

Table 3.4 First fourteen Fourier components of V_{rn}

for MI = 0.6, FR = 12 and V_{dc} = ±300 volts.

order	Amplitude	phase(rad)
1.	180.0906524658	-0.00008
2.	0.0587864928	-2.09354
3.	0.0000000075	3.14159
4.	0.0196315795	-3.03039
5.	0.0271209721	0.28122
6.	0.0000000068	-1.57080
7.	0.0393791124	-0.42683
8.	0.7357529402	-0.03161
9.	0.0000000145	1.83140
10.	39.4075279236	0.00129
11.	0.0432120189	-1.55101
12.	0.0001634657	1.57080
13.	0.0308299400	-0.59211
14.	39.3358001709	-0.00024

3.6 CONTROL STRATEGY

It has already been explained that the PWM voltage inverter has to produce a particular value of $V_{s2}(1)$ with a particular value of phase angle θ in order to maintain the desired power factor. Hence, at a particular load, the required magnitude and phase of $V_{s2}(1)$ has to be obtained and kept constant with the help of a controller.

Refering to the phasor diagram in Fig.3.5, active power associated with the auxiliary stator winding is given by :

$$P_{s2} = E_{s2} I_{s2} \sin(\theta - \beta) \quad \textit{watts per phase.} \tag{3.38}$$

The auxiliary stator winding receives this power from the main stator winding by transformer action.

Copper loss in the auxiliary stator winding is given by :

$$Ploss_{aux} = I_{s2}^{2} R_{s2} \quad \textit{watts per phase.} \tag{3.39}$$

Current through the auxiliary stator winding is given by :

$$\vec{I}_{s2} = \frac{\vec{E}_{s2} - \vec{V}_{s2}(1)}{R_{s2} + jX_{s2}} \tag{3.40}$$

Control strategy can be realized with the help of the above equations. Reactive power in the main stator winding can be sensed and compared with the desired reactive power (Q_{ref}) and the error signal thus obtained can be used to operate the controller. The controller selects proper modulation index to produce the required magnitude of $V_{s2}(1)$ to give the desired power factor.

Another variable that has to be controlled is the phase angle θ. This angle is related to the active power in the auxiliary stator winding.

If

$$E_{s2}I_{s2}\,sin\,(\theta-\beta) = I_{s2}^{\,2}R_{s2} \;\; [i.e.\;\; \theta = \beta + \sin^{-1}(\frac{I_{s2}R_{s2}}{E_{s2}})]$$

then there will be no power flow into the dc capacitor and the dc voltage across the capacitor will remain constant.

If θ is increased, active power entering the auxiliary stator winding [i.e. $E_{s2}I_{s2}\sin(\theta - \beta)$] will be greater than that required to supply the copper loss and the excess active power will cause charging current into the capacitor and the dc voltage across the capacitor will increase.

If θ is decreased, active power entering the auxiliary stator winding will be less than that required to compensate copper loss in the auxiliary stator winding. Hence the dc capacitor will get discharged through the auxiliary stator winding to supply copper loss in the auxiliary stator winding and the voltage across the dc capacitor will decrease.

Hence the dc voltage across the capacitor can be used to regulate the phase angle θ. The dc voltage across the capacitor can be sensed and compared with the V_{dc}(ref) and the error signal thus obtained can be used to operate the controller to give the desired value of θ. Hence a tentative control block diagram for the scheme can be realized as shown in Fig.3.13.

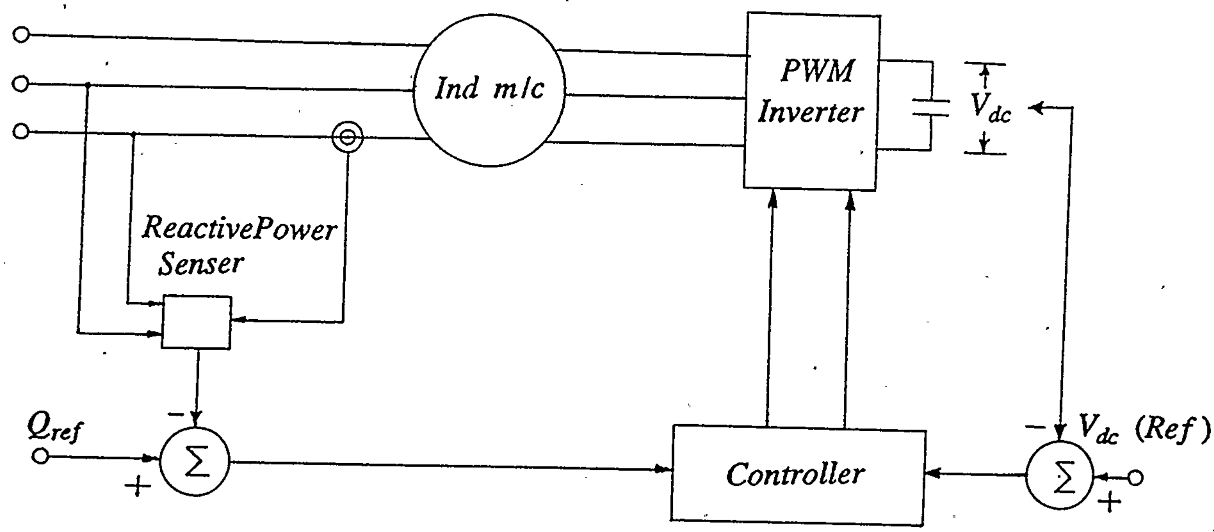


Fig.3.13 Control block diagram for the proposed scheme.

3.7 PERFORMANCE OF THE SCHEME IN THE PRESENCE OF HARMONICS

It has already been mentioned that the PWM output voltage has a fundamental as well as harmonic components. Therefore, it is worthwhile to study the effect of these harmonics on the performance of the scheme.

Fundamental currents through different branches of the circuit can be calculated by using the equivalent circuit shown in Fig.3.14. Here only the fundamental component of the PWM inverter output voltage $V_{s2}(1)$ has been considered to analyze the equivalent circuit. The main supply voltage V_{s1} is assumed to have only the fundamental component.

Harmonic currents through different branches of the circuit can be calculated by using the equivalent circuit shown in Fig.3.15. Harmonic current of each order shall be calculated one at a time.

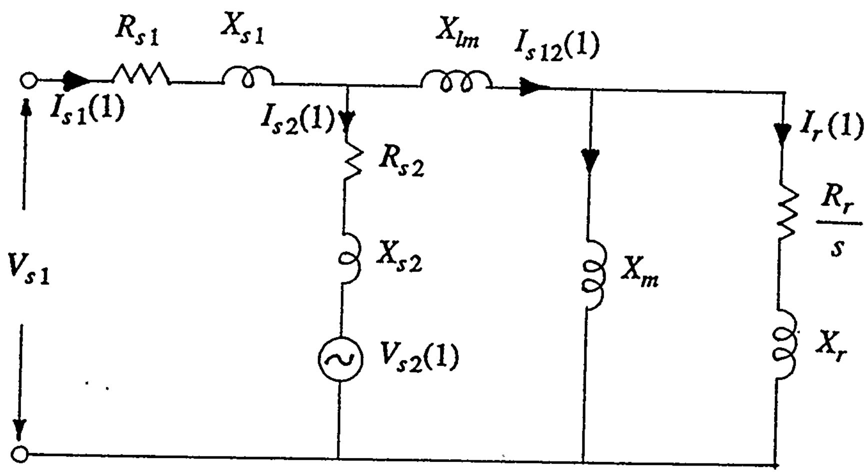


Fig.3.14 Equivalent circuit to calculate fundamental currents.

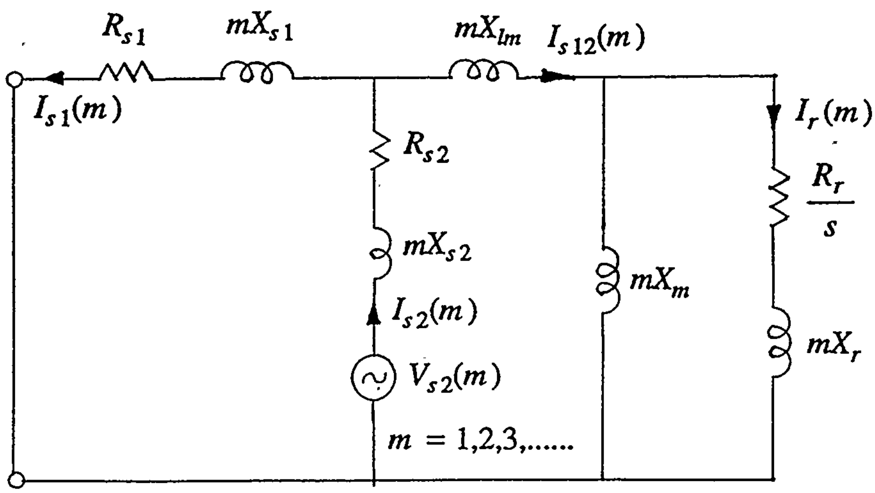


Fig.3.15 Equivalent circuit to calculate harmonic currents.

Total current through different branches of the circuit are given by :

$$I_{s1} = I_{s1}(1)\ sin(\omega\ t + \phi_{s1}(1)) + I_{s1}(2)\ sin(2\omega\ t + \phi_{s1}(2)) + I_{s1}(3)\ sin(3\omega\ t + \phi_{s1}(3)) + \ldots\ldots\ldots\ldots\ldots \quad (3.41)$$

$$I_r = I_r(1)\ sin(\omega\ t + \phi_r(1)) + I_r(2)\ sin(2\omega\ t + \phi_r(2)) + I_r(3)\ sin(3\omega\ t + \phi_r(3)) + \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.42)$$

Distortion factor in I_{s1} is given by :

$$d.f. = \frac{\sqrt{\sum_{m=2}^{\infty} I_{s1}(m)^2}}{I_{s1}(1)} \quad (3.43)$$

The voltage harmonics in the PWM output voltage V_{s2} can be reduced by operating the PWM inverter at a higher carrier frequency. The machine inductances also provide substantial filtering action to reduce harmonics in the current. The machine inductance provides higher reactance to the voltage of the higher order harmonics. Hence, if the PWM inverter is operated at a sufficiently high carrier frequency, the distortion factor in the main input current I_{s1} can be reduced to an acceptable value without any additional filter. A typical performance analysis in terms of numerical values will be given in Chapter 4.

3.8 RATING OF THE DC CAPACITOR

The function of the dc capacitor is to hold across it dc voltage required for inverter operation. The controller described above maintains constant average value of dc voltage across the capacitor. However, the dc voltage will have some ripple.

Fourier components of the PWM inverter output voltage calculated in section 3.5 are based on the assumption that the dc voltage is ripple free. The ripple in dc voltage across the capacitor will result in a higher distortion factor in the main supply input current I_{s1}. Hence the capacitance of the capacitor has to be selected to give an acceptable value of ripple in the dc voltage. The design of dc capacitor has to be done under the constraint that the ripple factor for the dc voltage is less than five percent [4].

The ripple factor is given by :

$$K_v = \frac{\sqrt{\sum_{m=0}^{\infty} V_c(m)^2}}{V_{dc}} \tag{3.44}$$

where,

$$V_c(m) = \frac{X_c}{m} I_{dc}(m) \tag{3.45}$$

and

K_v = Ripple factor

V_c(m) = Rms value of m^{th} voltage harmonic across the dc capacitor.

V_{dc} = Average value of dc voltage across the capacitor.

I_{dc}(m) = Rms value of the m^{th} current harmonic through the dc capacitor.

X_c = Reactance of the capacitor at fundamental frequency

(i.e. X_c = 1/2πfc).

and

$$X_c = \frac{K_v \ V_{dc}}{\sqrt{\sum_{m=6,12}^{\infty} \frac{I_{dc}(m)^2}{m^2}}} \tag{3.46}$$

As the 12^{th}, 18^{th}, .. harmonic components of the current are very small, the expression for X_c can be simplified by considering only the 6^{th} harmonic component of the current through the dc capacitor.

Hence,

$$X_c = \frac{6K_v V_{dc}}{I_{dc}(6)} \tag{3.47}$$

and

$$C = \frac{I_{dc}(6)}{12K_v V_{dc} \pi f} * 10^6 \quad \mu F \tag{3.48}$$

kVAr rating of required capacitor is

$$kVAr = V_{dc} I_{dc}(rms) \tag{3.49}$$

3.9 SUMMARY

The basic configuration of the proposed scheme has been described and equivalent circuit of the scheme has been developed in this Chapter. The operating principle of the scheme has been described based on the equivalent circuit. Mathematical and graphical analysis are performed to study the operating conditions of the scheme. A criterion has been developed to determine the optimum value of the power factor at which the machine gives better performance. Mathematical analysis of both the quasi-square wave three phase voltage inverter and the PWM three phase voltage inverter has been presented and advantage of the PWM voltage inverter over the quasi-square wave voltage inverter, in terms of harmonic component reduction, has been illustrated with simulation studies. A tentative control strategy of the scheme has been presented. Circuit models have been developed to study the performance of the scheme in the presence of harmonic components in the PWM inverter output voltage.

CHAPTER 4

SIMULATION STUDIES

In this Chapter, a detailed simulation of the proposed scheme is presented by using computer programming. The mathematical model of the proposed scheme described in Chapter 3 has been simulated to study operating conditions, performance and to calculate the ratings of various components of the scheme. A typical induction machine, whose parameters are given in Appendix 'A', is used in the simulation. Simulation results for a machine used in the experiments are also outlined. Parameters of this machine are given in Appendix 'B'.

4.1 BASIC ALGORITHM USED IN SIMULATION

A computer program has been devloped to simulate the proposed scheme and to study the operating conditions and performance. Basic components of the program are shown in Fig.4.1.

4.1.1 Analysis of the scheme without auxiliary winding

The equivalent circuit of the scheme without auxiliary stator winding is shown in Fig.4.2. Currents through different branches are calculated using a.c. circuit theory.

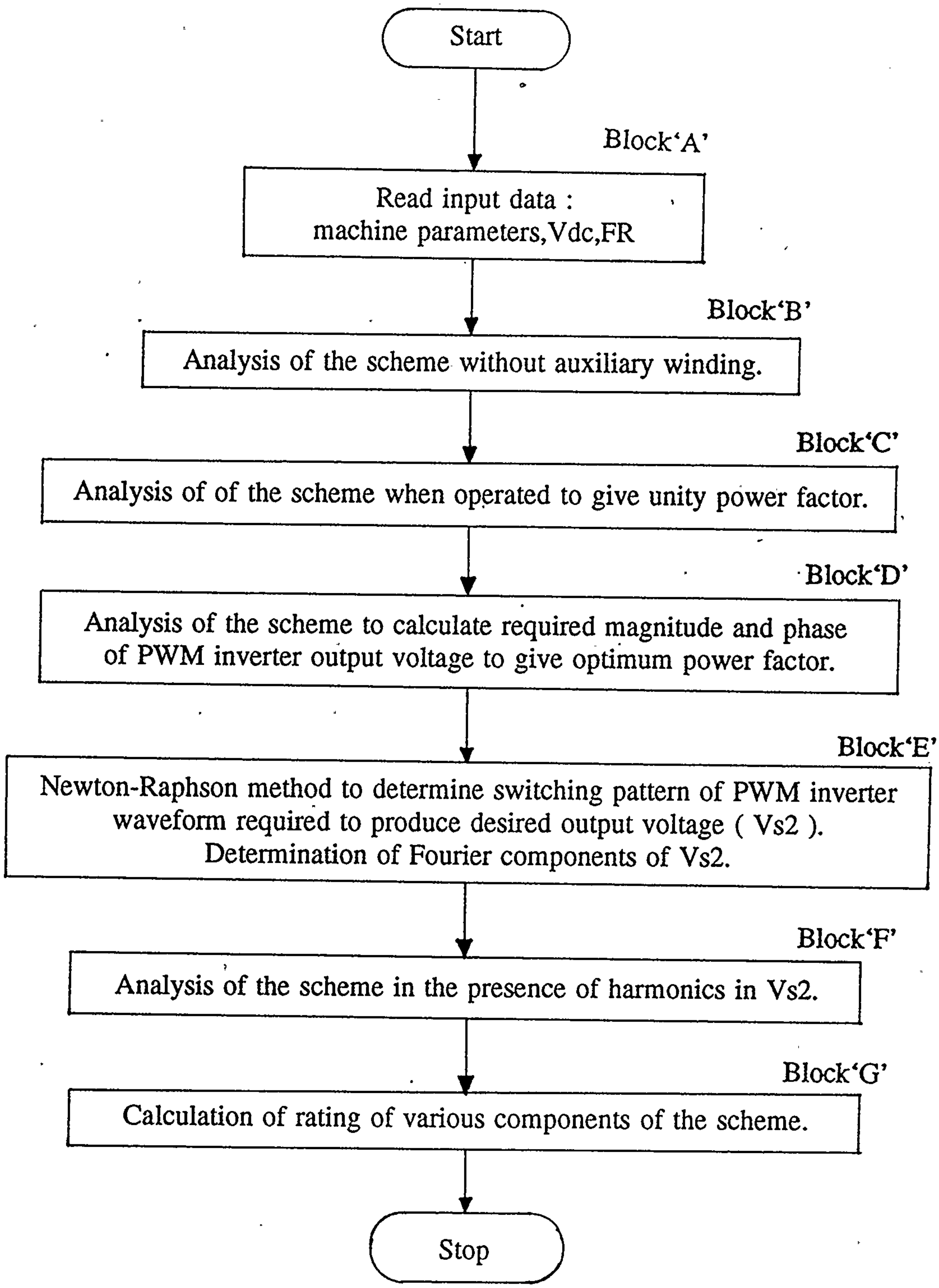


Fig.4.1 Basic components of the simulation program.

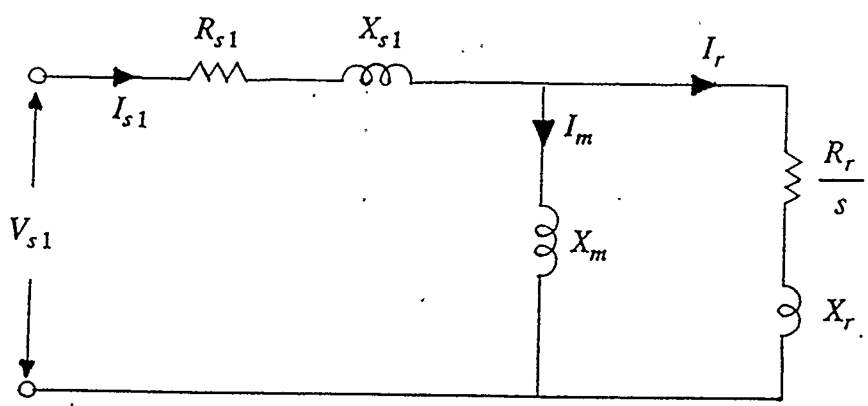


Fig.4.2 Equivalent circuit of the scheme without auxiliary winding.

Input power to the machine is given by :

$$P_{s1} = 3V_{s1}I_{s1}\cos\phi_{s1} \qquad W \tag{4.1}$$

Reactive power consumed by the machine is given by :

$$Q_{s1} = 3V_{s1}I_{s1}\sin\phi_{s1} \qquad Var. \tag{4.2}$$

where,

ϕ_{s1} = phase anngle by which I_{s1} lags with respect to V_{s1}.

The output power, which is responsible for producing net torque on the shaft, is given by :

$$P_o = P_{s1} - 3(I_{s1}^2R_{s1} + I_r^2R_r) - no\ load\ loss \tag{4.3}$$

and,

$$Efficiency = \frac{P_o}{P_{s1}} * 100\ \% \tag{4.4}$$

4.1.2 Analysis of the proposed scheme for unity power factor operation

The equivalent circuits of the proposed scheme given in Figs. 3.2, 3.3 and 3.4 are used to analyze the scheme for unity power factor operation. The required value of X_{c2} to give unity power factor is calculated by using equations (3.1) and (3.9) and again the performance of the scheme is calculated by using a.c. circuit theory on the basis of fundamental component of currents.

4.1.3 Selection of optimum value of power factor

The equivalent circuit of the proposed scheme shown in Fig.3.3 is used to calculate the efficiency of the scheme at different values of power factor (i.e. at different values of X_{c2}). The criterion explained in section 3.4 is used to select the optimum value of power factor and corresponding value of X_{c2}. Refering to the equivalent circuit given in Fig.3.3 and the phasor diagram given in Fig.3.5, the required magnitude and phase of the PWM inverter output voltage to give optimum value of power factor is given by :

$$\textit{Magnitude}: \quad V_{s2} = I_{s2}X_{c2} \tag{4.5}$$

$$\textit{Phase}: \quad \theta = \frac{\pi}{2} - \phi_{s2} \tag{4.6}$$

where,

ϕ_{s2} = phase angle by which I_{s2} leads V_{s1}

A detailed algorithm to select optimum value of power factor is shown in Fig.4.3. It is also a detail of block 'D' in Fig.4.1.

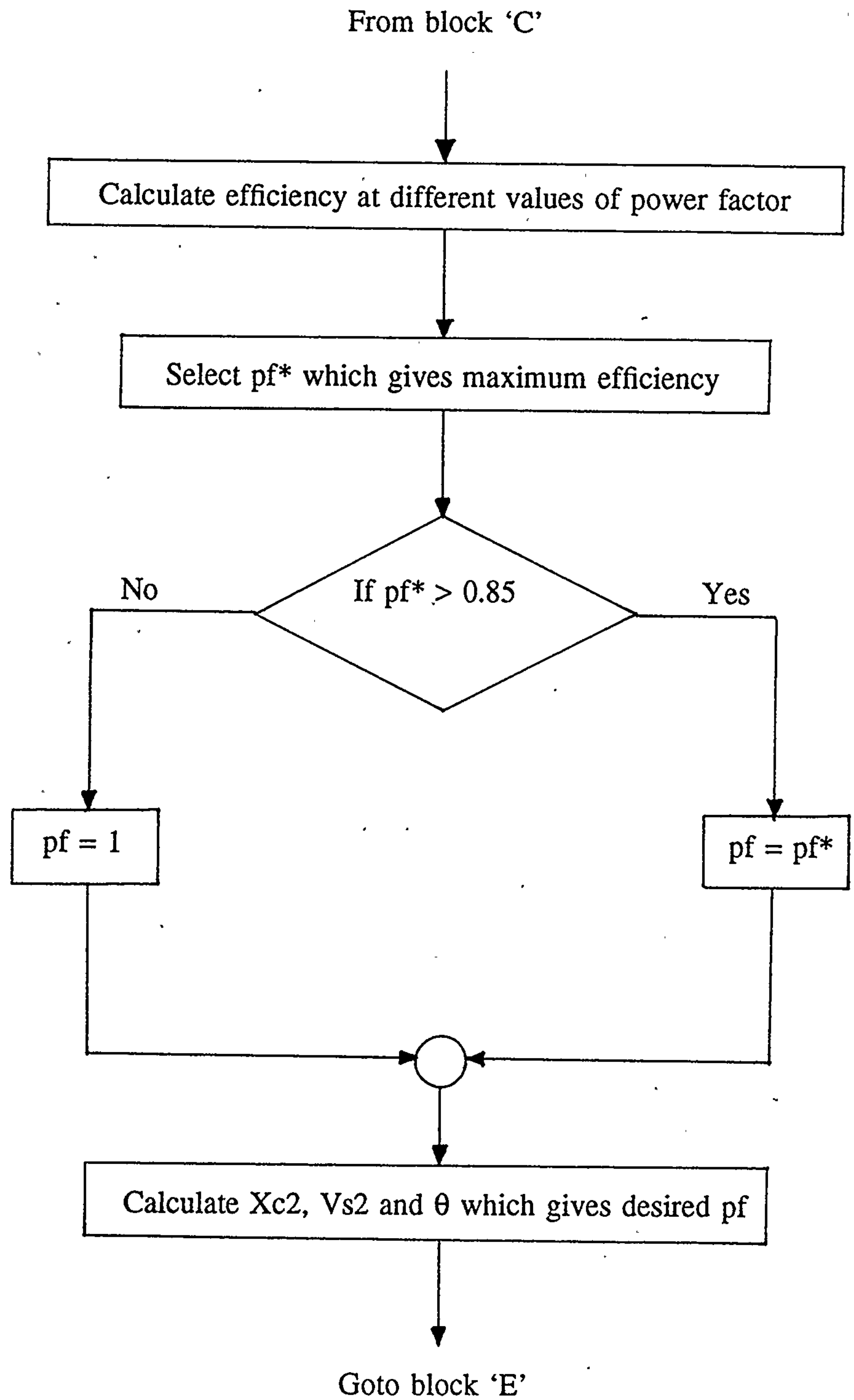


Fig.4.3 Algorithm to select optimum value of power factor.

4.1.4 Determination of switching pattern for PWM inverter

The switching pattern for the PWM inverter has to be determined so that the magnitude of fundamental component of the PWM output voltage corresponds to that given by equation (4.5). A modulating sinewave and triangular carrier for a frequency ratio of 6 are shown in Fig.4.4. The intersections of these two waves determine the switching pattern. Hence the switching pattern can be changed by changing the modulation index.

The modulating sine wave can be described by the following equation :

$$y_1(\theta) = MI{*}V_{cpk}\sin\theta_{rad} \tag{4.7}$$

The n^{th} carrier signal can be described by the following equation :

$$y_2(\theta) = k(n)\theta_{deg} + c(n) \tag{4.8}$$

where,

k(n) = slope of the n^{th} carrier.

c(n) = intercept made by the n^{th} carrier on y-axis.

and

$$k(n) = (-1)^{n+1}\frac{V_{cpk}}{\theta_{per}/2} \tag{4.9}$$

$$c(n) = -(-1)^{n+1}V_{cpk} - k(n)\theta_{st} \tag{4.10}$$

$$\theta_{per} = \frac{360}{2FR} \tag{4.11}$$

$$\theta_{st} = -\frac{\theta_{per}}{2} \tag{4.12}$$

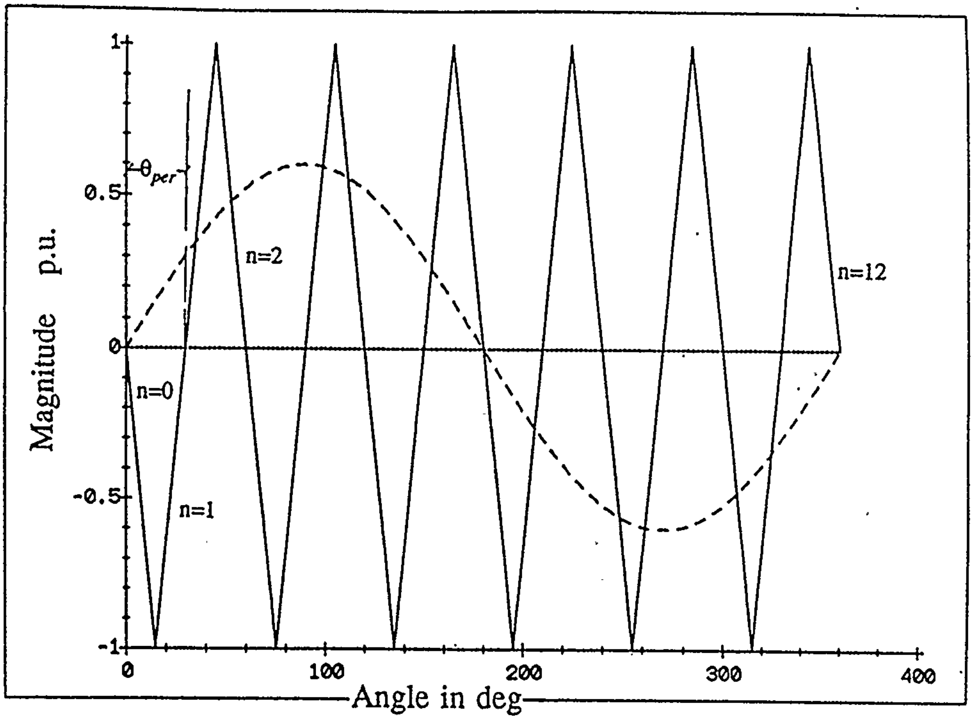


Fig.4.4 Modulating sine wave and triangular carrier for FR = 6, MI = 0.6.

When the modulating sine wave is equal to the triangular carrier, then

$$y_1(\theta) = y_2(\theta) \tag{4.13}$$

$$or \quad MI{*}V_{cpk}{*}\sin\theta_{rad} = k(n)\theta_{deg} + c(n) \tag{4.14}$$

Solution of equation (4.14) for n = 0,1,2,...etc gives the switching instants θ_0, θ_1,θ_2,....etc. Equation (4.14) is a transcendental equation and must therefore be solved by some iterative method. The Newton-Raphson method is used in the algorithm for this purpose [19].

Once the switching pattern θ_0, θ_1, θ_2,....etc is determined, the Fourier components of the PWM inverter output voltage can be determined by equations (3.23) - (3.27). A detailed algorithm to determine the switching pattern is shown in Fig.4.5 which is also a detail of block 'E' of Fig.4.1.

4.1.5 Analysis of the scheme in the presence of harmonics

The equivalent circuit models given in Figs.3.14 and 3.15 are used to analyze the scheme in the presence of harmonics in PWM output voltage. Harmonic components of PWM inverter output voltage are determined as explained in section 3.5 and a.c. circuit theory is used to determine the harmonic components of currents through different branches of the equivalent circuit.

4.2 RESULTS

A computer program (written in Fortran) to simulate the proposed scheme is given in Appendix 'C'. The proposed scheme is simulated for different load conditions and frequency ratio.

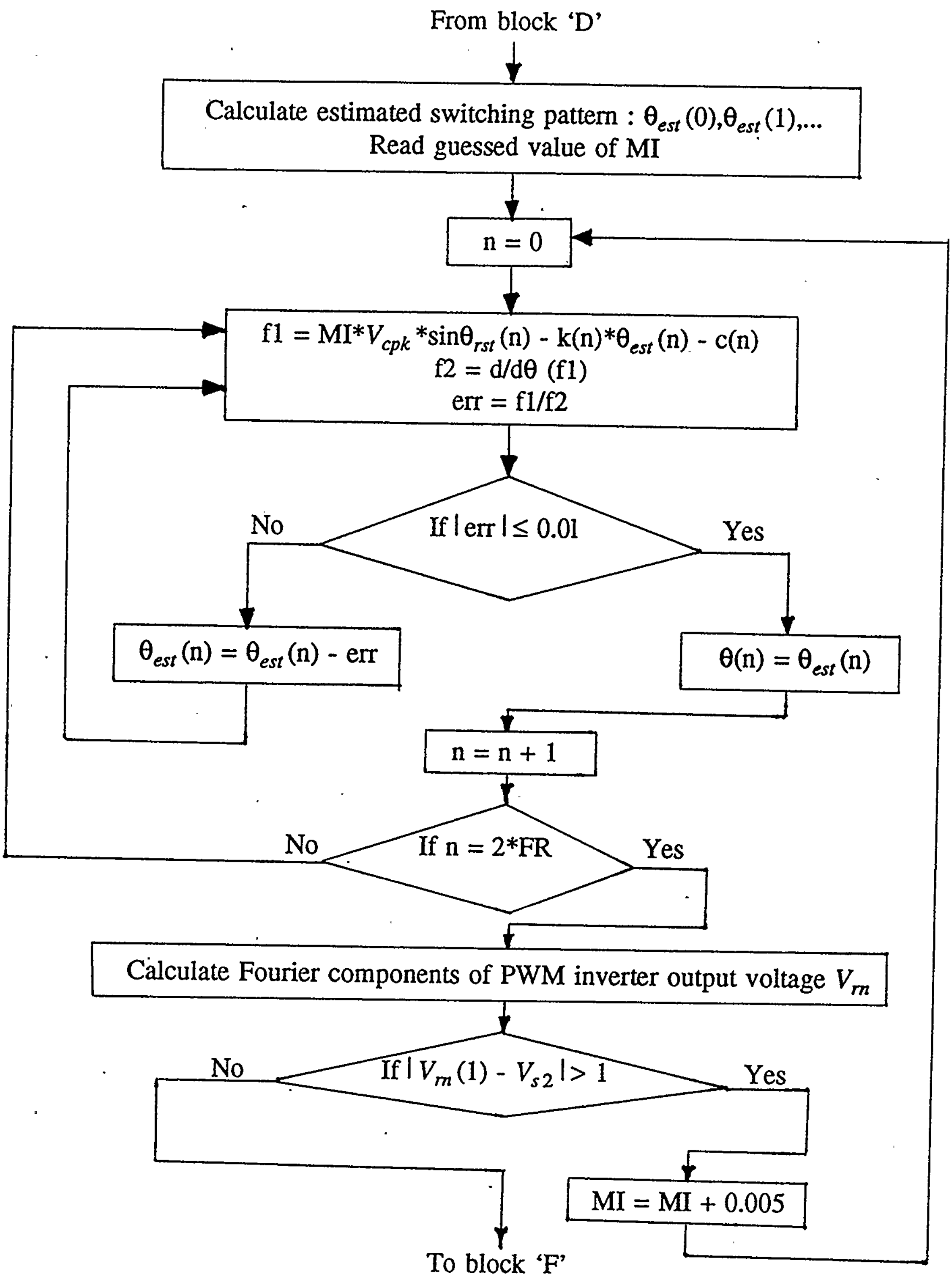


Fig.4.5 Algorithm to determine switching pattern in PWM inverter.

4.2.1 Simulation results for the 90 hp machine

A complete set of results obtained by the computer program is given in Appendix 'D'.

When the motor is operated at light load (s = 0.0015 p.u.) without an auxiliary stator winding, it draws a current of 14.38 amps with a power factor of 0.224 lagging which is fairly poor. The output power is 1.6 hp with an efficiency of 43.22 %. When the power factor is corrected by using auxiliary stator winding in conjuction with PWM inverter operated with a frequency ratio (FR) of 24, the optimum value of power factor as determined by the criterion described in section 3.4 is unity and required PWM inverter output voltage is 276.72 volts with a phase angle of 0.75 degree lagging with reference to Vs1. Harmonic current components are very significant with a distortion facxtor of 2.3 in I_{s1}, 0.557 in I_{s2} and 1.66 in I_r. Waveforms of I_{s1} and I_{s2} obtained from simulation are shown in Figs.4.6 and 4.7 respectively and they are highly distorted. These waveforms are obtained by reconstructing from the first fortyeight Fourier components of the currents. The fundamental component of I_{s1} is exactly in phase with V_{s1} and the fundamental component of I_{s2} leads V_{s1} by an angle of 89.2 degrees. The reactive component of I_{s2} is responsible for cancelling the lagging reactive component of the current drawn by the induction motor.

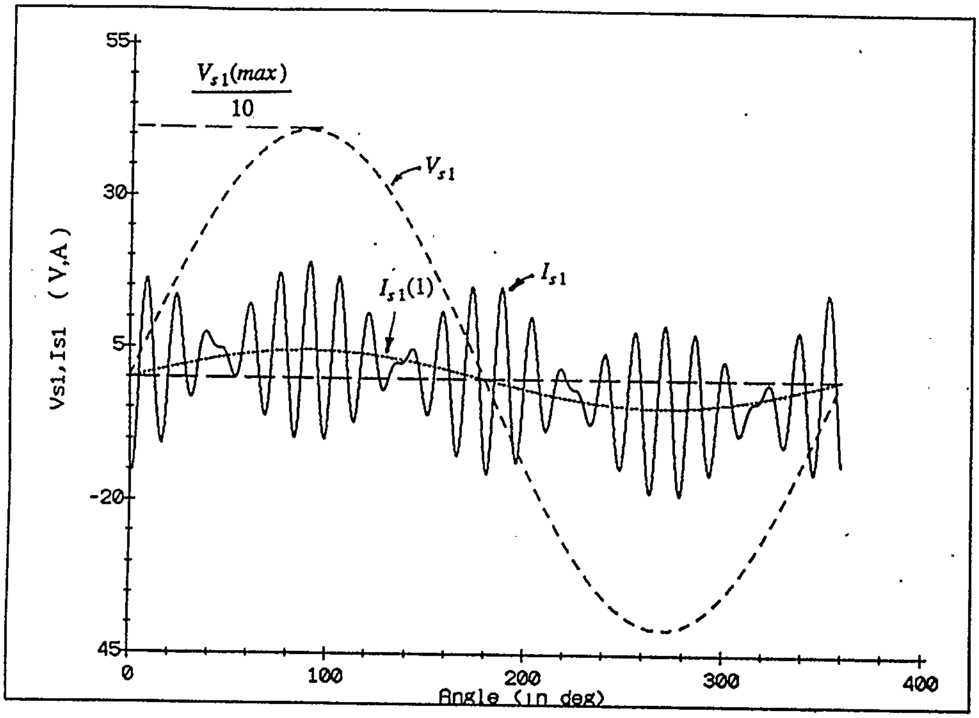


Fig.4.6 Waveforms of V_{s1} and I_{s1} at s = 0.0015 p.u.,FR = 24, 90 hp machine.

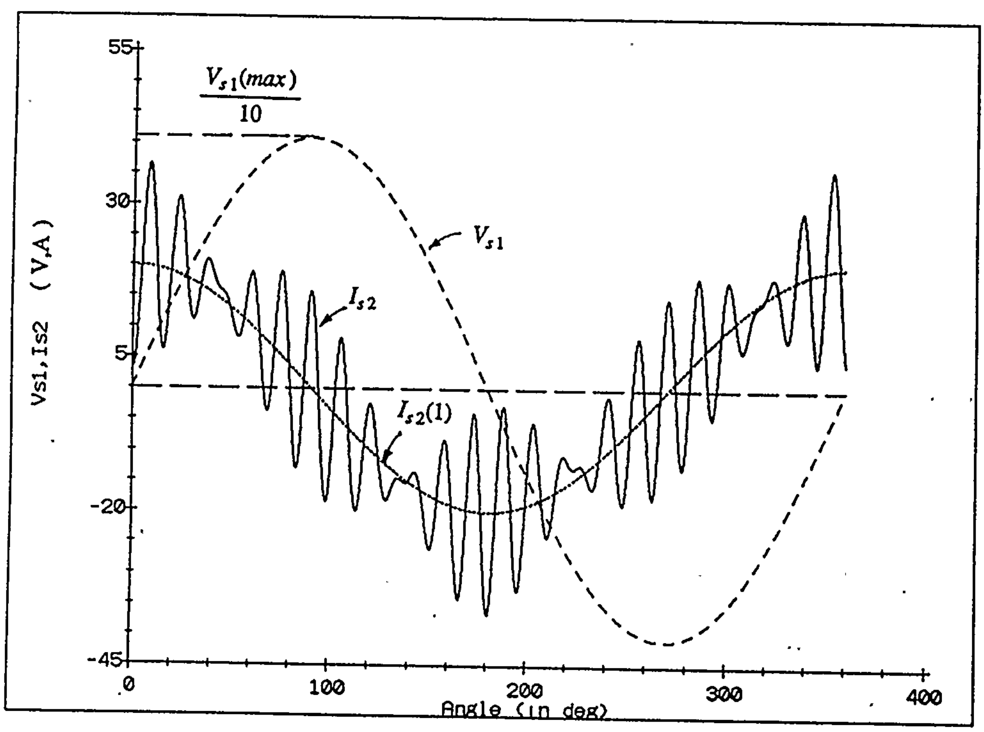


Fig.4.7 Waveforms of V_{s1} and I_{s2} at s = 0.0015 p.u.,FR = 24, 90 hp machine.

When the PWM inverter is operated with a frequency ratio (FR) of 42, the distorsion factors in the currents are reduced to some extent. The distortion factors in I_{s1}, I_{s2} and I_r are reduced to 0.1194, 0.0285 and 0.0237 respectively. The waveforms of I_{s1} and I_{s2} (for FR = 42), shown in Figs.4.8 and 4.9 respectively, are comparatively less distorted than those for frequency ratio of 24.

When the PWM inverter is operated with a frequency ratio of 54, the distortion factors in I_{s1}, I_{s2} and I_r are futher reduced to 0.0745, 0.0185 and 0.012 respectively and the waveforms of I_{s1} and I_{s2} are less distorted as shown in Figs.4.10 and 4.11 respectively.

Simulation results at full load (s = 0.055 p.u.) are summarized in Table 4.1. The Waveforms of I_{s1} and I_{s2} at frequency ratios of 24, 42 and 54 are shown in Figs.4.12, 4.13 and 4.14 respectively. The current waveforms are comparatively less distorted compared to those at light condition. It is clear from the results that operating the scheme at unity power factor does not give the best performance. The power loss in R_{s2} and kVA rating of PWM inverter can be reduced by operating the scheme at a power factor determined by the criterion for optimum power factor. The waveforms of the currents at full load are less distorted than those at light load.

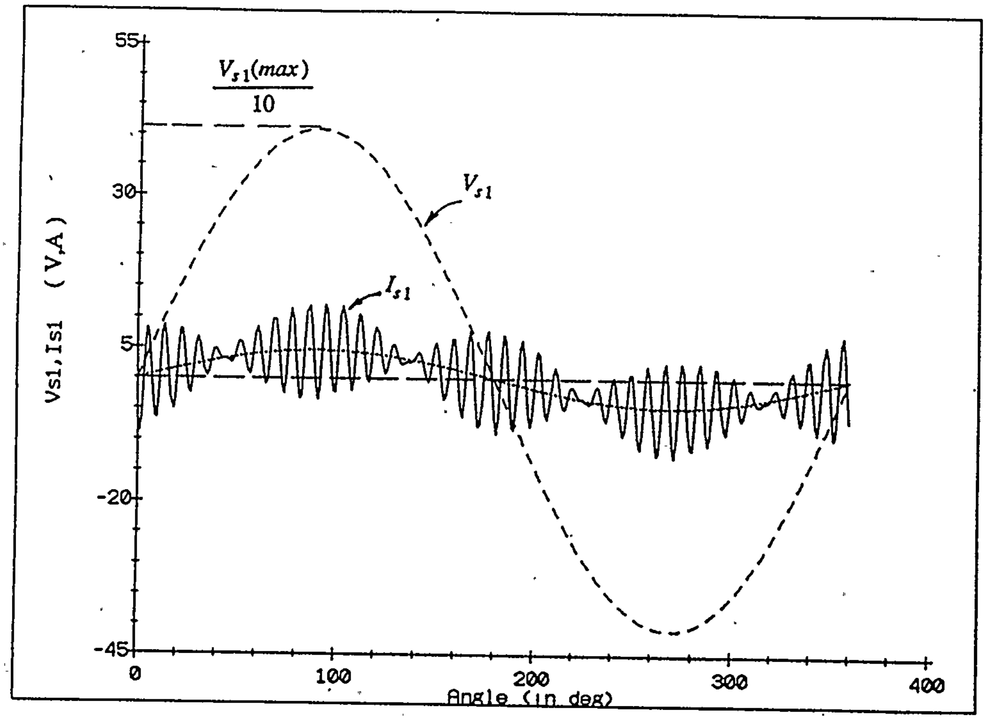


Fig.4.8 Waveforms of V_{s1} and I_{s1} at s = 0.0015 p.u.,FR = 42, 90 hp machine.

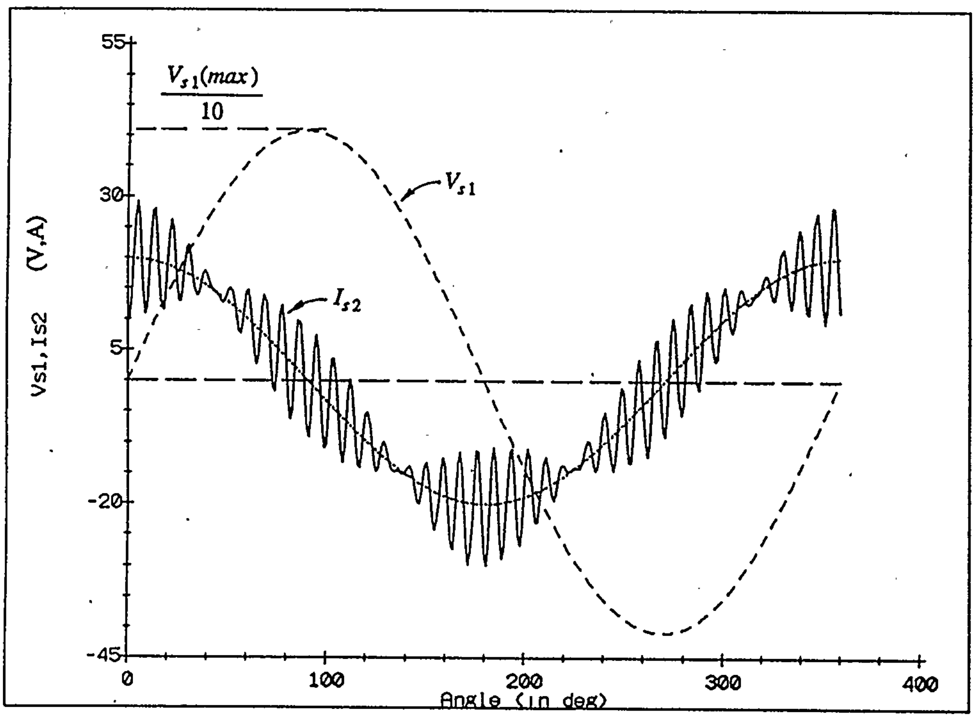


Fig.4.9 Waveforms of V_{s1} and I_{s2} at s = 0.0015 p.u.,FR = 42, 90 hp machine.

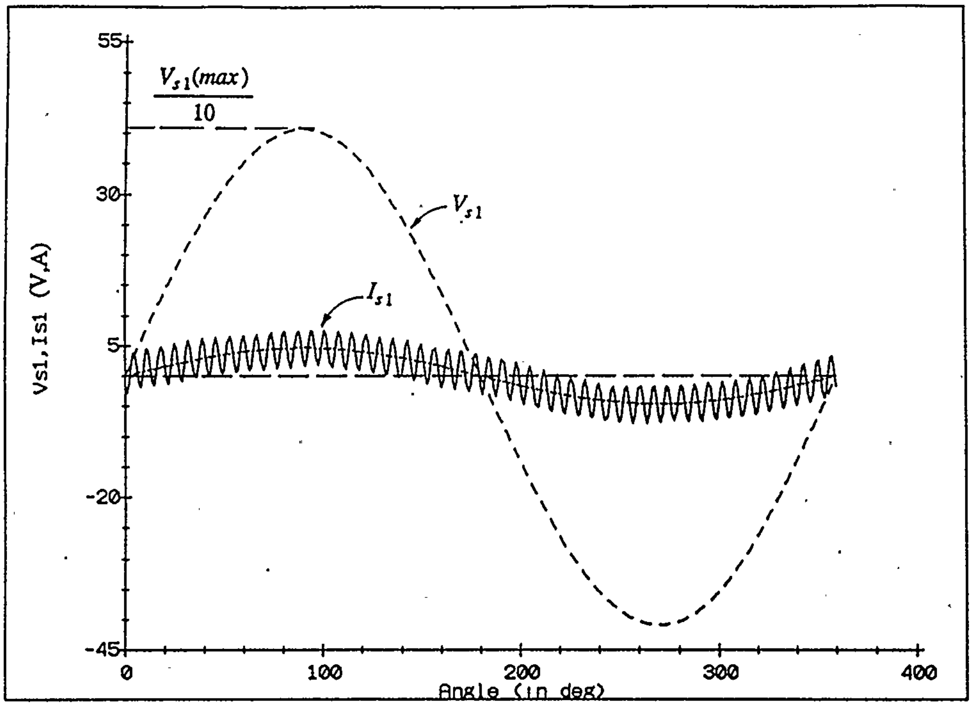


Fig.4.10 Waveforms of V_{s1} and I_{s1} at s = 0.0015 p.u.,FR = 54, 90 hp machine.

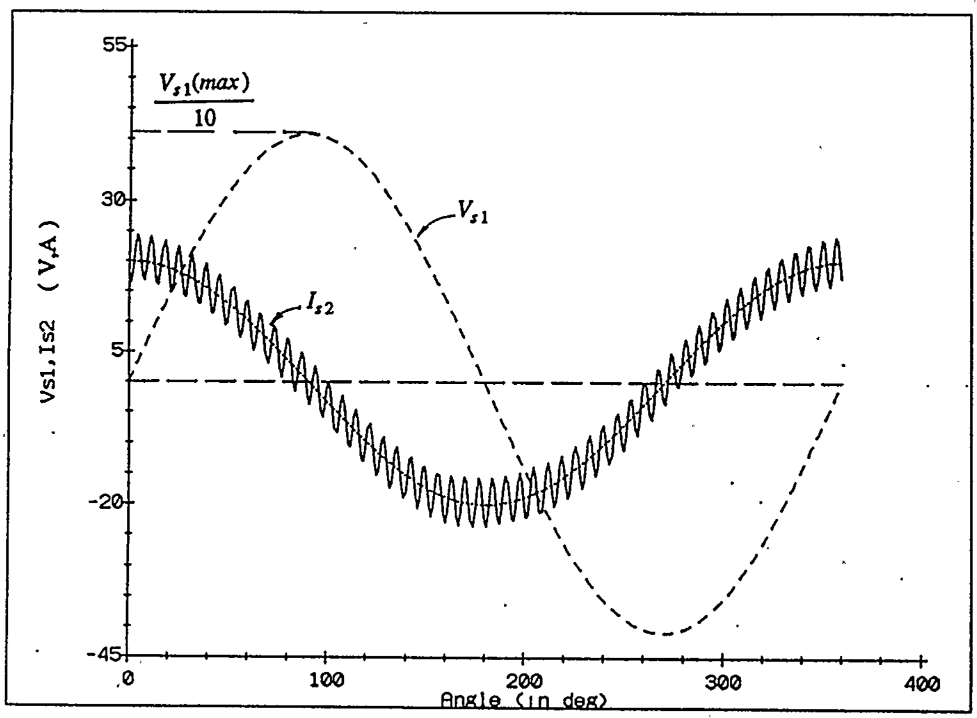
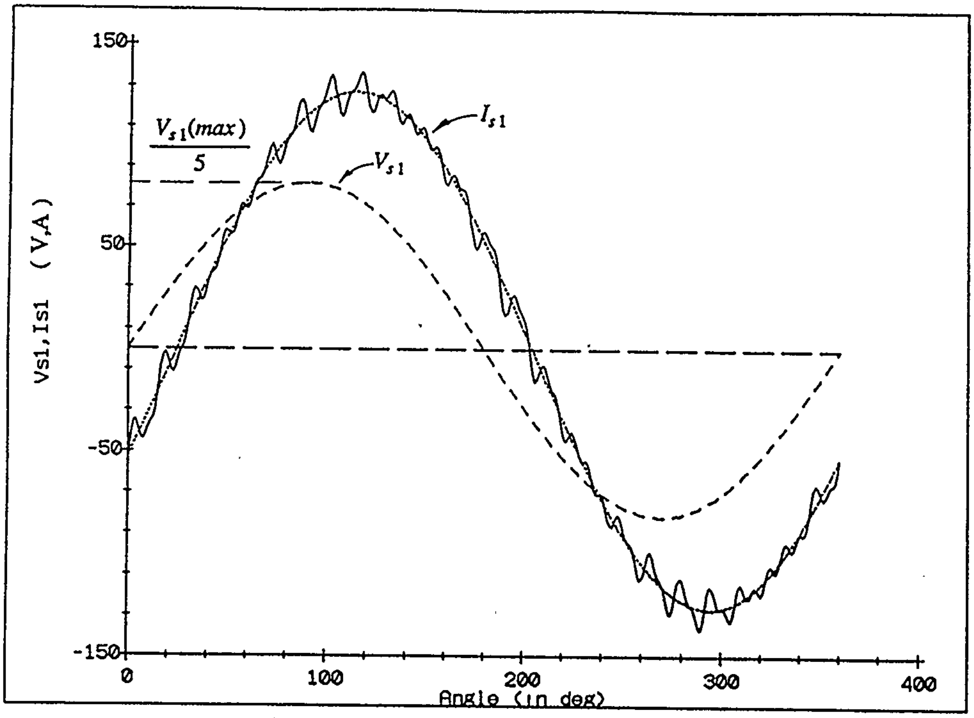


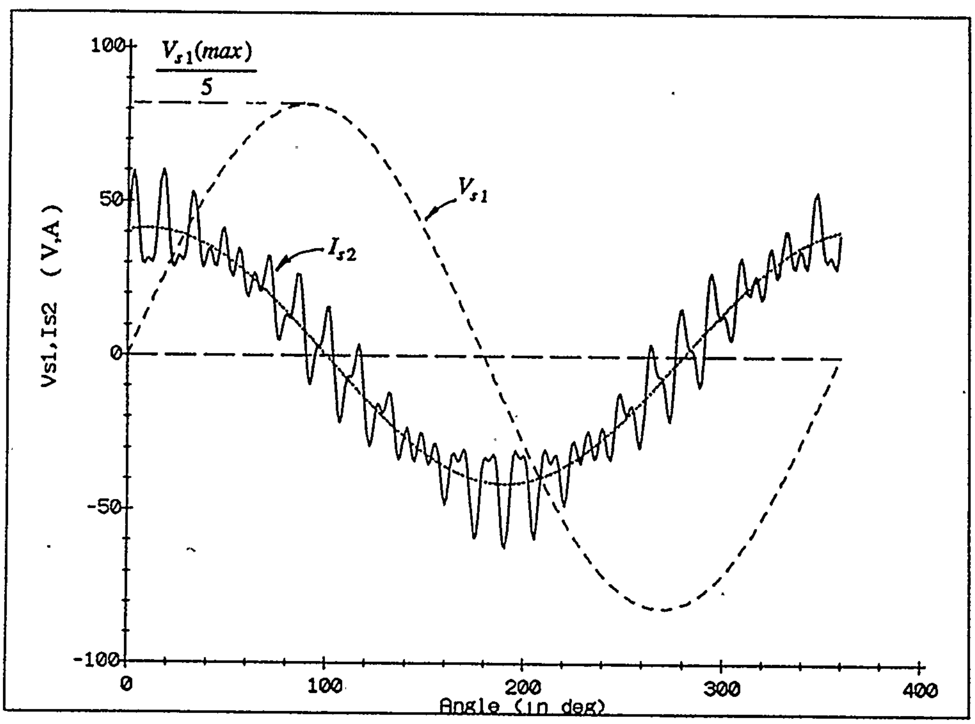
Fig.4.11 Waveforms of V_{s1} and I_{s2} at s = 0.0015 p.u.,FR = 54, 90 hp machine.

Table 4.1 Summary of simulation results at s = 0.055 p.u. for the 90 hp machine.

	FR = 24	FR = 42	FR = 54
Distortion factor in I_{s1}	0.05160	0.00634	0.00328
Distortion factor in I_{s2}	0.24560	0.00474	0.00170
Distortion factor in I_r	0.02940	0.01990	0.00172
	For unity p.f.	For optimum p.f.	--
$I_{s1}(1)$ (amps)	98.73	89.65	
$I_{s2}(1)$ (amps)	77.70	29.20	
$I_r(1)$ (amps)	105.78	84.21	
$V_{s2}(1)$ (volts)	328.56	276.85	
phase of V_{s2} (degree)	-14.15	-10.60	
Loss in R_{s2} (watts)	2354.00	332.79	
Rating of PWM inverter (kVA)	76.50	24.26	
Input power (watts)	85504.70	70526.80	
Output power (watts)	73484.60	62794.70	
Efficiency (%)	85.94	89.04	

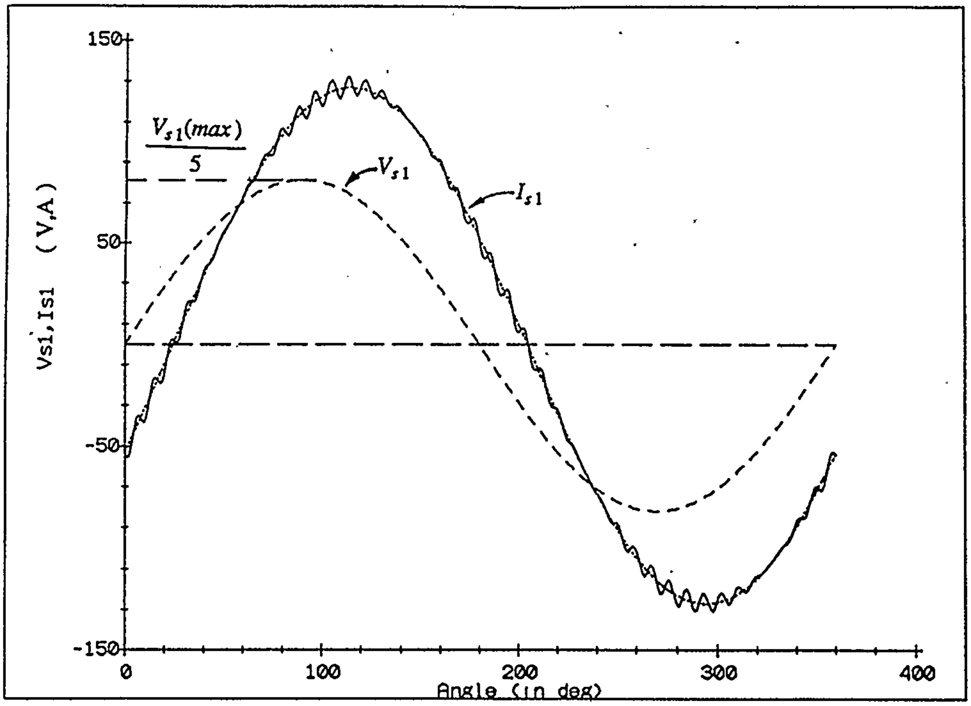


(a) Waveforms of V_{s1} and I_{s1}.

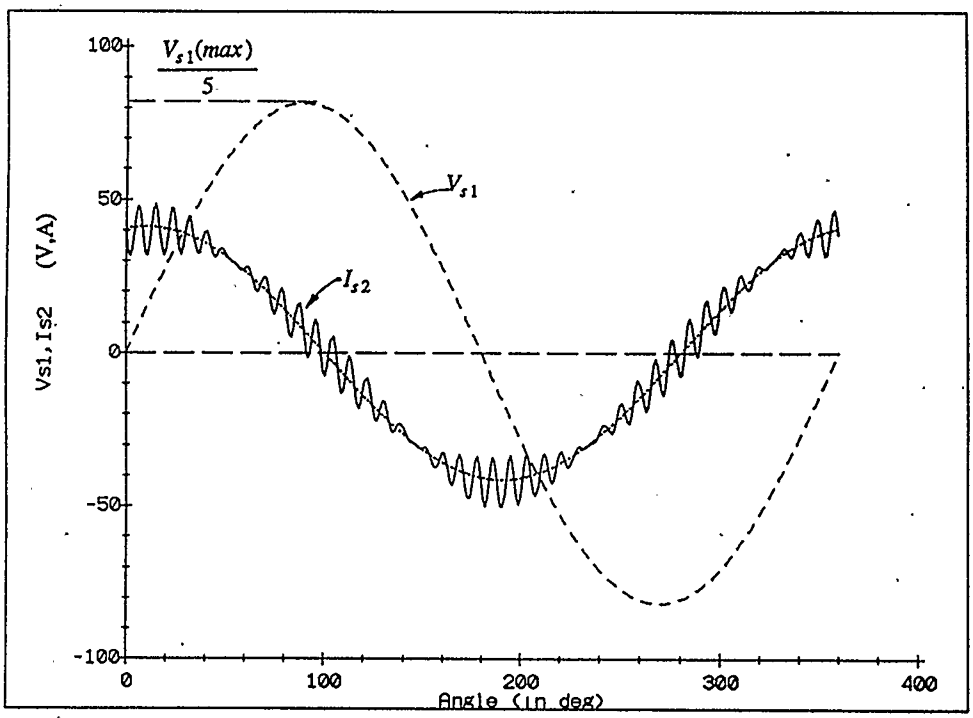


(b) Waveforms of V_{s1} and I_{s2}.

Fig.4.12 Waveforms of V_{s1}, I_{s1} and I_{s2} at s = 0.055 p.u.,FR = 24, 90 hp machine.

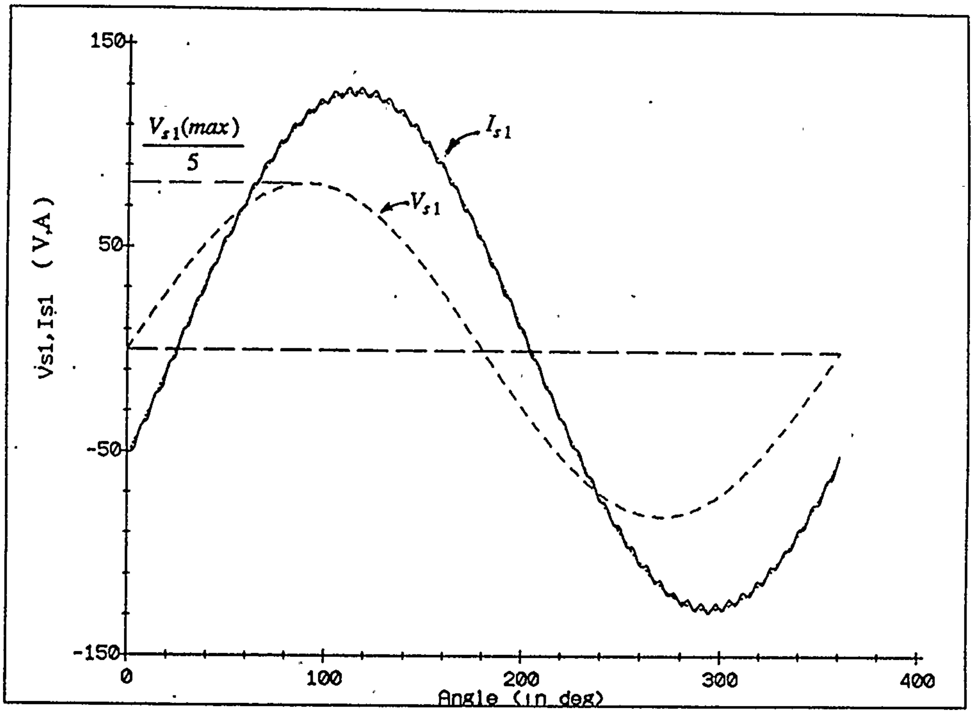


(a) Waveforms of V_{s1} and I_{s1}.

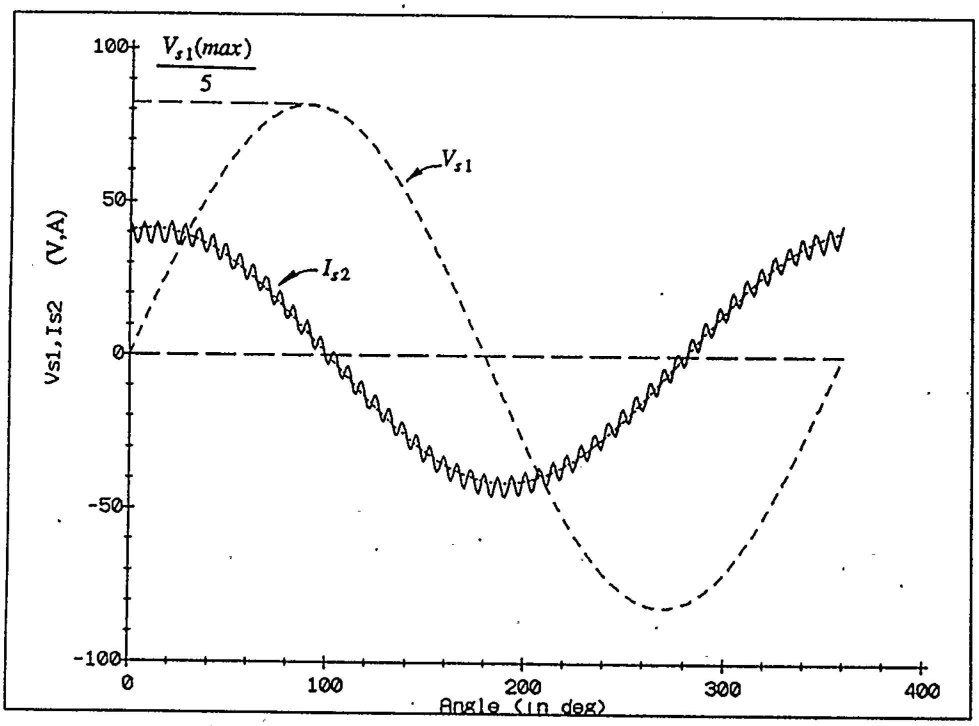


(b) Waveforms of V_{s1} and I_{s2}.

Fig.4.13 Waveforms of V_{s1}, I_{s1} and I_{s2} at s = 0.055 p.u.,FR = 42, 90 hp machine.



(a) Waveforms of V_{s1} and I_{s1}.



(b) Waveforms of V_{s1} and I_{s2}.

Fig.4.14 Waveforms of V_{s1}, I_{s1} and I_{s2} at s = 0.055 p.u.,FR = 54, 90 hp machine.

4.2.2 Simulation results for the 2 hp machine used in the experiment

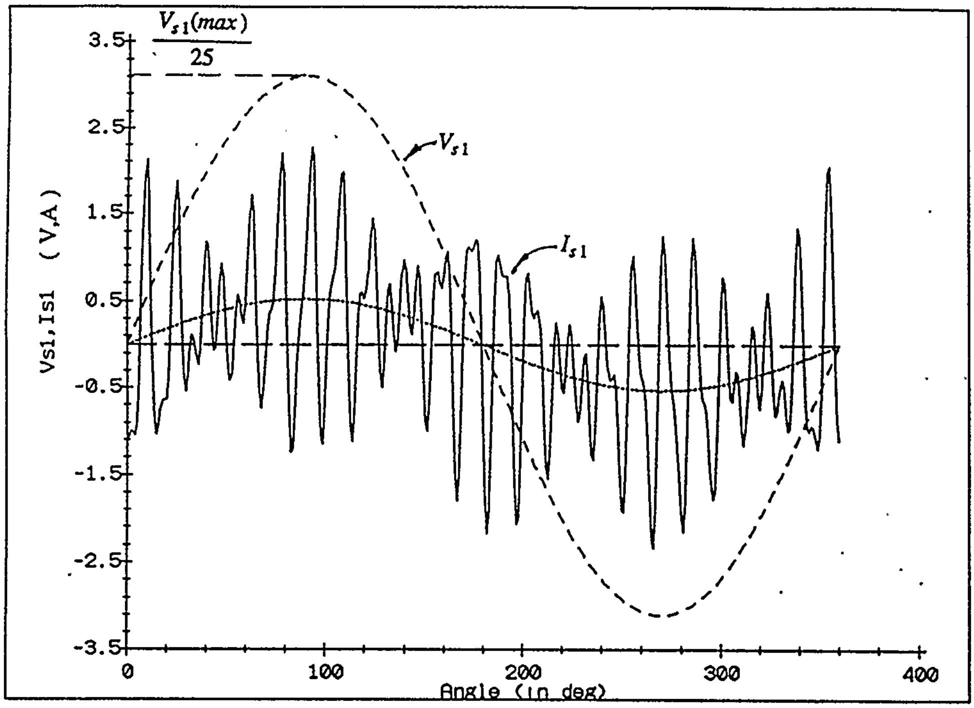
The parameters of the machine used in the experiment are given in Appendix 'B'. Complete simulation results determined by the computer program are given in Appendix 'E'.

Simulation results at light load (s = 0.0066 p.u.) are summarized in Table 4.2. The waveforms of I_{s1} and I_{s2} at frequency ratios of 20, 40 and 54 are shown in Figs.4.15, 4.16 and 4.17 respectively. These waveforms seem to be highly distorted, because the fundamental components are very small. Waveforms at higher frequency ratio are less distorted than those at lower frequency ratio.

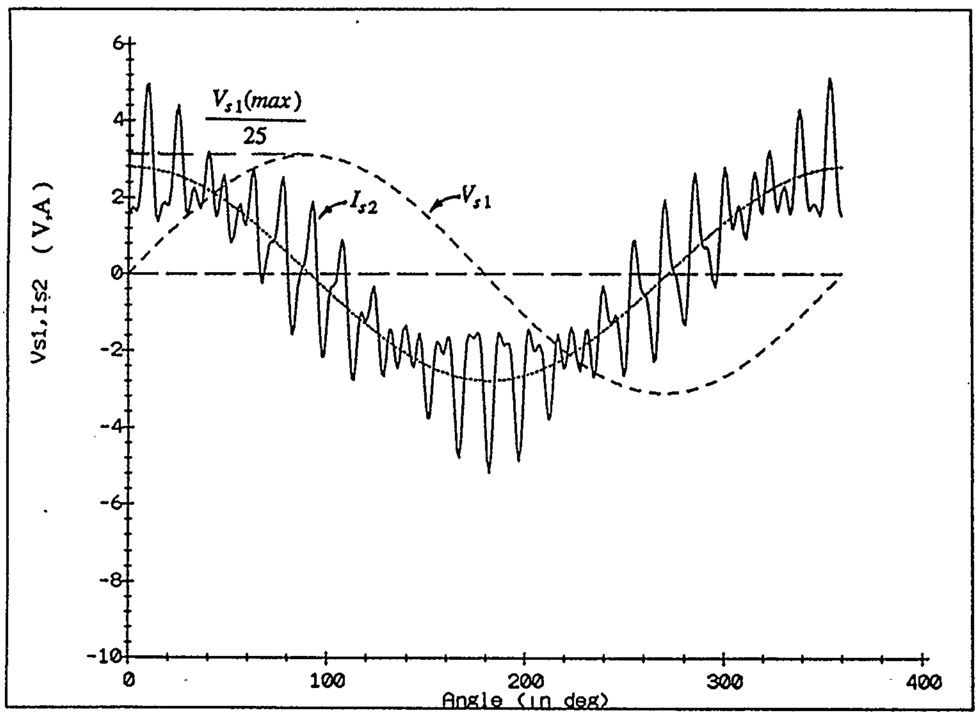
Simulation results at a slip of 0.06 p.u. are summarized in Table 4.3. The waveforms of I_{s1} and I_{s2} at frequency ratio of 20, 40 and 54 are shown in Figs.4.18, 4.19 and 4.20 respectively. These waveforms are comparatively less distorted than those at light load (s = 0.0066 p.u.).

Table 4.2 Summary of simulation results at s=0.0066 p.u. for the 2 hp machine.

	FR = 20	FR = 40	FR = 54
Distortion factor in I_{s1}	2.0890	0.0864	0.0536
Distortion factor in I_{s2}	0.4280	0.0169	0.0105
Distortion factor in I_r	2.1710	0.0284	0.0140
	Without auxiliary winding	With auxiliary winding	
$I_{s1}(1)$ (amps)	1.975	0.373	
power factor (lag)	0.185	1	
$I_{s2}(1)$ (amps)	-	1.97	
$V_{s2}(1)$ (volts)	-	56.58	
Phase of $V_{s2}(1)$ (degree)	-	-2.00	
Input power (watts)	60.19	61.30	
Output power (watts)	13.78	14.95	
Efficiency (%)	22.90	24.38	

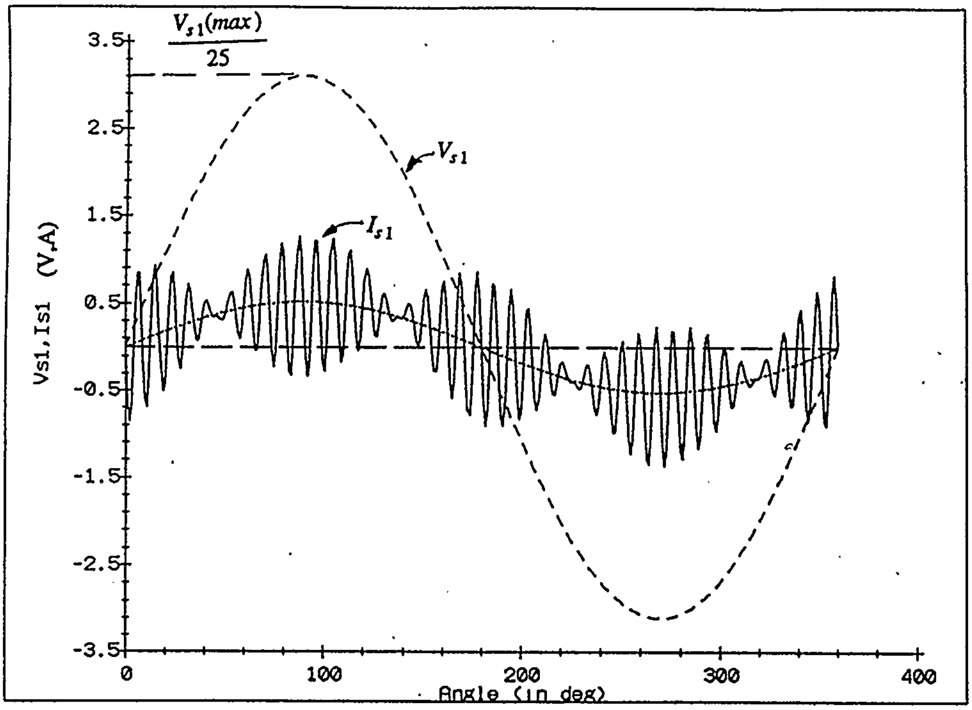


(a) Waveforms of V_{s1} and I_{s1}.

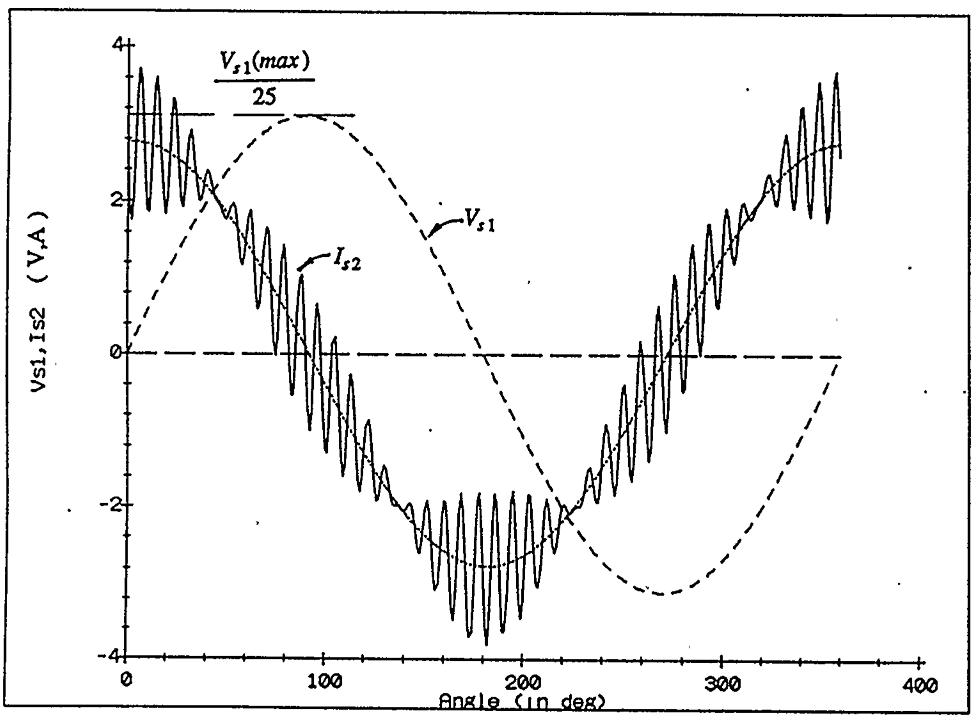


(b) Waveforms of V_{s1} and I_{s2}.

Fig.4.15 Waveforms of V_{s1}, I_{s1} and I_{s2} at s = 0.0066 p.u., FR=20, 2 hp machine.

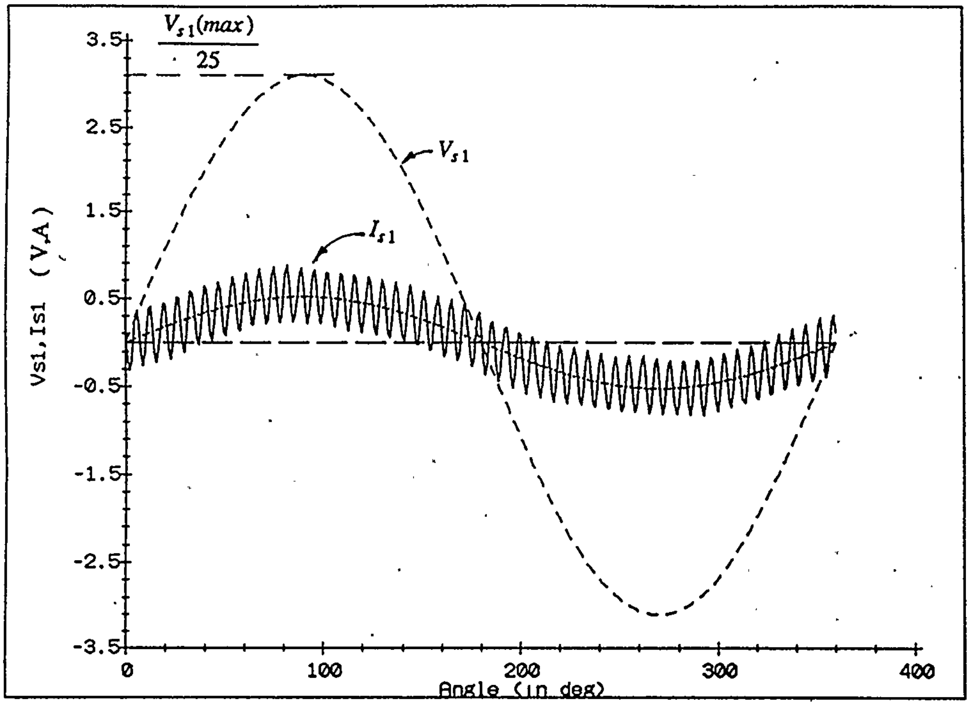


(a) Waveforms of V_{s1} and I_{s1}.

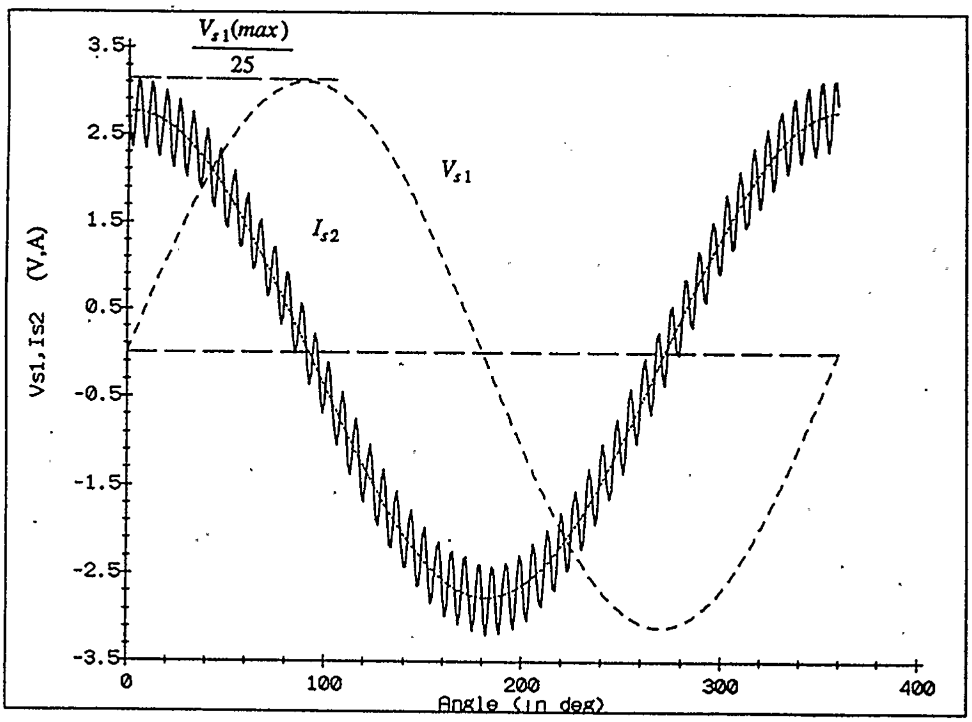


(b) Waveforms of V_{s1} and I_{s2}.

Fig.4.16 Waveforms of V_{s1}, I_{s1} and I_{s2} at s = 0.0066 p.u, FR=40, 2 hp machine.



(a) Waveforms of V_{s1} and I_{s1}.

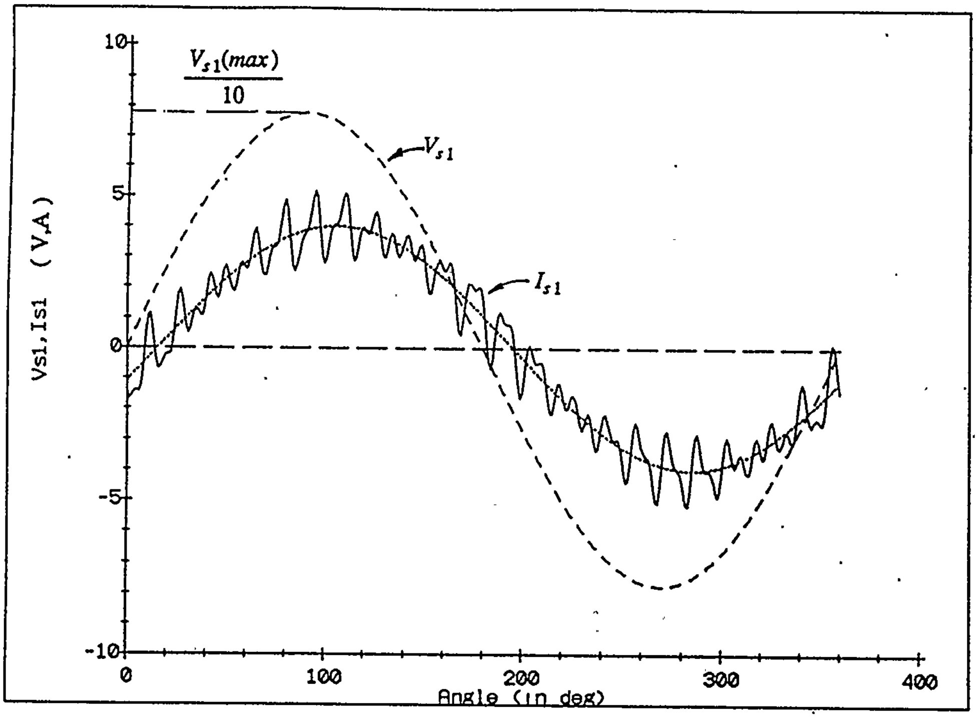


(b) Waveforms of V_{s1} and I_{s2}.

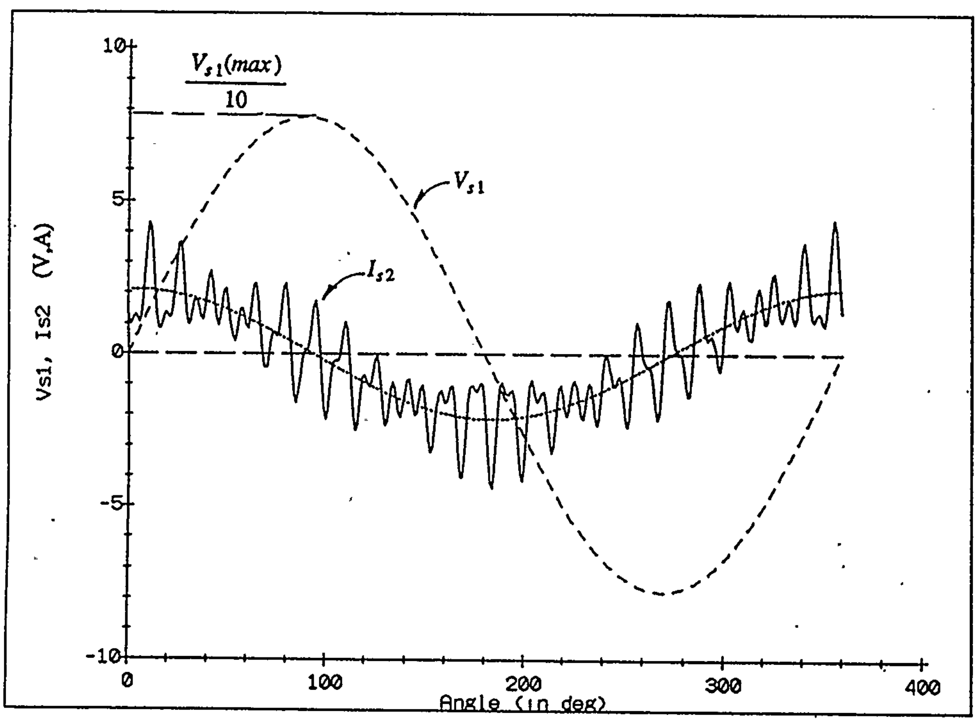
Fig.4.17 Waveforms of V_{s1}, I_{s1} and I_{s2} at s = 0.0066 p.u., FR= 54, 2 hp machine.

Table 4.3 Summary of simulation results at s = 0.06 p.u., for the 2 hp machine.

	FR = 20	FR = 40	FR = 54
Distortion factor in I_{s1}	0.1818	0.0054	0.0052
Distortion factor in I_{s2}	0.5172	0.0222	0.0115
Distortion factor in I_r	0.1174	0.0031	0.0016
	For unity pf	For optimum pf	
$I_{s1}(1)$ (amps)	2.85	2.83	
$I_{s2}(1)$ (amps)	2.34	1.50	
$I_r(1)$ (amps)	2.85	2.25	
$V_{s2}(1)$ (volts)	55.12	53.54	
Phase of $V_{s2}(1)$ (degree)	-5.18	-3.75	
Loss in R_{s2} (watts)	12.71	5.26	
Rating of PWM inverter (kVA)	0.38	0.24	
Input power (watts)	468.18	448.50	
Output power (watts)	373.45	371.42	
Efficiency (%)	79.76	82.81	

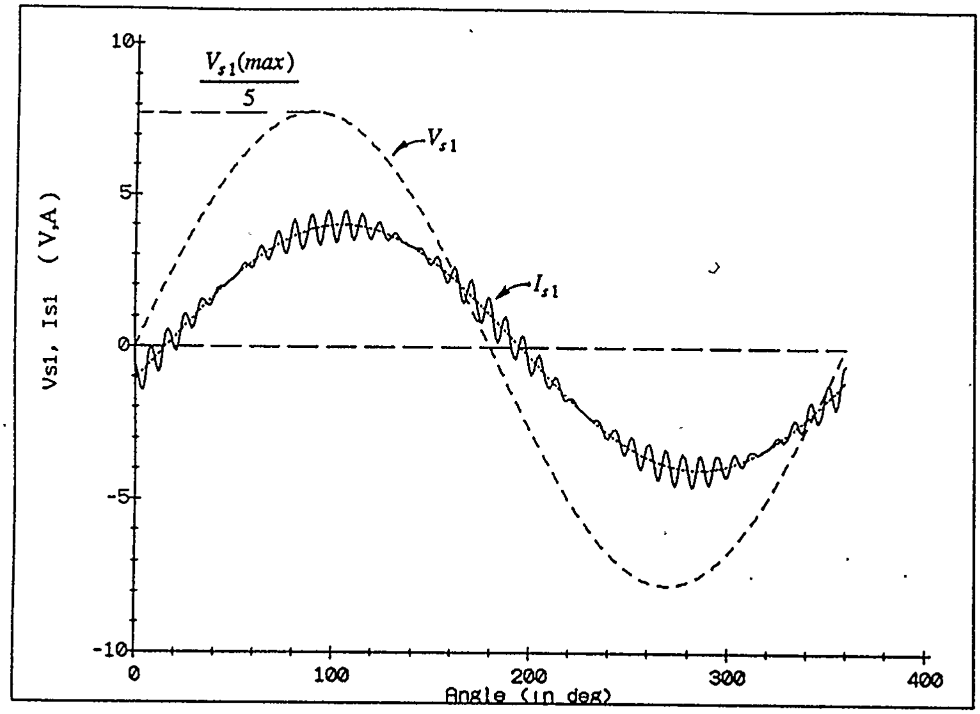


(a) Waveforms of V_{s1} and I_{s1}.

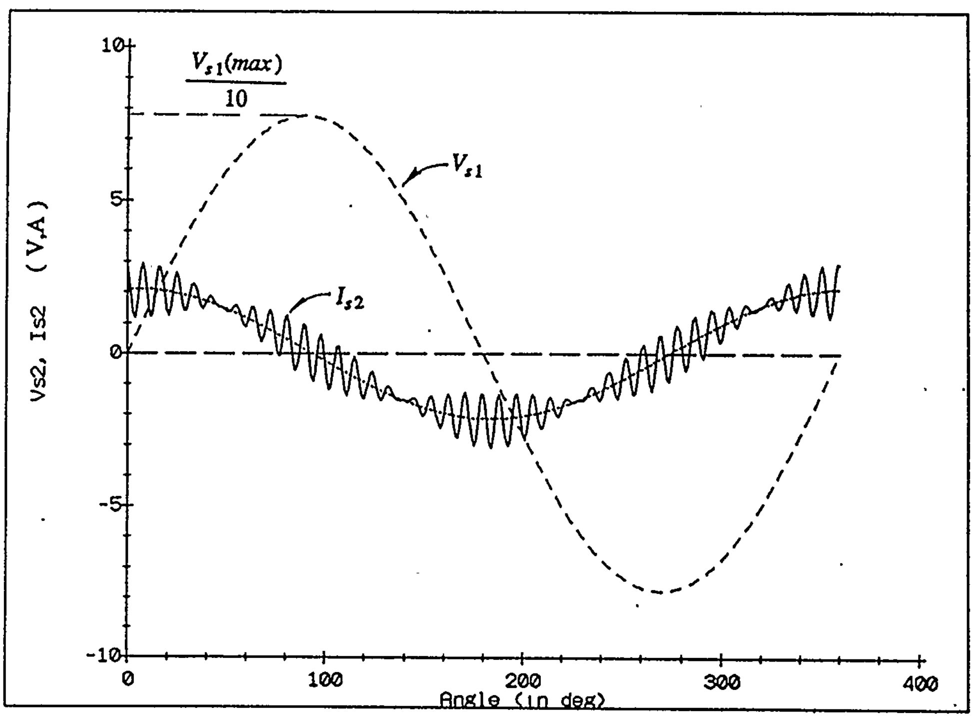


(b) Waveforms of V_{s1} and I_{s2}.

Fig.4.18 Waveforms of V_{s1}, I_{s1} and I_{s2} at s = 0.06 p.u., FR= 20, 2 hp machine.

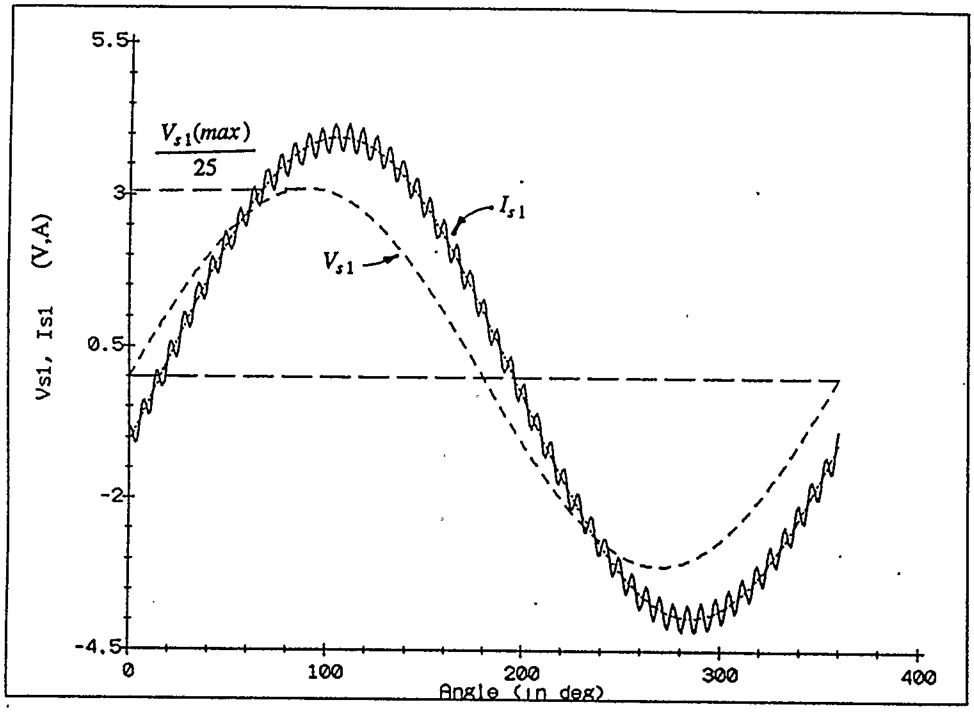


(a) Waveforms of V_{s1} and I_{s1}.

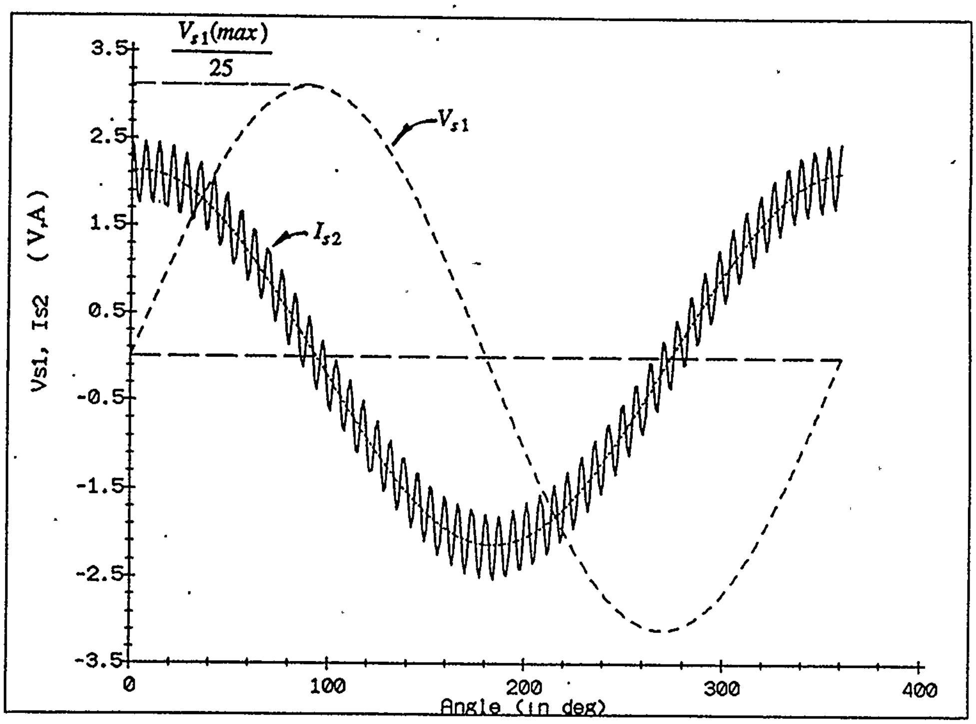


(b) Waveforms of V_{s1} and I_{s2}.

Fig.4.19 Waveforms of V_{s1}, I_{s1} and I_{s2} at s = 0.06 p.u., FR=40, 2 hp machine.



(a) Waveforms of V_{s1} and I_{s1}.



(b) Waveforms of V_{s1} and I_{s2}.

Fig.4.20 Waveforms of V_{s1}, I_{s1} and I_{s2} at s = 0.06 p.u., FR=54, 2 hp machine.

4.3 SUMMARY

In this Chapter, the simulation program has been described in block diagram form. Simulation results for a 90 hp induction machine (described in Appendix 'A') at light load and at full load for different PWM frequency ratios, have been described. Simulation results for a small machine, used in the experiment, also have been described.

Simulation results show that the harmonics in the main input current can be reduced to a low value to give smooth waveform of I_{s1} by operating the PWM inverter with frequency ratio (FR) of 54 (i.e. carrier frequency of 3240 Hz.). The waveforms of the currents in the small machine look comparatively more distorted than those for the large machine. The rating of the PWM inverter and dc capacitor required for 90 hp induction motor are given below :

Rating of PWM inverter :

500 volts, 25 kVA

Rating of dc capacitor :

1000 volts, 60 μF, 40 kVAr

or

2 units each of 500 volts, 120 μF, 20 kVAr

CHAPTER 5

EXPERIMENTAL STUDIES

Simulation studies presented in Chapter 4 show that the proposed scheme with the PWM inverter operated at a frequency ratio of 54 gives very good performance with nearly sinusoidal input current. When the PWM inverter is operated at a lower frequency ratio, the input current waveform is highly distorted. In order to verify the simulation results, some experiments have been performed.

The experimental set up for the proposed scheme is described in this Chapter. Due to the lack of proper equipment and control system, it was not possible to do the implementation exactly as described in the simulation study. In the first stage, the experiment is set up by replacing the PWM voltage inverter by a sinusoidal ac voltage source (an auto transformer). In the next stage, the experiment is set up with the PWM inverter with the dc side supplied by an independent dc voltage source. The experimental results are described and compared with the simulation results.

5.1 EXPERIMENTAL SET UP WITH AUTO TRANSFORMER

The main aim of this part of the experiment is to test the basic principle of power factor correction involved in the proposed scheme. Circuit arrangement and the instrumentation of the set up are shown in Fig.5.1. Equivalent circuit of this arrangement is shown in Fig.5.2 and its phasor diagrams are shown in Fig.5.3. In

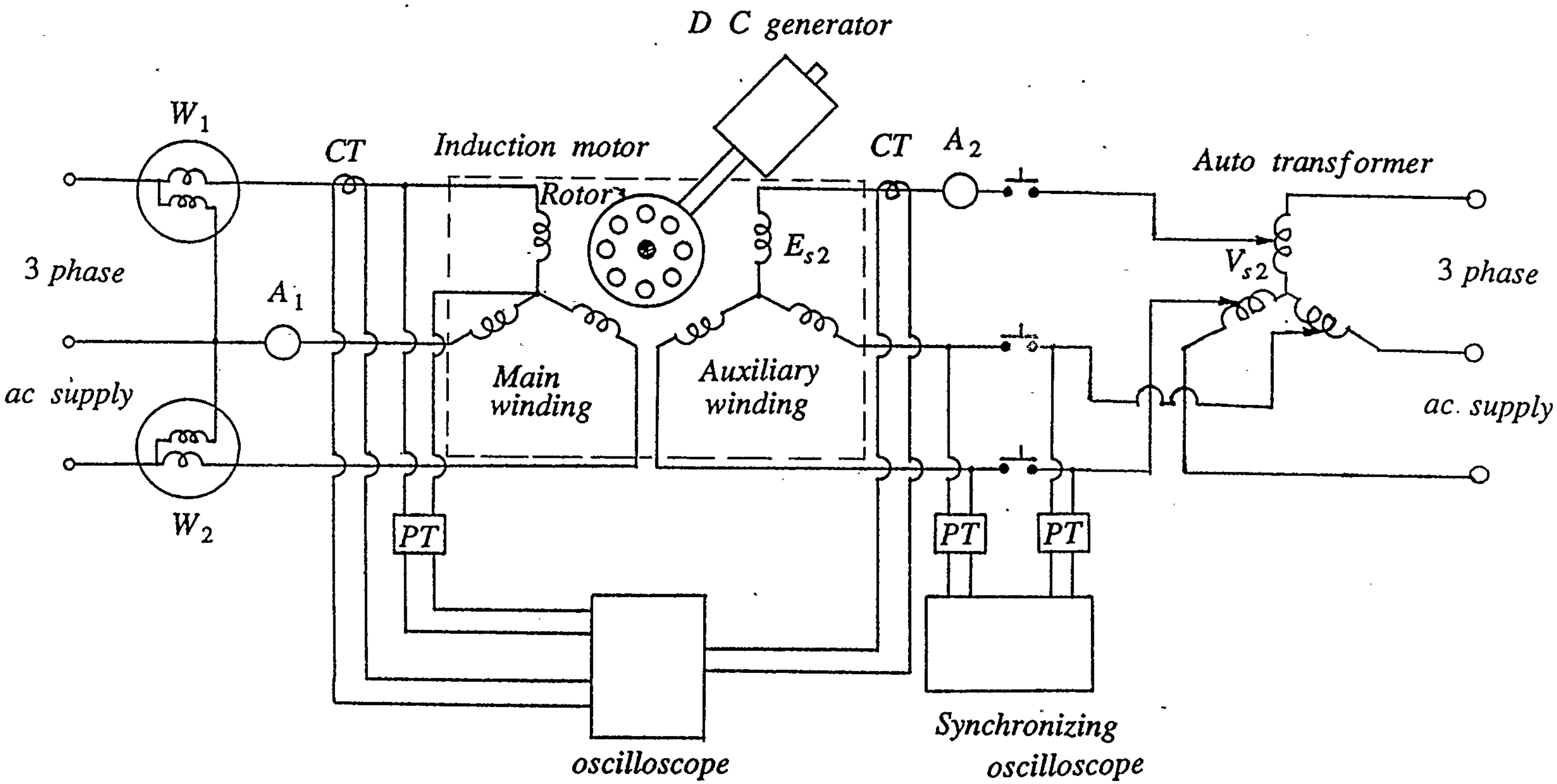


Fig.5.1 Experimental set up with auto transformer

order to simplify the phasor diagrams, voltage drop in the main stator winding impedance has been neglected so that the emf induced across the auxiliary stator winding E_{s2} is in phase with with V_{s1}.

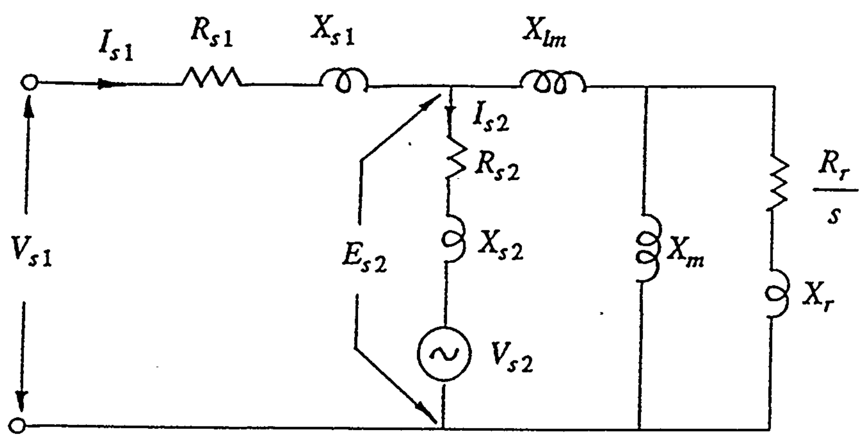


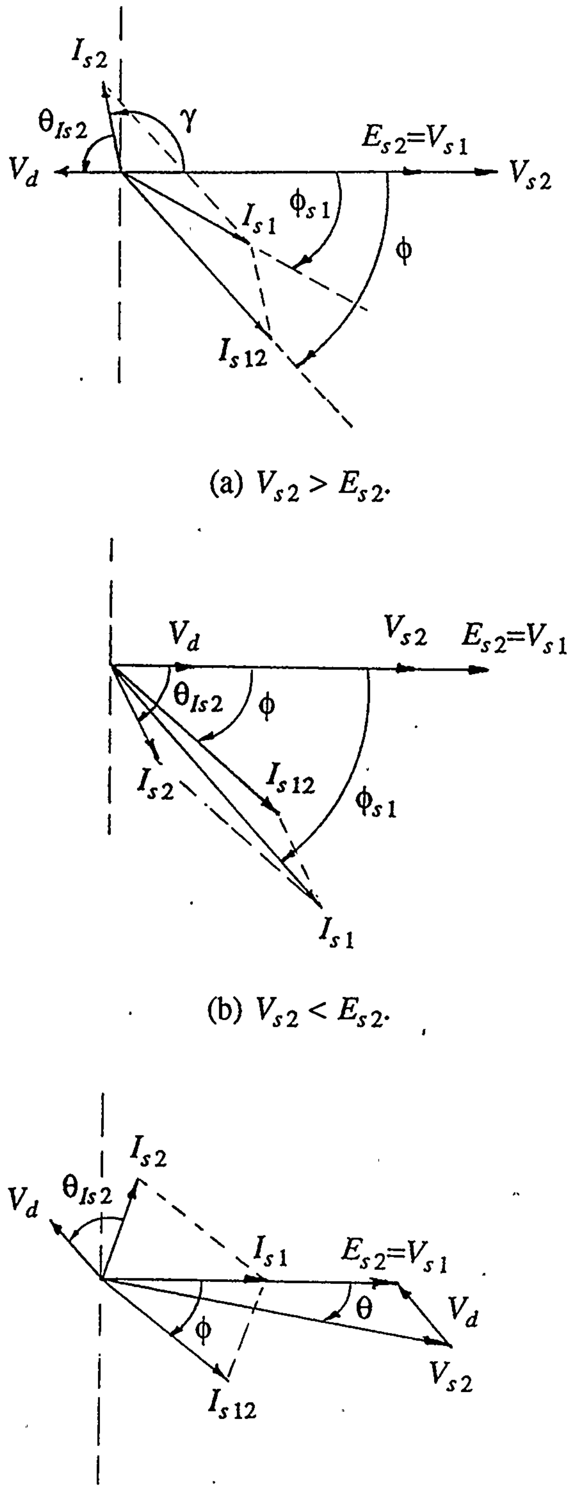
Fig.5.2 Equivalent circuit of the scheme with auto transformer.

Phasor diagram for $V_{s2} > E_{s2}$ is shown in Fig.5.3(a). I_{s12} is the current drawn by the induction motor when the auxiliary stator winding is not supplied by the auto transformer and cosϕ is the power factor. When the auxiliary stator winding is supplied by the auto transformer, the current through the auxiliary stator winding is given by :

$$\vec{I}_{s2} = \frac{\vec{V}_d}{R_{s2} + jX_{s2}} \tag{5.1}$$

where,

$$\vec{V}_d = \vec{E}_{s2} - \vec{V}_{s2} \tag{5.2}$$



(a) $V_{s2} > E_{s2}$.

(b) $V_{s2} < E_{s2}$.

(c) $V_{s2} > E_{s2}$ and V_{s2} lags V_{s1} by θ.

Fig.5.3 Phasor diagrams of the scheme with auto transformer.

I_{s2} lags V_d by an angle of θ_{Is2}.

where,

$$\theta_{Is2} = \tan^{-1}(\frac{X_{s2}}{R_{s2}}) \tag{5.3}$$

The main input current I_{s1} is given by the phasor sum of I_{s12} and I_{s2}. The corrected power factor is $\cos\phi_{s1}$.

When $V_{s2} < E_{s2}$, the scheme does not help to improve the power factor, which is clear from the phasor diagram shown in Fig.5.3(b).

In the phasor diagram shown in Fig.5.3(c) $V_{s2} > E_{s2}$ and V_{s2} lags E_{s2} by an angle of θ. If the angle θ is properly adjusted, I_{s2} can be made to lead V_{s2} exactly by 90 degrees. In that case, the voltage source V_{s2} in the equivalent circuit acts as a pure capacitor and the most effective power factor correction can be obtained.

5.2 EXPERIMENTAL SET UP WITH PWM INVERTER

Circuit arrangement and instrumentation for the set up is shown in Fig.5.4. It is mentioned in the literature [7] that the proposed scheme can be arranged either with self controlled dc bus in the inverter or with an independently controlled dc bus in the inverter. Independently controlled dc bus is used in this experimental setup. Here the inverter is operated as a reactive power source. It absorbs no active power from the main stator winding and the losses in the auxiliary stator winding and the inverter have to be supplied by the dc source itself. The reactive power supplied by the inverter can be changed by changing the inverter output voltage.

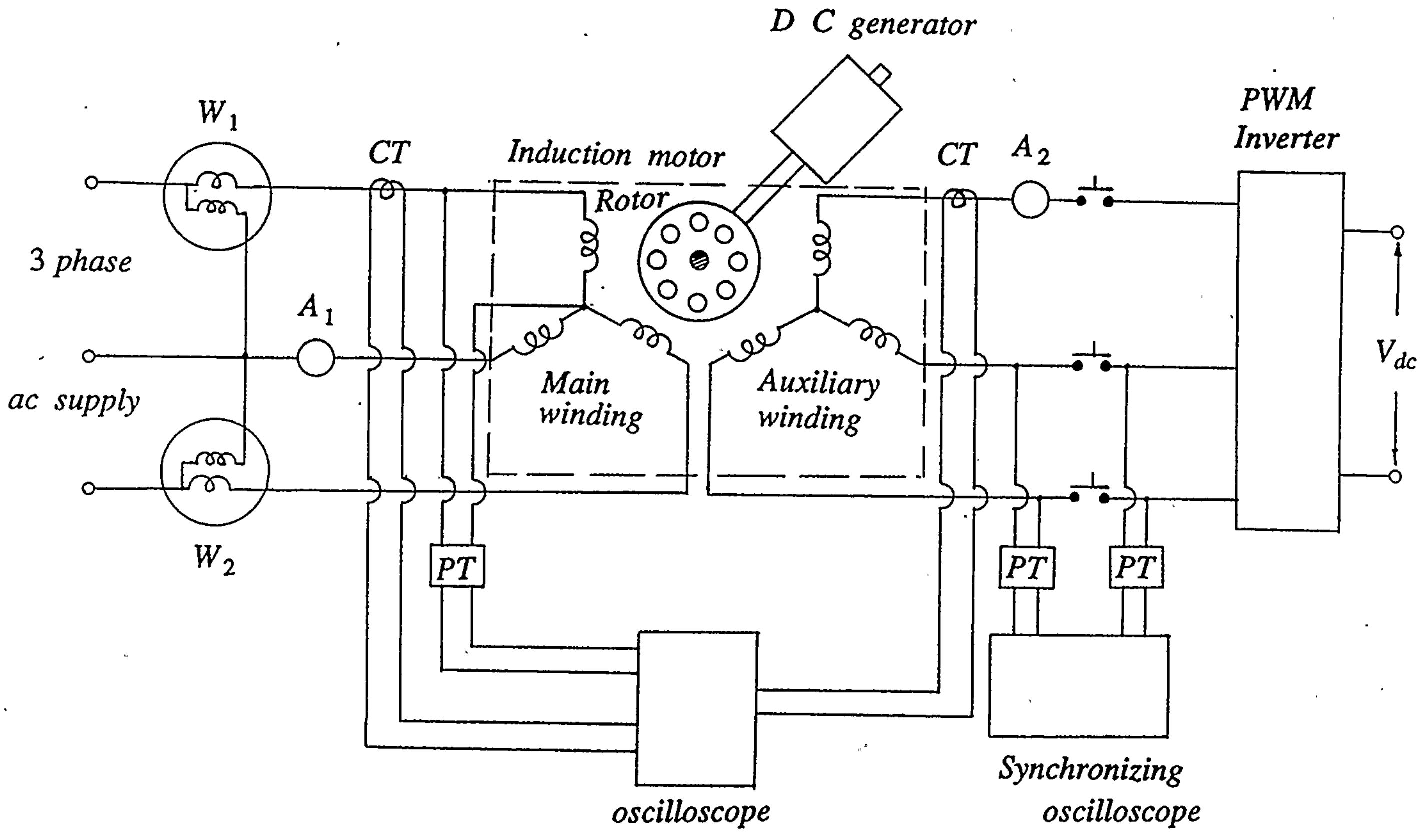


Fig.5.4 Experimental set up with PWM inverter

This experimental set up differs from the model used in the simulation study as follows :

(a) The dc bus in the inverter is independently controlled rather than self controlled.

(b) The inverter output voltage is exactly in phase with E_{s2} rather than adjustable lagging phase angle θ.

(c) The maximum carrier frequency, at which the inverter can be operated, is 2400 Hz.

5.3 RESULTS

The experiment was conducted for a light load on the motor corresponding to a slip of 0.0066 p.u.. The shaft of the motor was coupled to the shaft of a dc machine. The heavy mass of the rotor of the dc machine acted as the load on the induction motor.

With the induction motor running at light load as above, and the auxiliary winding unenergized, the applied voltage, input current, input power and speed were measured. The test was then repeated with the auxiliary winding supplied by an auto transformer. The supply from the auto transformer was connected to the auxiliary winding when the emf E_{s2} and V_{s2} were exactly equal and in phase. Then the magnitude of V_{s2} was adjusted to correct the power factor. A similar test was also conducted with the auxiliary winding supplied by the PWM inverter. The results are given in Table 5.1.

Table 5.1 Experimental results.

With auxiliary stator winding unenergized					
Speed RPM	V_L V	I_{s1} A	P_{in} W	pf(calculated) lag	ϕ(calculated) deg
1788	95	2.2	170	0.47	62

With auxiliaty stator winding supplied by auto transformer						
Speed RPM	V_L V	I_{s1} A	P_{in} W	pf(calculated) lag	ϕ_{s1}(calculated) deg	I_{s2} A
1788	95	1.4	180	0.78	38.6	1.0

With auxiliary stator windimg supplied by PWM inverter							
Carrier frequency Hz	Speed RPM	V_L V	I_{s1} A	P_{in} W	pf(cal) lag	ϕ_{s1}(cal) deg	I_{s2} A
1200	1788	95	4.6	255	0.34	70	5.2
2400	1788	95	2.5	195	0.47	61.7	3.2

For the case of motor operating with auxiliary stator winding unenergized, the recorded waveforms of V_{s1} and I_{s1} are given in Fig.5.5. Here the measured phase angle between V_{s1} and I_{s1} is 60 degree which is very close to the calculated value given in Table 5.1.

The recorded waveforms of V_{s1}, I_{s1} and I_{s2} for the case of the auxiliary winding supplied by the autotransformer are given in Fig.5.6. The phasor diagram reconstructed from the recorded data is given in Fig.5.7 which is similar to that given in Fig.5.3(a).

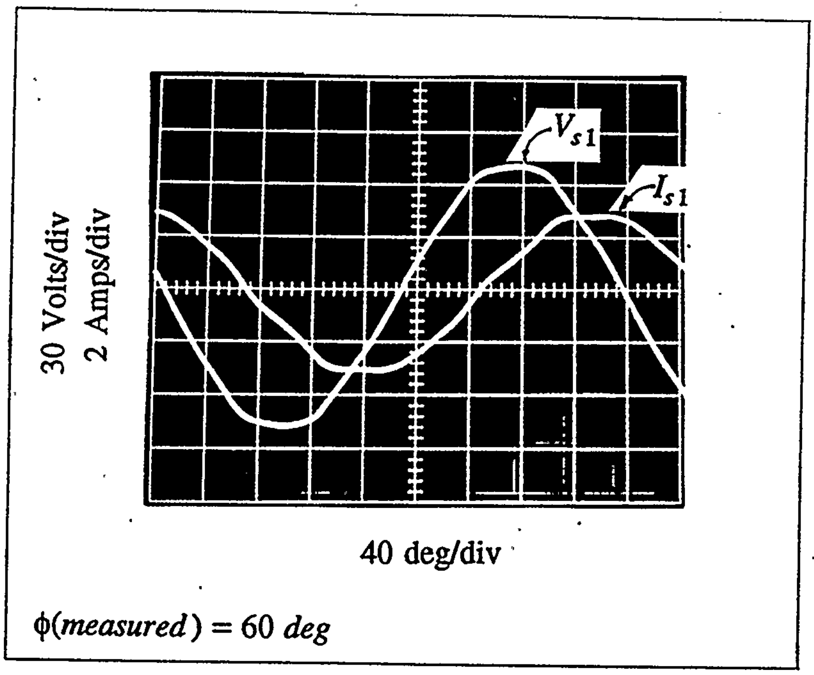
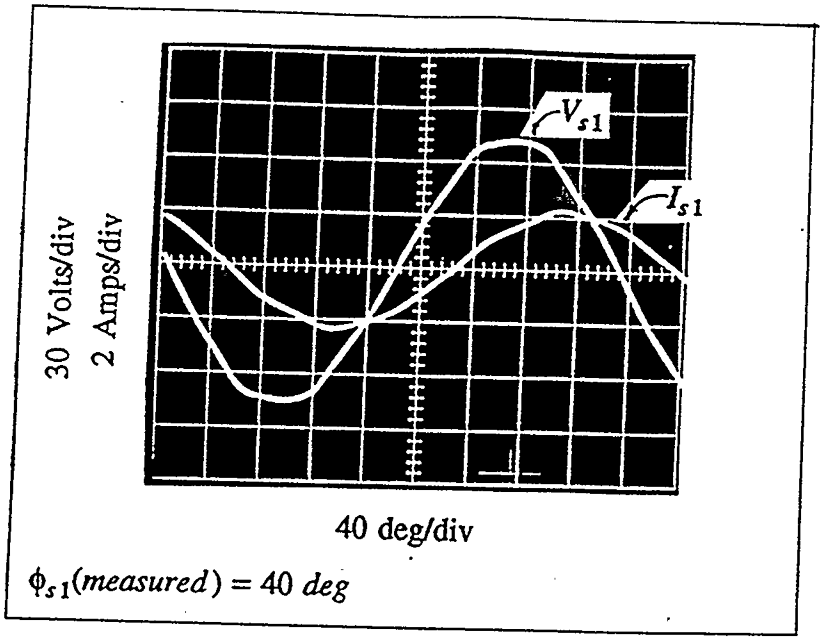
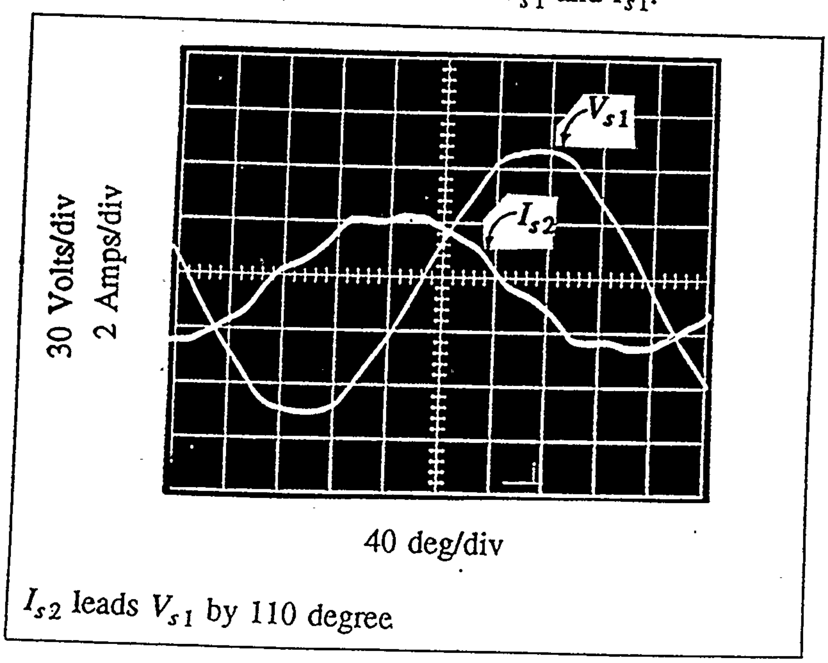


Fig.5.5 Waveforms of V_{s1} and I_{s1} with auxiliary winding unenergized.



(a) Waveforms of V_{s1} and I_{s1}.



(b) Waveforms of V_{s1} and I_{s2}.

Fig.5.6 Waveforms of V_{s1}, I_{s1} and I_{s2} with auxiliary winding supplied by auto transformer.

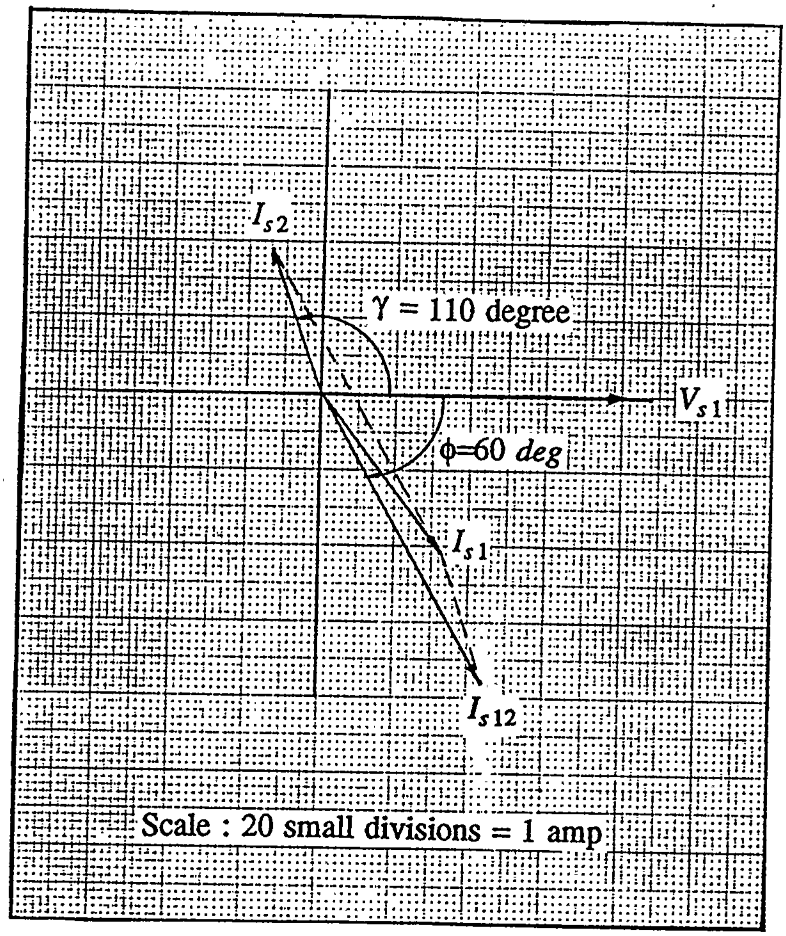
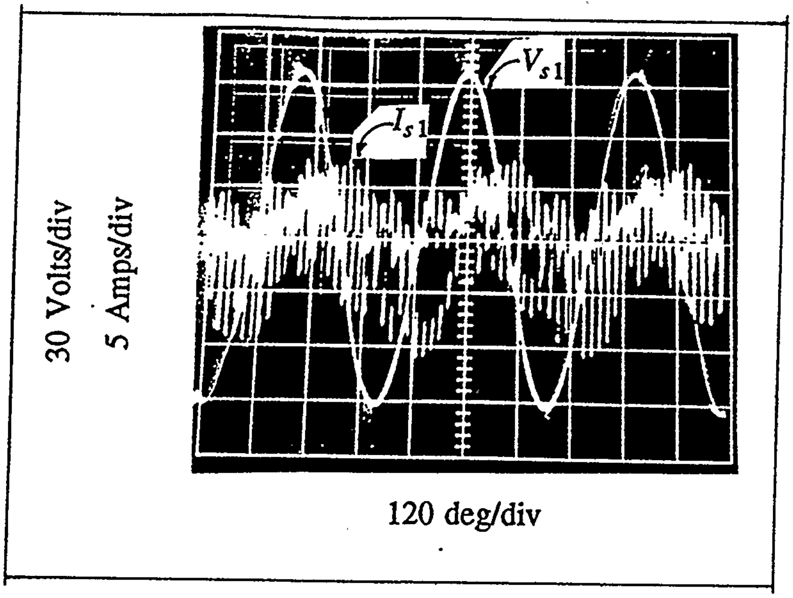


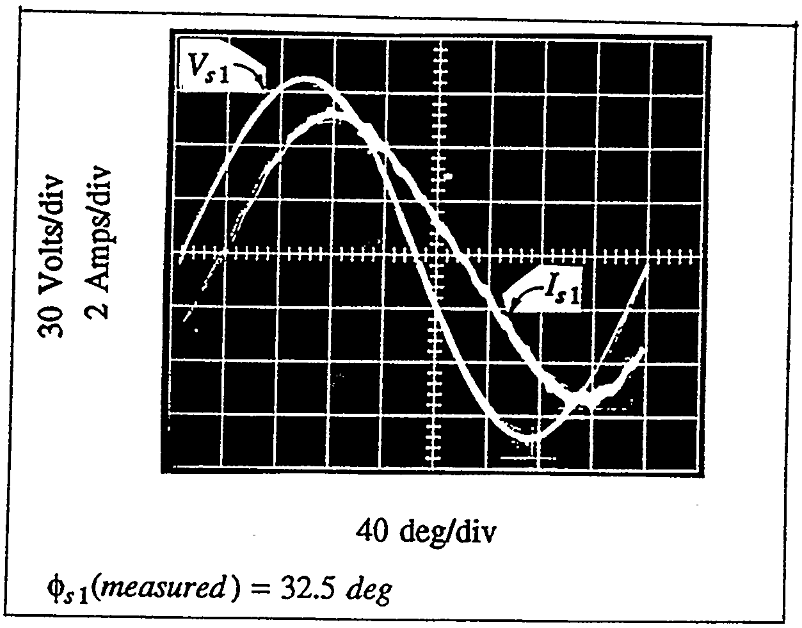
Fig.5.7 Phasor diagram reconstructed from experimental data for the scheme with auto transformer.

When the motor was operated with the auxiliary stator winding supplied by the PWM inverter at a carrier frequency of 1200 Hz (i.e. FR = 20), the main stator winding drew a current of 4.6 A and consumed 255 W. The calculated power factor based on these readings is 0.34, which is fairly poor. Here the harmonic currents are playing a significant role. The recorded waveform of I_{s1} is given in Fig.5.8(a) which is highly distorted. The current of 4.6 A indicated by the ammeter includes the fundamental and the harmonic components of certain order up to which the moving system of the ammeter can respond. Similarly the wattmeter reading includes fundamental power as well as harmonic power. That is why the calculated power is so low. The waveforms of V_{s1} and I_{s1} recorded by using a filter (available in the oscilloscope) are shown in Fig.5.8(b). These waveforms represent the fundamental components of V_{s1} and I_{s1}. Here I_{s1} lags V_{s1} by an angle of 32.5 degree which gives a power factor of 0.84. Hence the problem is due to harmonic currents.

When the PWM inverter was operated at a carrier frequency of 2400 Hz (i.e. FR = 40), the distortion factor in I_{s1} was significantly reduced which is clear from the recorded waveform of I_{s1} shown in Fig.5.9(a). The current and power decreased with an attendant improvement in calculated power factor. The waveforms of V_{s1} and I_{s1} recorded by using filter are shown in Fig.5.9(b). Here I_{s1} lags V_{s1} by an angle of 24 degree which gives a power factor of 0.9.



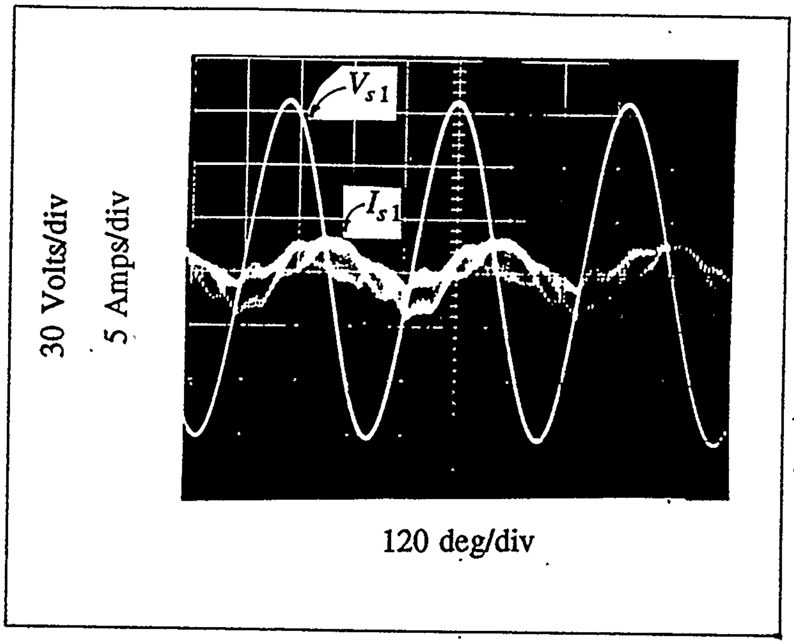
(a) Waveform of unfiltered I_{s1}.



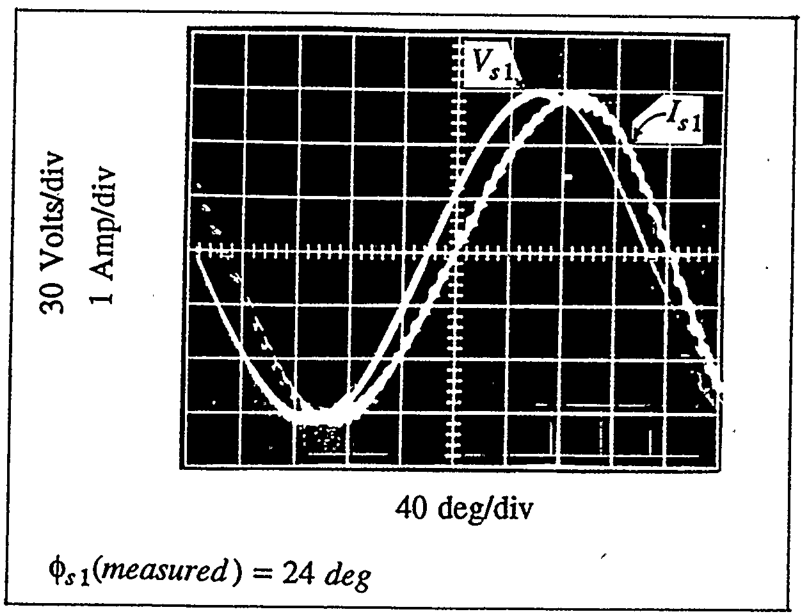
(b) Waveforms of filtered V_{s1} and I_{s1}.

Fig.5.8 Waveforms of V_{s1} and I_{s1} with auxiliary winding supplied by PWM inverter

(at carrier frequency of 1200 Hz)



(a) Waveform of unfiltered I_{s1}.



(b) Waveforms of filtered V_{s1} and I_{s1}.

Fig.5.9 Waveforms of V_{s1} and I_{s1} with auxiliary winding supplied by PWM inverter (at carrier frequency of 2400 Hz)

5.4 SUMMARY

In this Chapter, the experimental set up is described and the experimental results are explained. The basic principle of power factor correction involved in the proposed scheme has been tested by the experimental set up with an auto transformer.

Simulation studies given in Chapter 4 showed that the waveform of I_{s1} is very distorted (as shown in Fig.4.15(a)) at PWM carrier frequency of 1200 Hz (i.e. FR=20). This waveform is more or less similar to the waveform (recorded experimentally) given in Fig.5.8(a). Simulation studies also showed that the waveform of I_{s1} is less distorted (as shown in Fig.4.16(a)) at higher PWM carrier frequency of 2400 Hz (i.e. FR=40). This waveform is more or less similar to the waveform (recorded experimentally) given in Fig.5.9(a). According to the simulation results, distortion in I_{s1} can be further reduced by operating the PWM inverter at higher carrier frequency of 3250 Hz (i.e. FR=54).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The objective of the thesis outlined in Chapter 1 was to perform a detailed study of a scheme for power factor correction of an induction machine. Detailed mathematical analysis of the proposed scheme has been done and the scheme has been simulated on a digital computer using the mathematical models developed. Some experiments have been performed to verify the simulation results.

The proposed scheme is compared with the fixed capacitor thyristor controlled reactor scheme in this Chapter. Application of the proposed scheme for an induction generator is briefly described. Major conclusions drawn from the study and some recommendations for further research are outlined.

6.1 COMPARISION OF PROPOSED SCHEME WITH FIXED CAPACITOR THYRISTOR CONTROLLED REACTOR SCHEME

Power factor correction of induction motors by means of thyristor controlled reactor (TCR) has been described in section 2.3. This scheme provides continuous control of reactive power and the scheme is self adaptive for different load conditions. The proposed scheme is an alternative to this scheme.

Ratings of the major components required for the thyristor controlled reactor (TCR) scheme with 90 hp induction machine described in Appendix 'A' are listed below. These ratings are calculated by using equations (2.10) - (2.17).

3 units of ac capacitors

500 μF, 300 V, 16 kVAr

3 units of inductors

17 mH, 300 V, 45 A

3 pairs of thyristor switch and control system

300 V, 45 A

3 units of L-C filters as described in Fig.2.6.

Rating of major components required for the proposed scheme with the 90 hp machine have been listed in section 4.3. The proposed scheme requires one unit of 60 μF, 1000 V, 40 kVAr or two units of 120 μF, 500 V, 20 kVAr dc capacitor rather than three units of 500 μF, 300 V, 16 kVAr ac capacitors. Filter circuits are not required for the proposed scheme. The auxiliary stator winding and PWM inverter in the proposed scheme are more or less equivalent to the inductors and thyristor switch pairs in the TCR scheme. Hence the proposed scheme is likely to be more economical than TCR scheme.

6.2 APPLICATION OF THE PROPOSED SCHEME FOR INDUCTION GENERATOR

It has been well explained in the literature [20 - 22] that an induction machine with capacitors connected across its terminals can build up voltage in a manner similar to that of the self excited dc shunt generator. The capacitive current has to compensate for the lagging reactive components of the magnetizing current and load current in order to maintain a constant terminal voltage. Therefore, fixed capacitor excitation is not useful for an induction generator with varying power factor loads.

A static excitor with thyristor controlled reactor (TCR) has been proposed in the literature [23] to provide proper excitation at different load conditions. A single line diagram of this scheme is shown in Fig.6.1. The proposed scheme for power factor correction of an induction motor also can be used to provide excitation to the induction generator as shown in Fig.6.2.

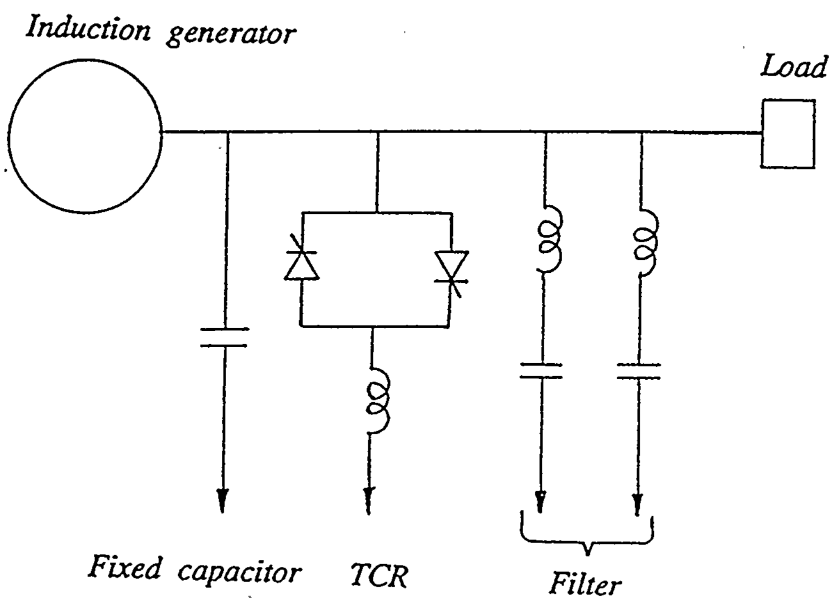


Fig.6.1 Excitation of induction generator with thyristor controlled reactor.

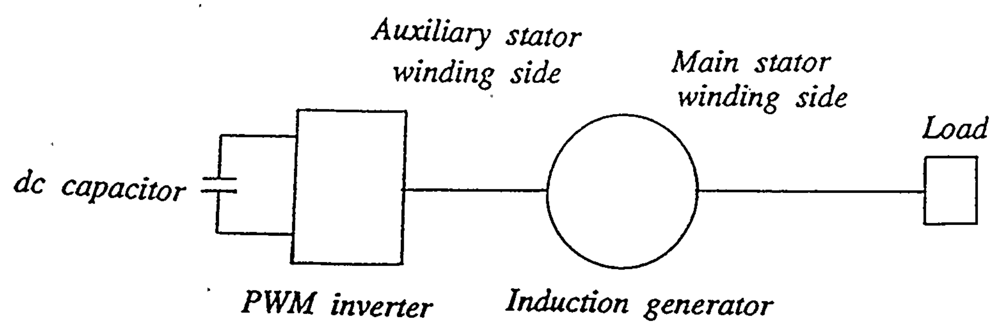


Fig.6.2 Excitation of induction generator with auxiliary stator winding in conjuction with PWM inverter.

6.3 CONCLUSIONS

The work presented in this thesis deals with a new scheme for power factor correction of an induction machine which requires less reactive components than other methods available. Major conclusions of the study are :

i) Need of continuously controllable reactive power compensator for large induction machine with variable load has been explained.

ii) The proposed scheme can provide continuous control of reactive power (lagging as well as leading) and it is an alternative to the fixed capacitor thyristor controlled reactor scheme.

iii) PWM technique is used to reduce harmonics in the inverter output voltage. Programmed PWM technique can be used to eliminate lower order harmonics [24].

iv) The inherent inductances of the induction machine are utilized as a filter to reduce harmonic currents in the proposed scheme.

v) Performance study of the proposed scheme based on the harmonic equivalent circuit shows a negligible harmonic power loss at high frequency ratio for PWM inverter.

vi) The proposed scheme requires a single low cost dc capacitor rather than three units of ac capacitors as in the fixed capacitor thyristor controlled reactor scheme. When the PWM inverter in the proposed scheme is operated at sufficiently high carrier frequency, the input current is nearly sinusoidal and the scheme does not need additional filter circuit. Hence this scheme could be an economical alternative to the fixed capacitor thyristor controlled reactor scheme.

vii) The proposed scheme could be a good excitor for an induction generator.

6.4 RECOMMENDATIONS FOR FURTHER RESEARCH

Some points for further investigation on the proposed scheme are given below :

i) Design and implementation of the control system for the proposed scheme has to be done.

ii) Transient behaviour of the proposed scheme has to be investigated.

iii) More detailed study has to be undertaken to use the proposed scheme for an induction generator.

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APPENDIX 'A'

Parameters of the induction machine used for simulation

90 hp 500 Volts 8 Pole 60 Hz

$R_{s1} = 0.13$ ohm

$X_{s1} = 0.6$ ohm

$R_{s2} = 0.13$ ohm

$X_{s2} = 0.6$ ohm

$R_r = 0.13$ ohm

$X_r = 0.6$ ohm

$X_m = 20$ ohms

$X_{lm} = 0.5$ ohm

No load loss = 1500 Watts

APPENDIX 'B'

Parameters of the induction machine used in experiment

2 hp 200 Volts	4 Pole 60 Hz
R_{s1} = 0.775 ohm	R_{s2} = 0.775 ohm
X_{s1} = 1.038 ohms	X_{s2} = 1.038 ohms
R_r = 1.07 ohms	X_m = 27 ohms
X_r = 1.038 ohms	X_{lm} = 0.8 ohm

No load loss = 60 Watts

As the PWM inverter available in the laboratory can produce a maximum line to line voltage of 100 Volts, the above machine is used in the experiment as low voltage motor with the the following parameters.

1 hp 95 Volts	4 Pole 60 Hz
R_{s1} = 0.775 ohm	R_{s2} = 0.775 ohm
X_{s1} = 1.038 ohm	X_{s2} = 1.038 ohm
R_r = 1.07 ohms	X_m = 27 ohms
X_r = 1.038 ohm	X_{lm} = 0.8 ohm

No load loss = 37 Watts

APPENDIX 'C'

Program For Simulation Of Proposed Scheme

```
*         >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
*         >>    PROGRAM FOR SIMULATION OF PROPOSED SCHEME     <<
*         >>                      FOR                         <<
*         >>  POWER FACTOR CORRECTION OF INDUCTION MACHINE    <<
*         >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
*         LEGEND :
*         -------
*         Rs1 = Resistance of the main stator winding per phase.
*         Xs1 = Reactance of the main stator winding per phase.
*         Rs2 = Resistance of the auxiliary stator winding.
*         Xs2 = Reactance of the auxiliary stator winding.
*         Xlm = Reactance dueto mutual inductance between main
*               and auxiliary windings.
*         Xm  = Magnitising reactance.
*         Xr  = Reactance of rotor winding per phase.
*         Rr  = Resistance of rotor winding per phase.
*         s   = Slip of the machine.
*         Imztot = Imaginary part of the total impedance.
*         Reztot = Real part of the total impedance.
*         Vs1 = Supply voltage across the main winding (RMS)
*         Is1 = Current through main stator winding (RMS)
*         phs1 = Phase angle of Is1 w.r.t. that of Vs1
*         Is2 = Current through auxilliary stator winding (RMS)
*         phs2 = Phase angle of Is2 w.r.t. that of Vs1
*         Vs2 = Output voltage of PWM inverter (RMS)
*         phvs2 = Phase angle of Vs2 w.r.t. that of Vs1
*         ***********************************************
*         Mi = Peak value of modulation index.
*         FR = Frequency ratio.
*         Vdc = Magnitude of dc supply voltage.
*         Vcpk = Peak value of triangular carrier.
*         ft = frequency of carrier.
*         Qest(i) = Estimated switching vector.
*         theta(i) = Refind switching vector.
*         K(i) = Slope of the ith carrier.
*         C(i) = intercept of of the ith carrier.
*         ***********************************************
*         Output files :
*         ------------
*         Waveform of modulating signal -- fort.2700
*         Waveform of triangular carrier -- fort.2725
*         Waveform of Vr -- fort.2812 or fort.2825
*         Waveform of Vn -- fort.2813
*         Waveform of Vrn -- fort.2814
*         Waveform of Vrn-fundamental --- fort.2826
*         ***********************************************
          real Rs1,Rs2,Xs1,Xs2,Xm,Xr,Rr,Req,s,Xmr,Xeq
          real mXs1,mXs2,mXm,mXr,mXlm,mXmr
          real Imztot,Reztot,Xlm,Rrs,aa,bb,cc
          real dis,Xceq1,Xceq2,a1,b1,c1,d1,Rz,Xz
          real Is1(124),phs1(124),Z(124),ph(124),Is2(124),phs2(124)
          real Is1max(124),Is2max(124),Irmax(124),Vs2max(124)
          real Vs2(124),phvs2(124),ReIs1(124),ImIs1(124)
          real ReIs2(124),ImIs2(124),ImZr(124),phZr(124)
```

```
      real ReI12(124),ImI12(124),I12(124),ph12(124)
      real Ir(124),phr(124),Zr(124),phzr(124),ReZr(124)
      real Vs1,Xc2,ReZy,ImZy,Zy,phy,m,X1,Y1,ReZt,ImZt
      real f,w1,Q,Qradian,t,dr,Imain,I2,V1,sum,disfac
      real ReZwt,ImZwt,Zwt,phZwt,Is1w,phIs1w,Zwr,Irw,phIrw
      real input,output,eff,culoss,lossRs2,n,mm,Zt,phZt
      real Z13,phZ13,ReZ13,ImZ13,I1fun,I2fun,Vpwm
      real X(0:48),ef(0:48),pf(0:48)
      real Idcrms,Vrip,capa,capvar,Vdc,rip,cuRs1,cuRs2,cuRr
      real pwmva,pff,m,Impow,Reinput,Iminput,noloadloss
      real Q,Vc,Vsr,n,Mi,an,dr,Vsy,Vsb,m,Vdc,Vcpk,Oper,Ost
      real k(0:150),c(0:150),theta(0:150),Qest(0:150)
      real Vcap(0:150),kk(0:150),yy(0:150),Qrad(0:150)
      real Acn(124),Bsn(124),Acrn(124),Bsrn(124)
      real Acr(124),Bsr(124),Amptr(124),phr(124)
      real Acy(124),Bsy(124),Acb(124),Bsb(124)
      real Amptn(124),Amptrn(124),phn(124),phrn(124)
      real Vs2max(124),phVs2(124),Idc(0:18)
      real Qper,Qst,f1,f2,err,Vr,Vy,Vb,FR,ix,jx,Qfn,Vm,Vavg
      real Vrn,Vn,y,Vrnfun,b,iter,d,er,seq,harloss
      integer i,j,h,count,itr
      parameter (pi = 3.1416)
      write(*,*) 'Input the value of s,Vs1,f,Vdc,rip'
      read*, s,Vs1,f,Vdc,rip
      write(*,*) 'Input the value of FR,Mi'
      read*, FR,Mi
      Vcpk = 1
      dr = pi/180
      open(2,file='para',status='unknown')
      read(2,*) Rs1,Xs1,Rs2,Xs2,Xm,Xlm,Rr,Xr,noloadloss
      write(1005,*)
      write(1005,*) '****************************************'
      write(1005,*) '* Output file of the program - simul.f *'
      write(1005,*) '*  For a slip s = ',s,' p.u.           *'
      write(1005,*) '*  With frequency ratio = ',FR,'       *'
      write(1005,*) '****************************************'
      write(1005,*) 'Input data :'
      write(1005,*) '**********'
      write(1005,*)
      write(1005,*) 'Parameters of the machine :'
      write(1005,*) '------------------------ '
      write(1005,*) 'Rs1 =',Rs1, ' ohm'
      write(1005,*) 'Rs2 =',Rs2, ' ohm'
      write(1005,*) 'Xs1 =',Xs1, ' ohm'
      write(1005,*) 'Xs2 =',Xs2, ' ohm'
      write(1005,*) 'Xm =',Xm, ' ohms'
      write(1005,*) 'Xr =',Xr, ' ohm'
      write(1005,*) 'Xlm =',Xlm, ' ohm'
      write(1005,*) 'Rr =',Rr, ' ohm'
      write(1005,*) 'Vs1 =',Vs1,' volts'
      write(1005,*) 'Noload loss =',noloadloss,' watts'
      write(1005,*) 's =',s,' p.u.'
      write(1005,*)
      write(1005,*) 'Peak value of MI (guess value) =',Mi
```

```
      write(1005,*) 'Frequency ratio(FR) =',FR
      write(1005,*) 'Avg value of Vdc across capa=',Vdc,'volts'
      write(1005,*) 'Ripple in Vdc =',rip,' %','(peak-peak)'
      write(1005,*)
      write(1005,*) 'Output data :'
      write(1005,*) '***********'
*     *******************************************
*     *   Program for equivalent ckt analysis     *
*     *******************************************
*     ** Selection of optimum value of power factor:
*     ------------------------------------------
*     ** Calculation of total input current :
      Rrs = Rr/s
      Xmr = Xm + Xr
      Req=(Xmr*Xm*Rrs - Xm*Xr*Rrs)/(Rrs*Rrs + Xmr*Xmr)
      Xeq=Xlm+(Xm*Xr*Xmr+Xm*Rrs*Rrs)/(Rrs*Rrs+Xmr*Xmr)
      aa= Xeq + Xs1
      bb= Req*(Rs2+Req)-Rs2*Req + Xeq*Xeq + 2*Xs1*Xeq
      cc=Xs1*((Rs2+Req)**2+Xeq**2)-Xeq*(Rs2*Req-Rs2*(Rs2+Req))
      dis = bb*bb - 4*aa*cc
      if (dis .lt. 0) goto 8000
      Xceq1 = (-bb + sqrt(dis))/(2*aa)
      Xceq2 = (-bb - sqrt(dis))/(2*aa)
      Xcm2 = Xceq2
      do 1400 i=0,48
      m = i
      n = m/4
      X(i) = Xceq2 - n
      a1 = Rs2*Req - X(i)*Xeq
      b1 = Rs2*Xeq + Req*X(i)
      c1 = Req + Rs2
      d1 = X(i) + xeq
      Rz = (a1*c1 + b1*d1)/(c1*c1 + d1*d1)
      Xz = (b1*c1 - a1*d1)/(c1*c1 + d1*d1)
      Imztot = Xz + Xs1
      Reztot = Rz + Rs1
      Z(1) = sqrt(Reztot**2 + Imztot**2)
      ph(1) = atan2(Imztot,Reztot)
      Is1(1) = Vs1/Z(1)
      Is1max(1) = 1.414*Is1(1)
      phs1(1) = -ph(1)
      pf(i) = cos(phs1(1))
*     *Calculation of current through aux winding Is2*
      ReZy = (Req*c1 + Xeq*d1)/(c1*c1 + d1*d1)
      ImZy = (Xeq*c1 - Req*d1)/(c1*c1 + d1*d1)
      Zy = sqrt(ReZy**2 + ImZy**2)
      phy = atan2(ImZy,ReZy)
      Is2(1) = Is1(1)*Zy
      phs2(1) = phs1(1) + phy
      Xc2 = -(Xceq2 - Xs2)
      Vs2(1) = Is2(1)*Xc2
      Vs2max(1) = 1.414*Vs2(1)
      phvs2(1) = phs2(1) - pi/2
      pwmva =3* Vs2(1)*Is2(1)/1000
```

```
        lossRs2 =3* Is2(1)**2*Rs2
*       *** Calculation of Rotor current ****
        ReIs1(1) = Is1(1)*cos(phs1(1))
        ImIs1(1) = Is1(1)*sin(phs1(1))
        ReIs2(1) = Is2(1)*cos(phs2(1))
        ImIs2(1) = Is2(1)*sin(phs2(1))
        ReI12(1) = ReIs1(1) - ReIs2(1)
        ImI12(1) = ImIs1(1) -ImIs2(1)
        I12(1) = sqrt(ReI12(1)**2 + ImI12(1)**2)
        ph12(1) = atan2(ImI12(1),ReI12(1))
        ReZr(1) = (Xm*Xmr)/(Rrs**2 + Xmr**2)
        ImZr(1) = (Rrs*Xm)/(Rrs**2 + Xmr**2)
        Zr(1) = sqrt(ReZr(1)**2 + ImZr(1)**2)
        phZr(1) = atan2(ImZr(1),ReZr(1))
        Ir(1) = I12(1)*Zr(1)
        phr(1) = ph12(1) + phZr(1)
        culoss=3*(Is1(1)**2*Rs1+Is2(1)**2*Rs2+Ir(1)**2*Rr)
        Iminput = 3*Vs1*Is1(1)*sin(phs1(1))
        Iminput = abs(Iminput)
        input = 3*Vs1*Is1(1)*cos(phs1(1))
        output = input - culoss - noloadloss
        ef(i) = output*100/input
        write(100,*) pf(i),lossRs2
        write(101,*) pf(i),Is2(1)
        write(103,*) pf(i),ef(i)
        if(m .eq. 0) then
        write(1005,*) 'With aux winding for unity pf:'
        write(1005,*) '------------------------------'
        write(1005,*) 'Is1(1) =',Is1(1),' amps'
        write(1005,*) 'phs1(1) =',phs1(1),' radian'
        write(1005,*) 'power factor = ',pf(0)
        write(1005,*) 'Is2(1) =',Is2(1),' amps'
        write(1005,*) 'phs2(1) =',phs2(1),' radian'
        write(1005,*) 'Vs2(1) =',Vs2(1),' volts'
        write(1005,*) 'phvs2(1) =',phvs2(1),' radian'
        write(1005,*) 'Xeq =',Xeq
        write(1005,*) 'Xceq2 =',Xceq2,' ohms'
        write(1005,*) 'Xc2 =',Xc2
        write(1005,*) 'Loss in Rs2 =',lossRs2,' watts'
        write(1005,*) 'Ir(1) =',Ir(1),' amps'
        write(1005,*) 'phr(1) =',phr(1),' radian'
        write(1005,*) 'Kva rating of inverter =',pwmva,'Kva'
        write(1005,*) 'Input power =',input,' watts'
        write(1005,*) 'Reactive power =',Iminput,' var'
        write(1005,*) 'Total cu loss =',culoss,' watts'
        write(1005,*) 'Output power =',output,' watts'
        write(1005,*) 'Efficency =',ef(i),' %'
        else
        endif
1400    continue
*       **Analysis of the ckt without auxilliary winding**
        ReZwt = Rs1 + (Rrs*Xm*Xmr - Xm*Xr*Rrs)/(Rrs**2 + Xmr**2)
        ImZwt = Xs1 + (Xm*Xr*Xmr + Rrs*Rrs*Xm)/(Rrs**2 + Xmr**2)
        Zwt = sqrt(ReZwt**2 + ImZwt**2)
```

```
      phZwt = atan2(ImZwt,ReZwt)
      Is1w = Vs1/Zwt
      phIs1w = -phZwt
      pff = cos(phIs1w)
      Zwr = sqrt((Xmr/Xm)**2 + (Rrs/Xm)**2)
      phrw = atan2((Rrs/Xm),(Xmr/Xm))
      Irw = Is1w/Zwr
      phIrw = phIs1w - phrw
      culoss = 3*(Is1w**2*Rs1 + Irw**2*Rr)
      Impow = 3*Vs1*Is1w*sin(-phIs1w)
      input = 3*Vs1*Is1w*cos(phIs1w)
      output = input - culoss - noloadloss
      eff = output*100/input
      write(1005,*) 'Without auxilliary winding :'
      write(1005,*) '--------------------------'
      write(1005,*) 'Is1 =',Is1w,' amps'
      write(1005,*) 'phIs1 =',phIs1w,' radian'
      write(1005,*) 'pf =',pff,' lagging'
      write(1005,*) 'Reactive power =',Impow,' Var'
      write(1005,*) 'Input power =',input,' watts'
      write(1005,*) 'Output power =',output,' watts'
      write(1005,*) 'Efficency =',eff,' %'
      write(1005,*)
*     *Analysis of the ckt with Selected value of Xceq2*
      do 3000 i=0,48
      if (ef(i) .gt. ef(i+1)) then
      if (pf(i) .ge. 0.9) then
      Xceq2 = X(i)
      goto 4000
      else
      Xceq2 = Xcm2
      endif
      else
      goto 3000
      endif
3000  continue
4000  goto 5000
*     **Calculation of input current Is1(1)**
5000  a1 = Rs2*Req - Xceq2*Xeq
      b1 = Rs2*Xeq + Req*Xceq2
      c1 = Req + Rs2
      d1 = Xceq2 + Xeq
      Rz = (a1*c1 + b1*d1)/(c1*c1 + d1*d1)
      Xz = (b1*c1 - a1*d1)/(c1*c1 + d1*d1)
      Imztot = Xz + Xs1
      Reztot = Rz + Rs1
      Z(1) = sqrt(Reztot**2 + Imztot**2)
      ph(1) = atan2(Imztot,Reztot)
      phs1(1) = -ph(1)
      Is1(1) = Vs1/Z(1)
      Reinput = 3*Vs1*Is1(1)*cos(phs1(1))
      Iminput = 3*Vs1*Is1(1)*sin(phs1(1))
      pff = cos(phs1(1))
      write(1005,*) 'With aux winding for optimum pf'
```

```
      write(1005,*) '-------------------------------'
      write(1005,*) 'neglecting harmonics :'
      write(1005,*) '--------------------'
      write(1005,*) 'Selected Xceq2 =',Xceq2,' ohms'
      write(1005,*) 'Is1(1) =',Is1(1),' amps'
      write(1005,*) 'phs1(1) =',phs1(1),' radian'
      write(1005,*) 'power factor =',pff
*     *Calculation of current through aux winding Is2 *
      ReZy = (Req*c1 + Xeq*d1)/(c1*c1 + d1*d1)
      ImZy = (Xeq*c1 - Req*d1)/(c1*c1 + d1*d1)
      Zy = sqrt(ReZy**2 + ImZy**2)
      phy = atan2(ImZy,ReZy)
      Is2(1) = Is1(1)*Zy
      Is2max(1) = 1.414*Is2(1)
      phs2(1) = phs1(1) + phy
      Xc2 = -(Xceq2 - Xs2)
      Vs2(1) = Is2(1)*Xc2
      Vs2max(1) = 1.414*Vs2(1)
      phvs2(1) = phs2(1) - pi/2
      lossRs2 = 3*Is2(1)**2*Rs2
      pwmva = 3*Vs2(1)*Is2(1)/1000
      write(500,*) Vs2max(1)
      write(500,*) phVs2(1)
      write(1005,*) 'Is2(1) =',Is2(1),' amps'
      write(1005,*) 'phs2(1) =',phs2(1),' radian'
      write(1005,*) 'Vs2(1) =',Vs2(1),' volts'
      write(1005,*) 'phvs2(1) =',phvs2(1),' radian'
      write(1005,*) 'Vs2max(1) =',Vs2max(1),' volts.'
      write(1005,*) 'Loss in Rs2 =',lossRs2,' watts'
      write(1005,*) 'Kva rating of inverter=',pwmva,'Kva'
*     ***** Calculation of rotor current *****
      ReIs1(1) = Is1(1)*cos(phs1(1))
      ImIs1(1) = Is1(1)*sin(phs1(1))
      ReIs2(1) = Is2(1)*cos(phs2(1))
      ImIs2(1) = Is2(1)*cos(phs2(1))
      ReI12(1) = ReIs1(1) - ReIs2(1)
      ImI12(1) = ImIs1(1) - ImIs2(1)
      I12(1) = sqrt(ReI12(1)**2 + ImI12(1)**2)
      ph12(1) = atan2(ImI12(1),ReI12(1))
      ReZr(1) = (Xm*Xmr)/(Rrs**2 + Xmr**2)
      ImZr(1) = (Rrs*Xm)/(Rrs**2 + Xmr**2)
      Zr(1) = sqrt(ReZr(1)**2 + ImZr(1)**2)
      phZr(1) = atan2(ImZr(1),ReZr(1))
      Ir(1) = I12(1)*Zr(1)
      Irmax(1) = 1.414*Ir(1)
      phr(1) = ph12(1) + phZr(1)
      culoss =3*(Is1(1)**2*Rs1+Is2(1)**2*Rs2+Ir(1)**2*Rr)
      output = Reinput - culoss - noloadloss
      eff = output*100/Reinput
      write(1005,*) 'I12(1) =',I12(1),' amps'
      write(1005,*) 'ph12(1) =',ph12(1),' radian'
      write(1005,*) 'Ir(1) =',Ir(1),' amps'
      write(1005,*) 'phr(1) =',phr(1),' radian'
      write(1005,*) 'Input power =',Reinput,' watts'
```

```
      write(1005,*) 'Reactive power =',Iminput,' Var'
      write(1005,*) 'Total cu loss =',culoss,' watts'
      write(1005,*) 'Output power =',output,' watts'
      write(1005,*) 'Efficency =',eff,' %'
*     ************************************************
*     *        Program for PWM voltage Inverter      *
*     * Following program determines the swt pattern *
*     *   to produce required output voltage Vs2     *
*     ************************************************
      write(1005,*) 'Output form PWM inverter program:'
      write(1005,*) '--------------------------------'
      write(1005,*) 'Required Vs2max(1)=',Vs2max(1),'volts'
      write(1005,*) 'Required phase of Vs2=',phVs2(1),'rad'
*     **Program for waveform of triangular carrier **
      Qper = 360/(2*FR)
      Q = 0
      Vc = 0
      write(2725,*) Q,Vc
      n = 1
      do 15 Q = Qper/2,360,Qper
      Vc = (-1)**n
      write(2725,*) Q,Vc
      n = n+1
15    continue
      Q = 360
      Vc = 0
      write(2725,*) Q,Vc
*     ***** Program for X-axis ******
      do 16 Q = 0,360,20
      y = 0*Q
      write(2718,*) Q,y
16    continue
*     **Calculation of est swt vector in the program.**
      b = 2*FR
      Qper = 360/b
      Qest(0) = 0
      do 20 i=1,b
      j = i-1
      Qest(i) = Qest(j) + Qper
20    continue
      write(1005,*) 'Estimated switching vector:'
      write(1005,*) '---------------------------'
      write(1005,21)
21    format(6x,'S.N.',t20,'Qest(i) in deg.')
      write(1005,22)
22    format(6x,'----',t20,'---------------')
      do 24 i=0,b
      m = i
      write(1005,23) m,Qest(i)
23    format(6x,f3.0,t20,f10.4)
24    continue
      write(1005,*)
*     * Newt-Raph method for refing the swt vector *
      Vcpk = 1
```

```
      b = 2*FR
      Qper = 360/(2*FR)
      Qst = -Qper/2
      do 45 i=0,b
      n = i
      k(i) = (-1)**(n+1)*2*Vcpk/Qper
      c(i) =-(-1)**(n+1)*Vcpk - k(i)*Qst
      Qst = Qst + Qper
45    continue
      itr = 0
25    do 50 i=0,b
      count = 0
      theta(i) = Qest(i)
      Qrad(i) = theta(i)*dr
40    f1 = Mi*Vcpk*sin(Qrad(i))-k(i)*theta(i)-c(i)
      f2 = Mi*Vcpk*dr*cos(Qrad(i)) - k(i)
      err = f1/f2
      if (abs(err) .le. 0.01) then
      Qrad(i) = Qrad(i) - phVs2(1)
      theta(i) = Qrad(i)/dr
      goto 100
      else
      theta(i) = theta(i) - err
      Qrad(i) = theta(i)*dr
      count = count + 1
      if (count .ge. 30 ) goto 100
      goto 40
      endif
100   write(*,*)'count=',count
50    continue
*     *Calculation of Vdc at different swt instants *
      Vrip = rip*Vdc/(100*2)
      Oper = 15
      Ost = -Oper/2
      do 51 i=0,24
      n = i
      kk(i) = (-1)**(n+1)*2*Vrip/Oper
      yy(i) = -(-1)**(n+1)*Vrip- kk(i)*Ost
      Ost = Ost+ Oper
51    continue
      Ost = -7.5
      n = 0
      do 53 i=0,b
52    if ( theta(i) .le. Ost+15 ) then
      j = int(n)
      else
      n = n + 1
      j = int(n)
      Ost = Ost + 15
      goto 52
      endif
      Vcap(i) = kk(j)*theta(i) + yy(j) + Vdc
53    continue
*     ** Program for Fourier components of Vr **
```

```
*       Ar(h) = cosine component of hth harmonic of Vr.
*       Br(h) = sine component of hth harmonic of Vr.
*       Amptr(h) = amplitude of hth harmonic of Vr.
*       phr(h) = phase of hth harmonic of Vr.
        do 150 h=1,60
        m = h
        Acr(h)= 0
        Bsr(h) = 0
        do 140 i=0,b-1
        j = i+1
        ix = i+1
        jx = j+1
        Qst = Qrad(i)
        Qfn = Qrad(j)
        Vavg = (Vcap(j)+Vcap(i))/2
        if ( h .eq. 1) then
        write(*,*) 'Vavg =',Vavg
        else
        endif
        Acr(h)=(-1)**jx*Vavg*(sin(m*Qfn)-sin(m*Qst))+Acr(h)
        Bsr(h)=(-1)**ix*Vavg*(cos(m*Qfn)-cos(m*Qst))+Bsr(h)
 140    continue
        Acr(h) = Acr(h)/(2*m*pi)
        Bsr(h) = Bsr(h)/(2*m*pi)
        Amptr(h) = sqrt(Acr(h)*Acr(h) + Bsr(h)*Bsr(h))
        phr(h) = atan2(Acr(h),Bsr(h))
 150    continue
*       **Program for Fourier components of Vn and Vrn**
        do 300 i=1,60
        m = i
        Acy(i) = Amptr(i)*sin(phr(i)-m*2*pi/3)
        Bsy(i) = Amptr(i)*cos(phr(i)-2*m*pi/3)
        Acb(i) = Amptr(i)*sin(phr(i)+2*m*pi/3)
        Bsb(i) = Amptr(i)*cos(phr(i)+2*m*pi/3)
        Acn(i) = (Acr(i) + Acy(i) + Acb(i))/3
        Bsn(i) = (Bsr(i) + Bsy(i) + Bsb(i))/3
        Amptn(i) = sqrt(Acn(i)*Acn(i) + Bsn(i)*Bsn(i))
        phn(i) = atan2(Acn(i),Bsn(i))
        Acrn(i) = Acr(i) - Acn(i)
        Bsrn(i) = Bsr(i) - Bsn(i)
        Amptrn(i)=sqrt(Acrn(i)*Acrn(i)+Bsrn(i)*Bsrn(i))
        phrn(i) = atan2(Acrn(i),Bsrn(i))
        er = abs(Amptrn(1) - Vs2max(1))
        if (er .gt. 1 ) then
        Mi = Mi + 0.005
        itr = itr + 1
        if (itr .gt. 50 ) goto 8000
        goto 25
        else
        endif
 300    continue
 304    write(77,*) 'itr =',itr
        write(77,*) 'er =',er
        write(1005,*)
```

```
      write(1005,*) 'Corrected value of MI = ',Mi
      write(1005,*) 'Refind switching vector:'
      write(1005,*) '------------------------'
*     *Newt-Raph method for refining switching vector *
      write(1005,26)
26    format(6x,'S.N.',t12,'Slope(k)',t25,'intercept(c)',
       t40,'theta(deg)')
      write(1005,27)
27    format(6x,'----',t12,'--------',t25,'------------',
       t40,'----------')
      do 28 i=0,b
      n = i
      write(1005,30) n,k(i),c(i),theta(i)
30    format(6x,f4.1,t12,f8.4,t25,f8.3,t40,f8.4)
28    continue
*     **Program for waveform of control signal**
      do 10 Q=0,360,2
      an = Q*dr
      Vsr = Mi*sin(an)
      Vsy = Mi*sin(an - 2*pi/3)
      Vsb = Mi*sin(an - 4*pi/3)
      write(2700,*) Q,Vsr
      write(2710,*) Q,Vsy
      write(2720,*) Q,Vsb
10    continue
      write(1005,*) 'First 24 Fourier components of Vr:'
      write(1005,*) '----------------------------------'
      write(1005,74)
74    format(6x,'order',t15,'Amplitude',t35,'Phase(rad)',
       t50,'phase seq.')
      write(1005,75)
75    format(6x,'-----',t15,'---------',t35,'----------',
       t50,'----------')
      do 77 h=1,24
      m = h
      if ((m/3 - int(m/3)) .eq. 0) then
      seq = 'Z'
      endif
      if (((m-1)/3 - int((m-1)/3)) .eq. 0) then
      seq = 'P'
      endif
      if (((m-2)/3 - int((m-2)/3)) .eq. 0) then
      seq = 'N'
      endif
      write(1005,142) m,Amptr(h),phr(h),seq
142   format(6x,f3.0,t15,f12.6,t35,f10.6,t50,a)
77    continue
*     **Program for waveforms of Vn and Vrn**
      Vm = mi*Vcpk
      d = 10*Qper
      i = 0
      iter = 0
      do 200 Q=-Qper/2,360,0.1
      iter = iter + 1
```

```
      an = Q*dr
      if (iter .eq. d) then
      i = i+1
      iter = 0
      endif
      Vc = k(i)*Q + c(i)
      Vsr = Vm*sin(an)
      Vsy = Vm*sin(an - 2*pi/3)
      Vsb = Vm*sin(an + 2*pi/3)
      if (Vsr .ge. Vc) then
      Vr = Vdc/2
      else
      Vr = -Vdc/2
      endif
      if (Vsy .ge. Vc) then
      Vy = Vdc/2
      else
      Vy = -Vdc/2
      endif
      if (Vsb .ge. Vc) then
      Vb = Vdc/2
      else
      Vb = -Vdc/2
      endif
      Vn = (Vr + Vy + Vb)/3
      Vrn = Vr - Vn
      write(2812,*) Q,Vr
      write(2813,*) Q,Vn
      write(2814,*) Q,Vrn
200   continue
      write(1005,*)
      write(1005,*) 'First twentyfour Fourier components
                     of load neutral voltage,Vn:'
      write(1005,*) '-----------------------------------
                     ---------------------------'
      write(1005,310)
310   format(6x,'order',t15,'Amplitude',t35,'phase(rad)')
      write(1005,320)
320   format(6x,'-----',t15,'---------',t35,'----------')
      do 350 i=1,24
      m = i
      write(1005,330) m,Amptn(i),phn(i)
330   format(6x,f3.0,t15,f15.10,t35,f10.5)
350   continue
      write(1005,*)
      write(1005,*)
      write(1005,*) 'First twentyfour Fourier components
                     of red phase voltage,Vrn:'
      write(1005,*) '-----------------------------------
                     -------------------------'
      write(1005,360)
360   format(6x,'order',t15,'Amplitude',t35,'phase(rad)')
      write(1005,370)
370   format(6x,'-----',t15,'---------',t35,'----------')
```

```
      do 400 i=1,24
      m = i
      write(1005,380) m,Amptrn(i),phrn(i)
380   format(6x,f3.0,t15,f15.10,t35,f10.5)
400   continue
      sum = 0
      do 402 i=2,30
      sum = sum + Amptrn(i)**2
402   continue
      disfac = sqrt(sum)/Amptrn(1)
      write(1005,*)
      write(1005,*) 'Distortion factor in Vrn=',disfac
*     *Program for waveform of fundamental compt of Vrn*
      do 450 Q=0,360,3
      Vrnfun = Amptrn(1)*sin(Q*dr)
      write(2826,*) Q,Vrnfun
450   continue
*     **Program for waveform of output voltage Vr**
      do 70 i = 0,b
      j = i + 1
      m = i
      n = j
      Vr = (m-n)**(n+1)*Vdc/2
      write(2825,*) theta(i),Vr
      write(2825,*) theta(j),Vr
70    continue
*     ************************************
*     *       Analysis of the scheme       *
*     *   in the presence of harmonics     *
*     ************************************
      write(1005,*) 'Analysis of the scheme in the
                     presence of harmonics:'
      write(1005,*) '*****************************'
      write(1005,*)
      write(1005,*) 'Harmonics components of main
                     input current Is1 :'
      write(1005,*) '----------------------------'
      write(1005,1100)
1100  format(6x,'order',t15,'magnitude(peak value)',
       t45,'phase(rad)')
      write(1005,1150)
1150  format(6x,'-----',t15,'---------------------',
       t45,'----------')
      m = 1
      Is1max(1) = 1.414*Is1(1)
      write(1005,1220) m,Is1max(1),phs1(1)
1220  format(6x,f3.0,t15,f10.4,t45,f10.6)
      do 1000 i=2,60
      m = i
      mXs1 = Xs1*m
      mXs2 = Xs2*m
      mXlm = Xlm*m
      mXm = Xm*m
      mXr = Xr*m
```

```
      mXmr = mXm + mXr
      Req=(mXm*Rrs*mXmr-mXm*mXr*Rrs)/(Rrs**2+mXmr**2)
      Xeq=mX1m+(mXm*mXr*mXmr+mXm*Rrs*Rrs)/(Rrs**2+mXmr**2)
      X1 = Rs2*(Rs1+Req) - mXs2*(mXs1+Xeq)
      Y1 = mXs2*(Rs1+Req) + Rs2*(mXs1+Xeq)
      ReZt = Rs1 + (X1*Req + Y1*Xeq)/(Req**2 + Xeq**2)
      ImZt = Xs1 + (Y1*Req - X1*Xeq)/(Req**2 + Xeq**2)
      Zt = sqrt(ReZt**2 + ImZt**2)
      phZt = atan2(ImZt,ReZt)
      Is1max(i) = Amptrn(i)/Zt
      Is1(i) = Is1max(i)/1.414
      phs1(i) = phrn(i) - Phzt
      ReZ13=(Req*(Rs1+Req)+Xeq*(mXs1+Xeq))/(Req**2+Xeq**2)
      ImZ13=(Req*(mXs1+Xeq)-Xeq*(Rs1+Req))/(Req**2+Xeq**2)
      Z13 = sqrt(ReZ13**2 + ImZ13**2)
      phZ13 = atan2(ImZ13,ReZ13)
      Is2max(i) = Is1max(i)*Z13
      Is2(i) = Is2max(i)/1.414
      phs2(i) = phs1(i) + phZ13
      ReI12(i)=Is2(i)*cos(phs2(i))-Is1(i)*cos(phs1(i))
      ImI12(i)=Is2(i)*sin(phs2(i))-Is1(i)*sin(phs1(i))
      I12(i) = sqrt(ReI12(i)**2 + ImI12(i)**2)
      ph12(i) = atan2(ImI12(i),ReI12(i))
      ReZr(i) = (mXm*mXmr)/(Rrs**2 + mXmr**2)
      ImZr(i) = (Rrs*mXm)/(Rrs**2 + mXmr**2)
      Zr(i) = sqrt(ReZr(i)**2 + ImZr(i)**2)
      phZr(i) = atan2(ImZr(i),ReZr(i))
      Ir(i) = I12(i)*Zr(i)
      Irmax(i) = 1.414*Ir(i)
      phr(i) = ph12(i) + phZr(i)
      write(1005,1200) m,Is1max(i),phs1(i)
1200  format(6x,f3.0,t15,f15.12,t45,f10.6)
1000  continue
      sum = 0
      do 1500 i=2,30
      sum = sum + Is1(i)*Is1(i)
1500  continue
      cuRs1 = sum* Rs1
      disfac = sqrt(sum)/Is1(1)
      write(1005,*) 'sum =',sum
      write(1005,*) 'Distortion factor in Is1=',disfac
      write(1005,*) 'Loss in Rs1 due to harmonic currents'
      write(1005,*) '= ',cuRs1, ' watt'
      write(1005,*) 'Harmonic components of Is2 :'
      write(1005,*) '--------------------------'
      write(1005,1520)
1520  format(6x,'order',t15,'magnitude(peak value)',
       t45,'phase(rad)')
      write(1005,1530)
1530  format(6x,'-----',t15,'---------------------',
       t45,'----------')
      do 1550 i=1,24
      m = i
      write(1005,1540) m,Is2max(i),phs2(i)
```

```
1540    format(6x,f3.0,t15,f15.12,t45,f10.6)
1550    continue
        sum = 0
        do 1560 i=2,30
        sum = sum + Is2(i)*Is2(i)
1560    continue
        cuRs2 = sum* Rs2
        disfac = sqrt(sum)/Is2(1)
        write(1005,*) 'sum =',sum
        write(1005,*) 'Distortion factor in Is2=',disfac
        write(1005,*) 'Loss in Rs2 due to harmonic current'
        write(1005,*) '= ',cuRs2,' watt'
        write(1005,*) 'Harmonic components of Ir :'
        write(1005,*) '-------------------------'
        write(1005,1580)
1580    format(6x,'order',t15,'magnitude(peak value)',
         t45,'phase(rad)')
        write(1005,1600)
1600    format(6x,'-----',t15,'---------------------',
        . t45,'----------')
        do 1620 i=1,24
        m = i
        write(1005,1610) m,Irmax(i),phr(i)
1610    format(6x,f3.0,t15,f17.12,t45,f10.6)
1620    continue
        sum = 0
        do 1622  i=2,30
        sum = sum + Ir(i)*Ir(i)
1622    continue
        disfac = sqrt(sum)/Ir(1)
        cuRr = sum* Rr
        write(1005,*) 'Distortion fac in Ir=',disfac
        write(1005,*) 'Loss in Rr due to harmonic current'
        write(1005,*) '= ',cuRr,' watt'
        harloss = cuRs1 + cuRs2 + cuRr
        input = 3*Vs1*Is1(1)*cos(phs1(1))
        output = input - 3*(Is1(1)**2*Rs1 + Is2(1)**2*Rs2
                + Ir(1)**2*Rr) - harloss - noloadloss
        eff = output*100/input
        write(1005,*) 'Total copper loss due to harmonic
                      currents = ',harloss,' watt'
        write(1005,*) 'Efficency = ',eff,' %'
*       **Program for drawing the waveform of Is1 **
        w1 = 2*pi*f
        do 3500 Q=0,360
        Qradian = Q*dr
        t = Qradian/w1
        V1 = 1.4142*Vs1*sin(w1*t)/25
        I1fun = Is1max(1)*sin(w1*t + phs1(1))
        I2fun = Is2max(1)*sin(w1*t + phs2(1))
        Imain = Is1max(1)*sin(w1*t + phs1(1))
        I2 = Is2max(1)*sin(w1*t + phs2(1))
        Vpwm = Vs2max(1)*sin(w1*t + phvs2(1))
        do 2580 j=2,52
```

```
      m = float(j)
      Imain = Imain + Is1max(j)*sin(m*w1*t + phs1(j))
      I2 = I2 + Is2max(j)*sin(m*w1*t + phs2(j))
      Vpwm = Vpwm + Vs2max(j)*sin(m*w1*t + phvs2(j))
2580  continue
      write(1004,*) Q,V1
      write(1006,*) Q,Imain
      write(1008,*) Q,I2
      write(1007,*) Q,Vpwm
      write(1009,*) Q,I1fun
      write(1010,*) Q,I2fun
3500  continue
      Idc(0) = 0.955*Is2max(1)
      Idc(6) = 0.154*Idc(0)
      Idc(12) = 0.036*Idc(0)
      Idc(18) = 0.015*Idc(0)
      Idcrms = sqrt(Idc(0)**2+Idc(6)**2+Idc(12)**2)
      Vrip = rip*Vdc/100
      capa = (Idc(6)*10**6)/(12*pi*f*Vrip)
      capvar = Idcrms*Vdc/1000
      write(1005,*) 'Rating of dc capacitor :'
      write(1005,*) '----------------------'
      write(1005,*) 'Rated voltage = ',Vdc,' Volts'
      write(1005,*) 'Capacitance = ',capa,' uF'
      write(1005,*) 'Var capacity =',capvar,' Kvar'
8000  stop
      end
```

APPENDIX 'D'

Simulation Results For Machine Described In Appendix 'A'

```
*******************************************
*   Output file of the program - simul.f  *
*     For a slip s =     1.50000E-03 p.u. *
*     With frequency ratio =     24.0000  *
*******************************************

Input data :
**********
Parameters of the machine :
-------------------------
Rs1 =   0.130000 ohm
Rs2 =   0.130000 ohm
Xs1 =   0.600000 ohm
Xs2 =   0.600000 ohm
Xm =    20.0000 ohms
Xr =   0.600000 ohm
Xlm =   0.500000 ohm
Rr =   0.130000 ohm
Vs1 =    288.670 volts
Noload loss =    1500.00 watts
s =    1.50000E-03 p.u.

Peak value of MI  (guess value) = 0.700000
Frequency ratio(FR) =  24.0000
Avg value of Vdc across capacitor = 1000.000 volts

Output data :
***********
With auxilliary winding for unity power factor :
----------------------------------------------
Is1(1) =    3.25527 amps
phs1(1) =    5.71326E-08 radian
power factor =     1.00000
Is2(1) =    14.1232 amps
phs2(1) =    1.55765 radian
Vs2(1) =    296.722 volts
phvs2(1) =   -1.31490E-02 radian
Xceq2 =   -20.4095 ohms
Loss in Rs2 =    77.7915 watts
Ir(1) =    3.24462 amps
phr(1) =   -1.93268E-02 radian
Kva rating of PWM inverter =  12.5720 Kva
Input power =    2819.10 watts
Reactive power =     1.61062E-04 var
Total cu loss =    86.0300 watts
Output power =    1233.07 watts
Efficency =    43.7398 %

Without auxilliary winding :
-------------------------
Is1 =    14.3816 amps
phIs1 =   -1.34476 radian
pf =   0.224119 lagging
Reactive power =    12137.8 Var
Input power =    2791.31 watts
Output power =    1206.58 watts
Efficency =    43.2263 %
```

With auxilliary winding for optimum value
of pf neglecting harmonics :

```
Selected Xceq2 =   -20.4095 ohms
Is1(1) =    3.25527 amps
phs1(1) =    5.71326E-08 radian
power factor =    1.00000
Is2(1) =    14.1232 amps
phs2(1) =    1.55765 radian
Vs2(1) =    296.722 volts
phvs2(1) =   -1.31490E-02 radian
Loss in Rs2 =    77.7915 watts
Kva rating of PWM inverter =  12.5720 Kva
I12(1) =    3.07523 amps
ph12(1) =   -6.04062E-02 radian
Ir(1) =   0.690432 amps
phr(1) =    1.27703 radian
Input power =    2819.10 watts
Reactive power =    1.61062E-04 Var
Total cu loss =    82.1101 watts
Output power =    1236.99 watts
Efficency =    43.8788 %
```

Output form PWM inverter program :

```
Required value of Vs2max(1) =    419.564 volts.
Required phase angle of Vs2 =   -1.31490E-02 radian

Corrected value of modulation index Mi =    0.840000
```

First twentyfour Fourier components of Vrn:

order	Amplitude	phase(rad)
1.	420.4897155762	-0.01110
2.	2.1192815304	1.65419
3.	0.0000000703	1.01220
4.	1.0897814035	1.48891
5.	0.1772217602	1.44873
6.	0.0000000119	2.24554
7.	0.1801636070	-1.74040
8.	0.0552019142	-0.77079
9.	0.0000001085	2.86329
10.	0.0772338212	-2.05294
11.	0.1212675944	-1.83784
12.	0.0000000269	2.15880
13.	0.2362101376	1.32976
14.	0.0323422179	-2.81433
15.	0.0000002800	-0.43984
16.	0.0426843800	0.99629

17.	0.1585962325	1.26714
18.	0.0000000401	-1.19029
19.	1.4058933258	-1.86174
20.	4.5504174232	-0.25610
21.	0.0000019222	-0.51915
22.	119.7963714600	-0.28980
23.	1.3371289968	-1.92529
24.	0.0000610352	1.57080

Distortion factor in Vrn = 0.403302

****

Analysis of the scheme in the presence of harmonics:

****

Harmonics components of main input current Is1 :

order	magnitude(peak value)	phase(rad)
1.	4.6030	0.000000
2.	1.142022371292	0.219651
3.	0.000000028459	-0.464342
4.	0.353039979935	-0.015412
5.	0.047817189246	-0.076217
6.	0.000000002756	0.704097
7.	0.036380685866	-3.295727
8.	0.009894374758	-2.338247
9.	0.000000017472	1.284975
10.	0.011287753470	-3.641177
11.	0.016214348376	-3.435264
12.	0.000000003308	0.552786
13.	0.026951350272	-0.284351
14.	0.003435777733	-4.436125
15.	0.000000027810	-2.068948
16.	0.003979717847	-0.639806
17.	0.013925394043	-0.375638
18.	0.000000003328	-2.839487
19.	0.110422633588	-3.517093
20.	0.339287221432	-1.917381
21.	0.000000136353	-2.186114
22.	8.100603103638	-1.962237
23.	0.086344748735	-3.602989
24.	0.000003770075	-0.111957

Distortion factor in Is1 = 2.31467

Copper loss in main winding due to harmonic currents
= 7.38068 watt

Harmonic components of Is2 :

order	magnitude(peak value)	phase(rad)
1.	19.970232009888	1.557651
2.	1.177509307861	0.229315
3.	0.000000029358	-0.447306
4.	0.364445388317	0.008454
5.	0.049406111240	-0.045763
6.	0.000000002850	0.740988
7.	0.037678517401	-3.252512
8.	0.010262341239	-2.288810
9.	0.000000018151	1.340538
10.	0.011748177931	-3.579587
11.	0.016909392551	-3.367746
12.	0.000000003458	0.626127
13.	0.028232777491	-0.205296
14.	0.003608044935	-4.351470
15.	0.000000029281	-1.978811
16.	0.004201801028	-0.544309
17.	0.014745083638	-0.274908
18.	0.000000003534	-2.733655
19.	0.117644667625	-3.406291
20.	0.362654477358	-1.801747
21.	0.000000146233	-2.065786
22.	8.717627525330	-1.837357
23.	0.093251198530	-3.473699
24.	0.000004086408	0.021599

Distortion factor in Is2 = 0.577318

Copper loss in the auxi winding due to harmonic current
= 8.64254 watt

Harmonic components of rotor current (Ir) :

order	magnitude(peak value)	phase(rad)
1.	0.976271152496	-0.011101
2.	0.015512275510	1.657437
3.	0.000000000578	0.996723
4.	0.009539960884	1.451110
5.	0.001613179687	1.388598
6.	0.000000000111	2.163628
7.	0.001714284415	-1.843508
8.	0.000532149745	-0.894605
9.	0.000000001056	2.719215
10.	0.000756641035	-2.216907
11.	0.001193579054	-2.021362
12.	0.000000000265	1.956033
13.	0.002335896948	1.108035
14.	0.000320019812	3.228435
15.	0.000000002769	-0.698689
16.	0.000421698031	0.719261
17.	0.001563863363	0.972190
18.	0.000000000395	-1.502925

19.	0.013784899376	-2.191808
20.	0.044455777854	-0.603366
21.	0.000000018702	-0.883356
22.	1.160324811935	-0.670710
23.	0.012887706049	-2.322658
24.	0.000000585184	1.157220

Distortion factor in Ir = 1.66446
Copper loss in rotor winding due to harmonic current
= 0.171685 watt

Total power loss due to harmonic currents=16.1949 watt
Efficency = 43.3043 %

Rating of dc capacitor :

Rated voltage = 1000.000 Volts
Capacitance = 25.954 uF
Var capacity = 19.0716 Kvar

```
*****************************************
*   Output file of the program - simul.f  *
*     For a slip s =     5.50000E-02 p.u. *
*     With frequency ratio =     24.0000  *
*****************************************

Input data :
**********
Parameters of the machine :
-------------------------
Rs1 =   0.130000 ohm
Rs2 =   0.130000 ohm
Xs1 =   0.600000 ohm
Xs2 =   0.600000 ohm
Xm =    20.0000 ohms
Xr =   0.600000 ohm
Xlm =   0.500000 ohm
Rr =   0.130000 ohm
Vs1 =    288.670 volts
Noload loss =    1500.00 watts
s =    5.50000E-02 p.u. ( Full load slip )

Peak value of MI  (guess value) =  0.750000
Frequency ratio(FR) =    24.0000
Avg value of Vdc across capacitor = 1000.000 volts

Output data :
***********
With auxilliary winding for unity power factor :
-----------------------------------------------
Is1(1) =    98.7341 amps
phs1(1) =    4.07733E-08 radian
power factor =     1.00000
Is2(1) =    77.6910 amps
phs2(1) =    1.32344 radian
Vs2(1) =    328.558 volts
phvs2(1) =  -0.247365 radian
Xceq2 =   -3.62904 ohms
Loss in Rs2 =    2354.00 watts
Ir(1) =    105.784 amps
phr(1) =  -0.642879 radian
Kva rating of PWM inverter =    76.5780 Kva
Input power =    85504.7 watts
Reactive power =    3.48631E-03 var
Total cu loss =   10520.06 watts
Output power =    73484.6 watts
Efficency =    85.9422 %

Without auxilliary winding :
-------------------------
Is1 =    105.527 amps
phIs1 =  -0.552154 radian
pf =   0.851396 lagging
Reactive power =    47934.8 Var
Input power =    77806.9 watts
Output power =    67923.4 watts
Efficency =    87.2974 %
```

```
With auxilliary winding for optimum value of p.f.
-------------------------------------------------
neglecting harmonics :
--------------------
Selected Xceq2 =   -8.87904 ohms
Is1(1) =    89.6451 amps
phs1(1) =  -0.431215 radian
power factor =   0.908458
Is2(1) =    29.2072 amps
phs2(1) =    1.38571 radian
Vs2(1) =    276.856 volts
phvs2(1) =  -0.185087 radian
Loss in Rs2 =    332.693 watts
Kva rating of PWM inverter =    24.2586 Kva
I12(1) =    87.3004 amps
ph12(1) =  -0.512973 radian
Ir(1) =    84.2052 amps
phr(1) =  -0.398733 radian
Input power =    70526.8 watts
Reactive power =   32448.9 Var
Total cu loss =    6232.13 watts
Output power =    62794.7 watts
Efficency =    89.0366 %


Output form PWM inverter program :
--------------------------------
Required value of Vs2max(1) =    391.474 volts.
Required phase angle of Vs2 =  -0.185087 radian

Total power loss due to harmonic currents=10.27438 watts
Efficency =     89.0221 %


Rating of dc capacitor :
----------------------
Rated voltage =    1000.000 Volts
Capacitance =     53.754 uF
Var capacity =    39.944 Kvar
```

APPENDIX 'E'

Simulation Results For Machine Used In Experiment

```
*****************************************
*   Output file of the program - simul.f  *
*     For a slip s =     6.60000E-03 p.u. *
*     With frequency ratio =    20.0000   *
*****************************************
Input data :
**********
Parameters of the machine :
-------------------------
Rs1 =   0.775000 ohm
Rs2 =   0.775000 ohm
Xs1 =    1.03800 ohm
Xs2 =    1.03800 ohm
Xm =   27.0000 ohms
Xr =   1.03800 ohm
Xlm =   0.800000 ohm
Rr =   1.07000 ohm
Vs1 =    54.8500 volts
Noload loss =    37.0000 watts
s =    6.60000E-03 p.u.

Peak value of MI  (guess value) = 0.700000
Frequency ratio(FR) =    20.0000
Avg value of Vdc across capacitor = 200.000 volts

Output data :
***********
With auxilliary winding for unity power factor :
---------------------------------------------
Is1(1) =   0.372537 amps
phs1(1) =   -3.29532E-07 radian
power factor =     1.00000
Is2(1) =    1.96965 amps
phs2(1) =    1.53573 radian
Vs2(1) =    56.5858 volts
phvs2(1) =    -3.50711E-02 radian
Xceq2 =   -27.6909 ohms
Loss in Rs2 =    9.01989 watts
Ir(1) =   0.326849 amps
phr(1) =   -1.82821E-02 radian
Kva rating of PWM inverter =   0.334363 Kva
Input power =    61.3010 watts
Reactive power =    2.02006E-05 var
Total cu loss =    9.68549 watts
Output power =    14.6155 watts
Efficency =    23.8422 %

Without auxilliary winding :
-------------------------
Is1 =    1.97565 amps
phIs1 =   -1.38455 radian
pf =   0.185176 lagging
Reactive power =    319.470 Var
Input power =    60.1993 watts
Output power =    13.7870 watts
Efficency =    22.9022 %
```

With auxilliary winding for optimum value of p.f.

neglecting harmonics :

```
Selected Xceq2 =    -27.6909 ohms
Is1(1) =    0.372537 amps
phs1(1) =    -3.29532E-07 radian
power factor =     1.00000
Is2(1) =    1.96965 amps
phs2(1) =     1.53573 radian
Vs2(1) =    56.5858 volts
phvs2(1) =    -3.50711E-02 radian
Loss in Rs2 =     9.01989 watts
Kva rating of PWM inverter =    0.334363 Kva
I12(1) =    0.311238 amps
ph12(1) =   -0.223739 radian
Ir(1) =     5.10760E-02 amps
phr(1) =     1.17581 radian
Input power =     61.3010 watts
Reactive power =    2.02006E-05 Var
Total cu loss =     9.35093 watts
Output power =     14.9500 watts
Efficency =    24.3879 %
```

Output form PWM inverter program :

```
Required value of Vs2max(1) =     80.0123 volts.
Required phase angle of Vs2 =    -3.50711E-02 radian

Corrected value of modulation index Mi =     0.790000
```

First twentyfour Fourier components of Vrn:

order	Amplitude	phase(rad)
1.	79.0368576050	-0.03539
2.	0.0238753408	-1.59920
3.	0.0000000009	1.57080
4.	0.0221923813	-1.07691
5.	0.0267914478	0.23347
6.	0.0000000029	-0.32175
7.	0.0167902149	0.77236
8.	0.0543432273	2.04604
9.	0.0000000002	1.57080
10.	0.4527082145	-2.31470
11.	0.2229249179	2.82945
12.	0.0000005960	-0.92730
13.	0.1890877783	0.27561
14.	0.3866034746	-2.48090
15.	0.0000000134	0.98279
16.	0.0280716494	1.91161

17.	0.0075450717	-2.78578
18.	0.0000000064	-1.57080
19.	0.0084937997	2.81729
20.	0.7168021202	-0.70726
21.	0.0000000028	-2.18152
22.	21.5611152649	-0.77183
23.	0.0015206762	2.01842
24.	0.0000297937	-2.44685

Distortion factor in Vrn = 0.386110

****
Analysis of the scheme in the presence of harmonics:
****

Harmonics components of main input current Is1 :

order	magnitude(peak value)	phase(rad)
1.	0.5268	0.000000
2.	0.006684572902	-2.709666
3.	0.000000000204	0.347870
4.	0.003970046062	-2.373632
5.	0.004038021900	-1.115804
6.	0.000000000383	-1.710793
7.	0.001916762092	-0.648187
8.	0.005525525659	0.599607
9.	0.000000000021	0.102498
10.	0.037704579532	-3.801899
11.	0.017013603821	1.325611
12.	0.000000041959	-2.446017
13.	0.012346368283	-1.256576
14.	0.023527367041	-4.025394
15.	0.000000000765	-0.573057
16.	0.001502122846	0.345220
17.	0.000380534242	-4.362014
18.	0.000000000305	-3.156278
19.	0.000383791426	1.223100
20.	0.030769450590	-2.309687
21.	0.000000000116	-3.791758
22.	0.840532243252	-2.389489
23.	0.000056649955	0.393697
24.	0.000001062378	-4.078318

Distortion factor in Is1 = 2.08911

Copper loss in main winding due to harmonic currents
= 0.469423 watt

Harmonic components of Is2 :

order	magnitude(peak value)	phase(rad)
1.	2.785085439682	1.535729
2.	0.006966108456	-2.711554
3.	0.000000000213	0.356171
4.	0.004140978679	-2.357392
5.	0.004214889836	-1.092545
6.	0.000000000400	-1.680995
7.	0.002004534239	-0.612145
8.	0.005785396788	0.641686
9.	0.000000000022	0.150456
10.	0.039589155465	-3.748196
11.	0.017893021926	1.384940
12.	0.000000044205	-2.381171
13.	0.013032174669	-1.186320
14.	0.024884695187	-3.949834
15.	0.000000000811	-0.492295
16.	0.001595841837	0.431077
17.	0.000405245490	-4.271167
18.	0.000000000326	-3.060549
19.	0.000410812267	1.323602
20.	0.033025331795	-2.204523
21.	0.000000000125	-3.682044
22.	0.907327175140	-2.275339
23.	0.000061334860	0.512168
24.	0.000001153772	-3.955642

Distortion factor in Is2 = 0.428723

Copper loss in the auxi winding due to harmonic current
= 0.552628 watt

Harmonic components of rotor current (Ir) :

order	magnitude(peak value)	phase(rad)
1.	0.072221517563	-0.035391
2.	0.000088716115	-1.518549
3.	0.000000000004	1.641171
4.	0.000100353704	-1.032121
5.	0.000126743442	0.250843
6.	0.000000000014	-0.330871
7.	0.000083650797	0.738141
8.	0.000274971768	1.988022
9.	0.000000000001	1.490107
10.	0.002336532110	-2.417114
11.	0.001157695660	2.706107
12.	0.000000003109	-1.070901
13.	0.000989287626	0.112328
14.	0.002026399830	-2.663345
15.	0.000000000070	0.781631
16.	0.000147270679	1.692143
17.	0.000039555955	3.260007
18.	0.000000000034	-1.825787

19.	0.000044386532	2.545036
20.	0.003736856161	-0.996475
21.	0.000000000015	-2.487407
22.	0.111715845764	-1.094104
23.	0.000007850414	1.680028
24.	0.000000153193	-2.801105

Distortion factor in Ir = 2.17139

Copper loss in rotor winding due to harmonic current
= 1.31612E-02 watt

Total powerloss due to harmonic currents=1.03521 watt
Efficency = 22.6992 %

Rating of dc capacitor :

Rated voltage = 200.000 Volts
Capacitance = 17.994 uF
Var capacity = 0.531951 Kvar

```
****************************************
*   Output file of the program - simul.f  *
*     For a slip s =     6.00000E-02 p.u. *
*     With frequency ratio =     20.0000  *
****************************************
Input data :
**********
Parameters of the machine :
-------------------------
Rs1 =   0.775000 ohm
Rs2 =   0.775000 ohm
Xs1 =    1.03800 ohm
Xs2 =    1.03800 ohm
Xm =    27.0000 ohms
Xr =    1.03800 ohm
Xlm =   0.800000 ohm
Rr =    1.07000 ohm
Vs1 =    54.8500 volts
Noload loss =    37.0000 watts
s =    6.00000E-02 p.u.

Peak value of MI (guess value) =  0.700000
Frequency ratio(FR) =    20.0000
Avg value of Vdc across capacitor =   200.000 volts

Output data :
***********
With auxilliary winding for unity power factor :
---------------------------------------------
Is1(1) =    2.84522 amps
phs1(1) =  0. radian
power factor =     1.00000
Is2(1) =    2.33836 amps
phs2(1) =    1.48038 radian
Vs2(1) =    55.1238 volts
phvs2(1) =   -9.04204E-02 radian
Xceq2 =   -22.5357 ohms
Loss in Rs2 =    12.7130 watts
Ir(1) =    2.85685 amps
phr(1) =  -0.157466 radian
Kva rating of PWM inverter =   0.386698 Kva
Input power =    468.180 watts
Reactive power =  0. var
Total cu loss =    57.7332 watts
Output power =    373.447 watts
Efficency =    79.7657 %

Without auxilliary winding :
-------------------------
Is1 =    3.48134 amps
phIs1 =  -0.649318 radian
pf =  0.796496 lagging
Reactive power =    346.373 Var
Input power =    456.276 watts
Output power =    365.412 watts
Efficency =    80.0857 %
```

```
With auxilliary winding for optimum value of p.f.
--------------------------------------------------
neglecting harmonics :
--------------------
Selected Xceq2 =   -34.5357 ohms
Is1(1) =    2.82978 amps
phs1(1) =  -0.272164 radian
power factor =   0.963191
Is2(1) =    1.50520 amps
phs2(1) =    1.50527 radian
Vs2(1) =    53.5456 volts
phvs2(1) =   -6.55272E-02 radian
Loss in Rs2 =    5.26761 watts
Kva rating of PWM inverter =   0.241791 Kva
I12(1) =    2.76402 amps
ph12(1) =  -0.316108 radian
Ir(1) =    2.24589 amps
phr(1) =   0.250392 radian
Input power =    448.501 watts
Reactive power =   125.172 Var
Total cu loss =    40.0768 watts
Output power =    371.424 watts
Efficency =    82.8146 %


Output form PWM inverter program :
---------------------------------
Required value of Vs2max(1) =    75.7135 volts.
Required phase angle of Vs2 =   -6.55272E-02 radian

Total power loss due to harmonic currents=0.749402 watt
Efficency =    82.6475 %

Rating of dc capacitor :
----------------------
Rated voltage =    200.000 Volts
Capacitance =    13.838 uF
Var capacity =   0.406516 Kvar
```