MOTORING AND GENERATING MODE OF 3-Φ INDUCTION MACHINE - A COMPARATIVE EVALUATION FOR ENERGY EFFICIENCY

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A Thesis submitted in partial fulfillment of the requirements for the degree of

Bachelor of Technology in "Electrical Engineering"

By

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CERTIFICATE

This is to certify that the thesis entitled "Motoring and Generating mode of 3-Φ Induction Machine – A Comparative Evaluation For Energy Efficiency", submitted by **Mr. Smruti Ranjan Behera (Roll no. 107EE047)** and **Mr. Saroj Prasad (Roll no. 107EE044)** in partial fulfillment of the requirements for the award of **Bachelor of Technology** in **Electrical Engineering** during session 2010-2011 at National Institute of Technology, Rourkela. A bonafide record of research work carried out by him under my supervision and guidance.

The candidates have fulfilled all the prescribed requirements.

The Thesis which is based on candidates own work, has not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a bachelor of technology degree in Electrical Engineering.

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ABSTRACT

Vast use of fossil fuels is leading to energy deficiency. Hence the renewable energy sources like wind energy and solar energy are being used. Classical asynchronous induction generators are being used in wind energy based power generation system. In markets of micro electric energy generation unit system, induction generators are getting popularized, as it is cheap, robust and maintenance free. But generally induction machines are used as motor, hence the catalogues have only information about motoring mode. This report gives a comparative analysis between motoring and generating mode of induction machines. From this report we conclude that the induction motors have more efficiency and less losses than induction generators.

CONTENTS

CHAPTER 1

INTRODUCTION

CHAPTER 2

INDUCTION MACHINE & ITS ENERGY EFFICIENCY

CHAPTER 3

ANALYSIS OF INDUCTION MACHINE DURING MOTORING MODE

CHAPTER 4

ANALYSIS OF INDUCTION MACHINE DURING GENERATING MODE

CHAPTER 5

EXPERIMENTAL ANALYSIS AND COMPARATIVE STUDY

CHAPTER 6

CONCLUSION AND FUTURE WORK

List of Symbols

P_{el} = electrical power

$P_c = P_{Fe}$ = Core loss

P_g = air gap power

P_m = mechanical power developed at rotor

P_{cu} = copper loss

P_{stator} = stator loss

P_{rotor} = Rotor loss

P_{sh} = shaft power

r_1 = stator resistance

r_2 = rotor resistance

η = efficiency

V_{nl} = no load voltage

I_{nl} = no load current

P_{nl} = no load power

V_{br} = blocked rotor voltage

I_{br} = blocked rotor current

P_{br} = blocked rotor power

List of Figures

Figure Page no

LIST OF TABLES:

CHAPTER 1

Introduction

1.1 INTRODUCTION:

The conventional energy sources are limited and have pollution to environment as more attention and interest have been paid on the utilization of renewable energy sources such as wind energy, fuel cells and solar energy. The increasing importance of fuel saving leads to the decentralization of power generation and increasing use of non-conventional energy sources such as wind energy, bio-gas, solar and hydro potential, etc. So the market of small or micro energy generating units is becoming increasingly important[1]. For these applications classical asynchronous machine with cage rotor is a better option. The grid connected induction generators are being considered as an alternative choice to the well-developed synchronous generators because of their lower unit cost, inherent ruggedness, operational and maintenance simplicity and ability to generate power at varying speed. The induction generator’s ability to generate power at varying speed facilitates its application. Irrespective of the chosen mechanism for alternative energy source, the efficiency of the system is important. Based on efficiency, classical asynchronous machines have some disadvantages with respect to synchronous generators. Induction machines have better position in market due to their lower price. In induction machines no rotor excitation, voltage regulation equipment or slip rings are required which results lower maintenance cost.

In this report the energy efficiency of induction machines are analyzed. Induction machines are mainly used as motor, however they can be used generator when rotor is rotated with speed more than synchronous speed. The power flow of induction machines is studied in motoring and generating mode. This is necessary to explain the operational difference and efficiency of motoring and generating mode of induction machines. Other aspects that can influence the efficiency are studied.

In market catalogues data such as power rating, power factor and efficiency are only provided for motoring mode of induction machines. This report will help to compare these parameters for generating and motoring mode. These values can differ significantly for motor and generator mode depending upon the size and efficiency class of induction machine.

1.2 MOTIVATION OF WORK:

The conventional energy sources are limited and have pollution to environment as more attention and interest have been paid on the utilization of renewable energy sources such as wind energy, fuel cells and solar energy. In Europe and countries like DENMARK and INDIA, wind farms are mostly used to generate some part of electricity. So asynchronous machines like induction generators are being used[2]. But information about energy efficiency of induction machines is available for motoring mode mostly. Hence this report gives a comparative study between motoring and generating mode of induction machines.

1.3 ELECTRICAL MACHINES – AN OVERVIEW:

From the past days, human beings have been using the energies for improving their living conditions. Among those energies electrical energy hold the top in because electrical energy is adaptable to all human needs in an easy way due to some advantages. It is pollution free, easily controlled and economic and can be used in efficient way. Electrical machines are divided onto dc machines and ac machines. In this chapter we discussed about different types of electrical motors, 3-Φ induction machines (their classification, construction and principle of operation).

1.3.1 – DC MOTORS:

Direct current motors use a dc supply for their operation. It converts dc power to mechanical power. They are mostly used in steel mills, mines. The construction of a dc motor is given below:

It has three main components:

1. **Field system**: It consists of yoke, field windings, field poles. The DC motor field poles are stationary and an armature that turns on bearings in the space between the field poles. A simple DC motor has two field poles: a north pole and a south pole. The magnetic lines of force extend across the opening between the poles from north to south. For larger or more complex motors there are one or more electromagnets. These electromagnets receive electricity from an outside power source and serve as the field structure. The main work of these components is to produce and carry the working flux. The yoke is laminated to reduce the eddy current loss.

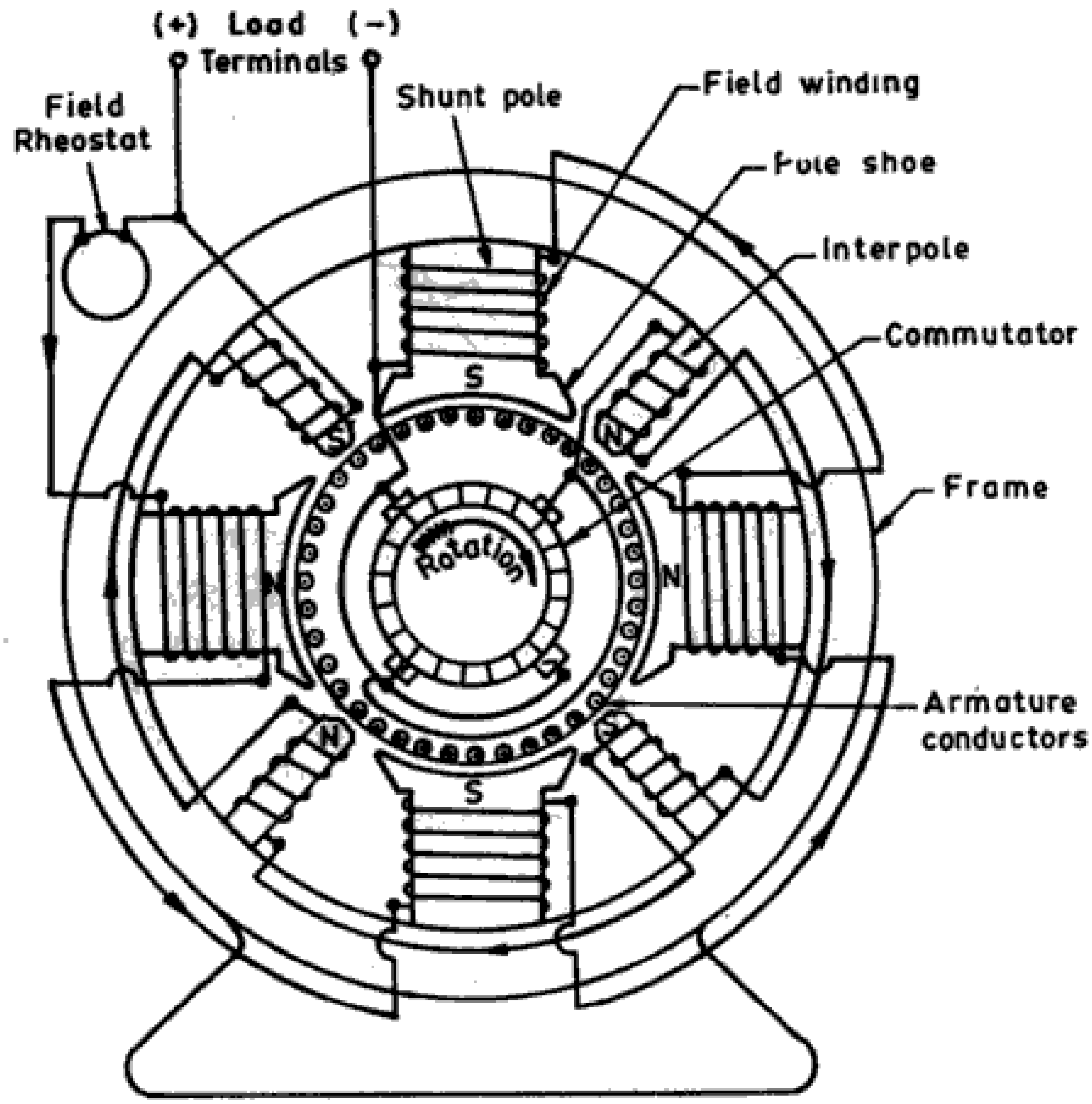

FIGURE 1.1: Constructional view of dc motor

2. **Armature:** It has armature core, armature windings. Armature core houses the armature coils and provides low reluctance path to magnetic flux. When current goes through the armature, it becomes an electromagnet. The armature, cylindrical in shape, is linked to a drive shaft in order to drive the load. For the case of a small DC motor, the armature rotates in the magnetic field established by the poles, until the north and south poles of the magnets change location with respect to the armature. Once this happens, the current is reversed to switch the south and north poles of the armature.

3. **Commutator:** This component is found mainly in DC machines. Its purpose is to overturn the direction of the electric current in the armature i.e. changing ac current into dc current and vice-versa. The commutator also aids in the transmission of current between the armature and the power source.

The operation of DC motor is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force whose direction is given by Fleming's left hand rule. DC motors have usually been applied in two types of application. One of these categories is when the power source is itself DC. This is why motors in automobiles are all DC, from the motors that drive fans for engine cooling and passenger compartment ventilation to the engine starter motor. A second reason for using DC motors is that their torque-speed characteristic has, historically, been easier to tailor than that of all AC motor categories. This is why most traction and servo motors have been DC machines.

Types of DC Motors:

1. **Shunt-wound motor:** In shunt wound motor, field winding is connected in parallel with the armature such that the field winding current and armature current are not same.
2. **Series-wound motor:** In series wound motor, field winding is connected in series with the armature such that the series field winding carries the armature current.
3. **Compound-wound motor:** Compound wound motor has two field windings; one connected in parallel with the armature and the other in series with it.

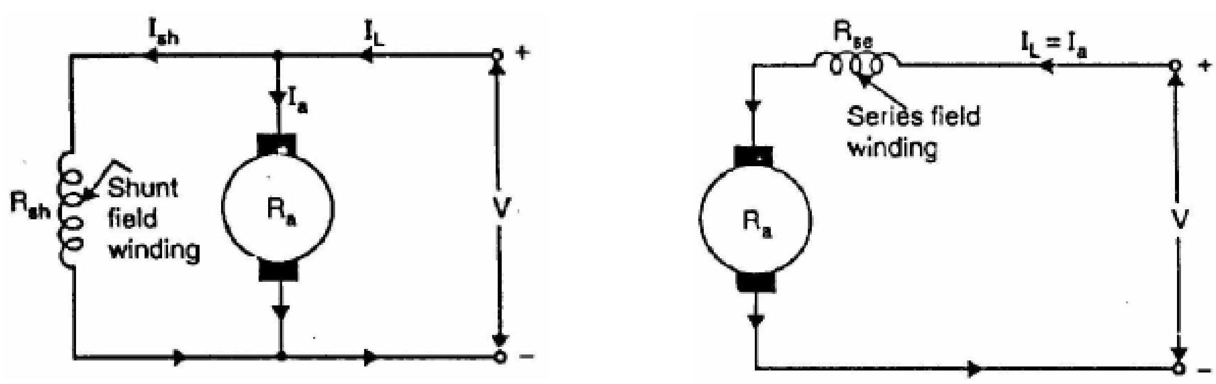

FIGURE 1.2: Shunt and Series wound dc motor

1.3.2 AC MOTORS:

AC Motors use an electric current which reverses its direction at regular intervals. An AC motor has two basic electrical parts: a stator and a rotor. The stator is in the stationary electrical component. The rotor is the rotating electrical component, which rotates the motor shaft. AC motor is shown in the figure.

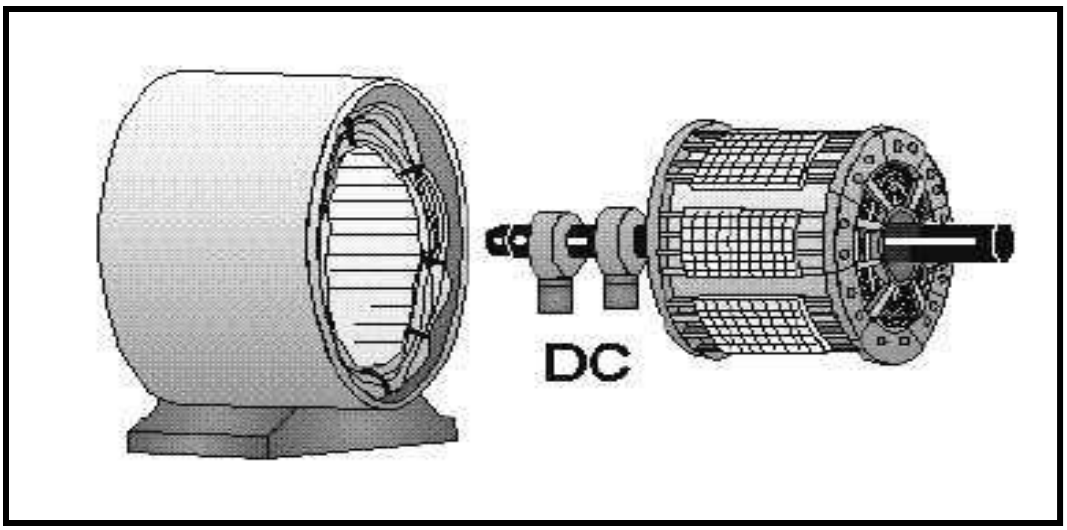

FIGURE 1.3 AC motor

There are two types of AC motors:

- Synchronous motor
- Asynchronous motor or induction motor

. The synchronous motors are doubly excited electrical machines as they require both dc and ac supply. The rotor rotates at synchronous speed. These are for delivering mechanical power and improving system power factor. The synchronous motors have no self starting torque so external means used to start it.

The induction motors require no dc excitation, hence called singly excited ac machines. They have self starting torque. Speed control of induction motors is possible.

1.3.3 SPECIAL MACHINES:

1. BLDC Motor
2. PMSM Motor
3. SR Motor

1. **BLDC Motor:** BLDC Motor means brushless DC motors which are electronically commutated motors. They are synchronous electric motor. BLDC Motor is shown in the figure below:

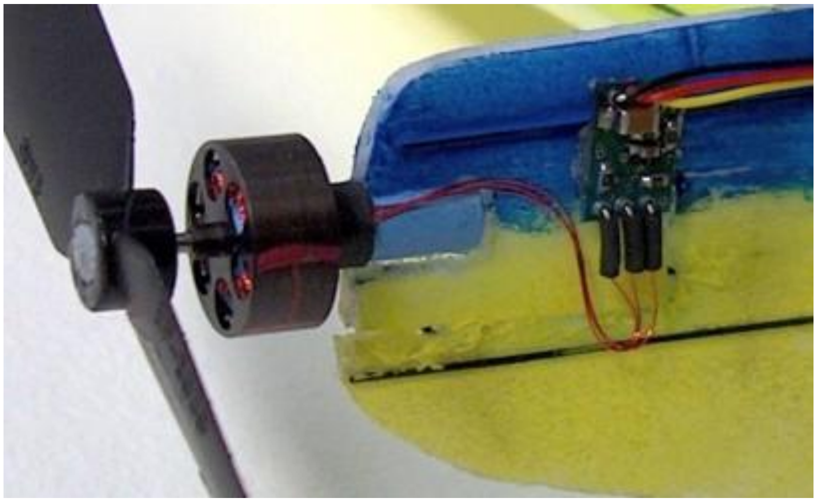

FIGURE 1.4 BLDC motor

Brushless motor are the smallest available motors for a given power rating. The brushless motor

has highest efficiency for an industrial application. The stator winding also creates a rotating field which creates a rotating torque by pulling the permanent magnet rotor. This permits the rotor to develop a smooth torque regardless the speed.

PMSM Motor: PMSM Motor is permanent magnet synchronous motor which is also known as brushless ac electric motor. In this rotor magnetic field is supplied by the permanent magnets rather than by electromagnets.

SR Motor: SR Motor is switched reluctance motor which is a synchronous machine and runs by reluctance torque. SRM is a form of stepper motor which uses few poles. Because of its simple structure, SRM has the lowest construction cost. It has its applications in mining areas and where the rotor must be held for longer period of time[25]. SR Motor is shown in figure:

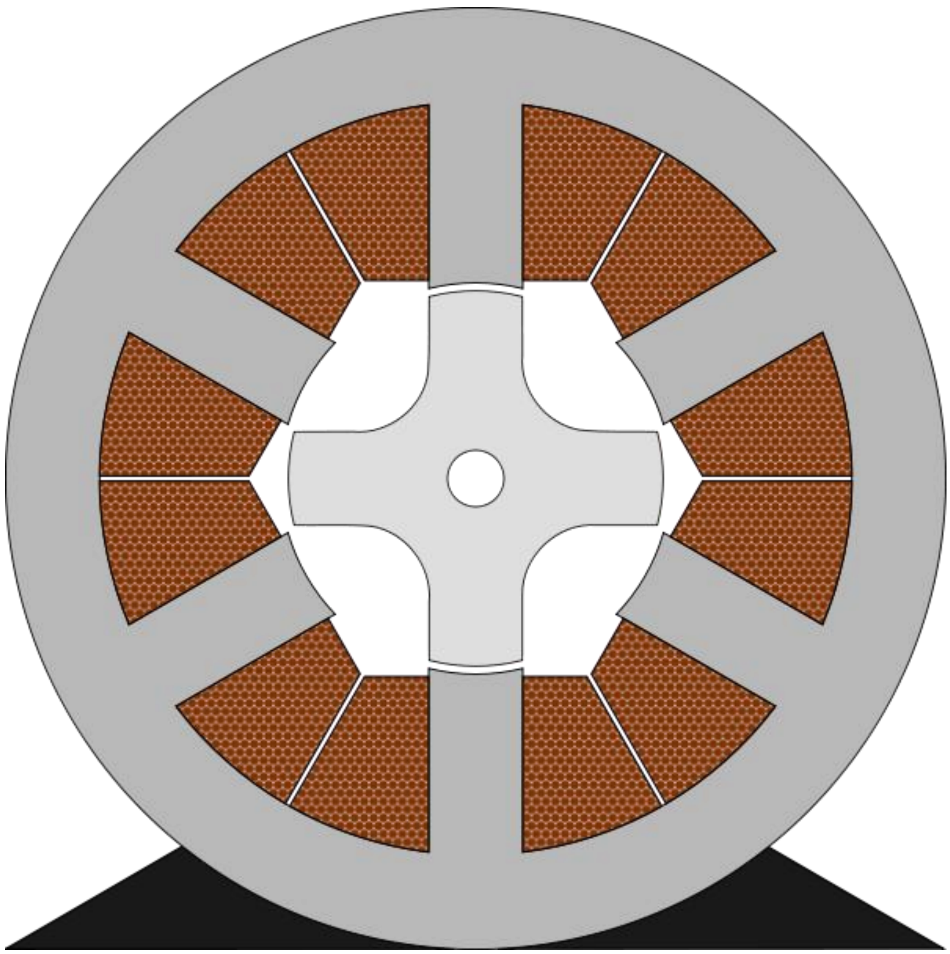

FIGURE 1.5 SR motor

1.4 THREE PHASE INDUCTION MACHINE:

Construction- The main parts of a three phase Induction motor are stator and rotor.

Stator- It consists of a steel frame which encloses a hollow, cylindrical core made up of thin laminations of silicon steel. Slots are provided on the inner periphery of the laminations. In the stator slots the insulated conductors are placed and connected to form a balanced 3-phase star or delta connected circuit. Numbers of poles are provided according to the requirement of speed in stator winding.

Rotor- The rotor is mounted on a shaft which is a hollow laminated core having slots on its outer periphery. The two types of windings are done on the rotor slots –Squirrel cage type and Wound type.

(i) **Squirrel cage rotor:** It consists of a laminated cylindrical core having parallel slots on its outer periphery. Each copper or aluminum bar is placed in each slot and all these bars are joined at each end by metal rings. This forms a permanently short-circuited winding. The entire construction resembles a squirrel cage and hence the name is given. The current induced in the rotor circuit by transformer action from the stator.

(ii) **Wound rotor:** It consists of a laminated cylindrical core and carries a three phase winding. The rotor winding is generally star connected and uniformly distributed in the slots. The open ends of the rotor winding are joined to three insulated slip rings mounted with brushes on each slip ring. These brushes are connected to a three phase star connected rheostat. These external resistances are connected to give large starting torque at starting.

Principle: Three phase balanced power supply is given to the stator winding of a three phase induction motor by which three phase currents flow in the stator winding which produces a rotating magnetic field .This rotating flux wave cuts the stationary rotor conductors and e.m.f.s are induced in it . As the rotor circuit is short circuited, these induced e.m.f.s give rise to current in the rotor conductors. The interaction of these rotor currents with rotating flux wave produces torque in the rotor of a three phase induction motor and as a result rotor begins to rotate. The figure shows the three phase induction motor.

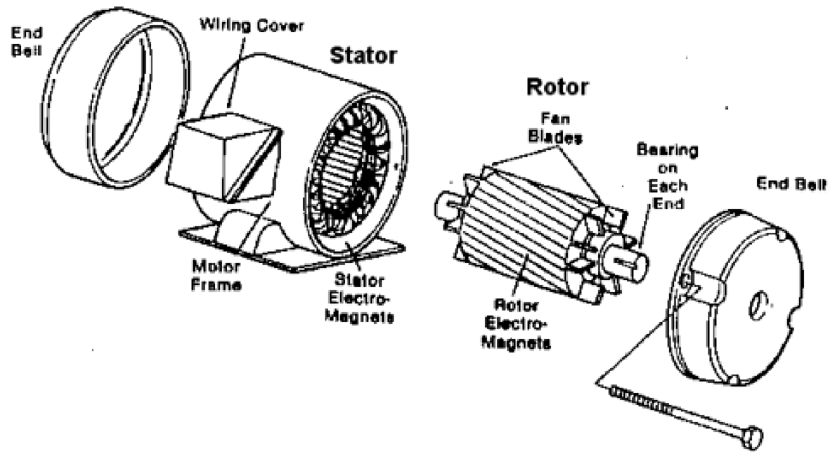

FIGURE 1.6 Squirrel cage induction machine

1.4.1 INDUCTION GENERATOR:

The construction of induction generator is same as of induction motor. In case of induction generator the rotor speed is advanced with respect to stator magnetic field rotation. The rotor is being driven at a speed more than synchronously rotating magnetic field for prime mover speed above synchronous speed. Rotating flux cut the rotor conductors in a direction opposite to that during motoring mode. So rotor generated emf, rotor current and hence its stator components change their signs. When the speed during induction generator operation is not synchronous then it is called an asynchronous generator.

Classification of Induction Generators:

For hydro and wind power plants, the induction machine has great advantages because of its easy operation as either a motor or generator. It has different application in different areas.

Induction generators can be classified on the basis of excitement process as

- Grid connected induction generator
- Self-excited induction generator

Further induction generators are classified on the basis of rotor construction as

- Wound rotor induction generator
- Squirrel cage induction generator

Depending upon the prime movers used and their locations, generating schemes can be broadly classified as under

- Constant speed constant frequency [CSCF]
- Variable speed constant frequency [VSCF]
- Variable speed variable frequency [VSVF]

Grid Connected Induction generator:

For excitement process the grid connected induction generator takes its reactive power from the grid supply where generator is driven by a prime mover above its synchronous speed and hence in case of grid connected induction generator the slip is negative.

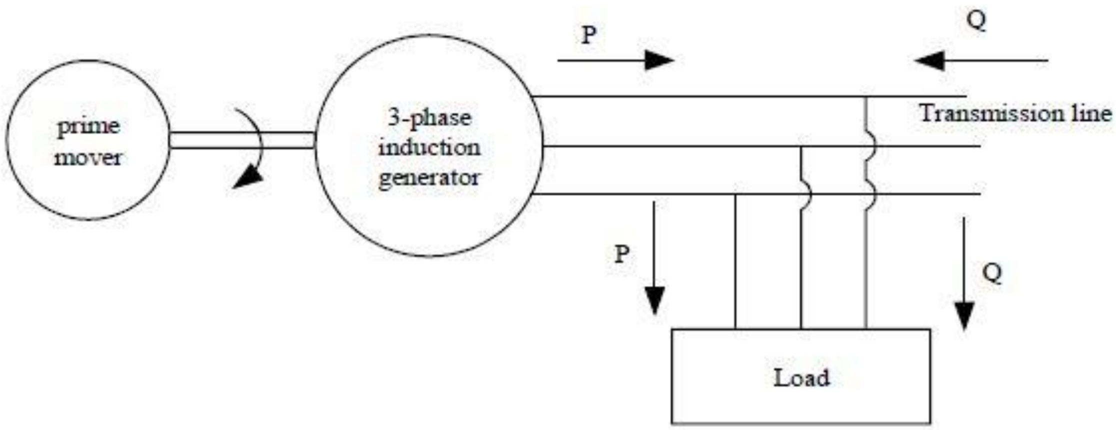

FIGURE 1.7 Grid connected Induction generator

Self-excited Induction Generator:

Self-excited induction generator (SEIG) means cage rotor induction machines with shunt capacitors connected at their terminals for self-excitation. The shunt capacitors may be constant or may be varied through power electronics. A capacitor bank supply the reactive power to the induction generator for self excitement process and as well as to the load.

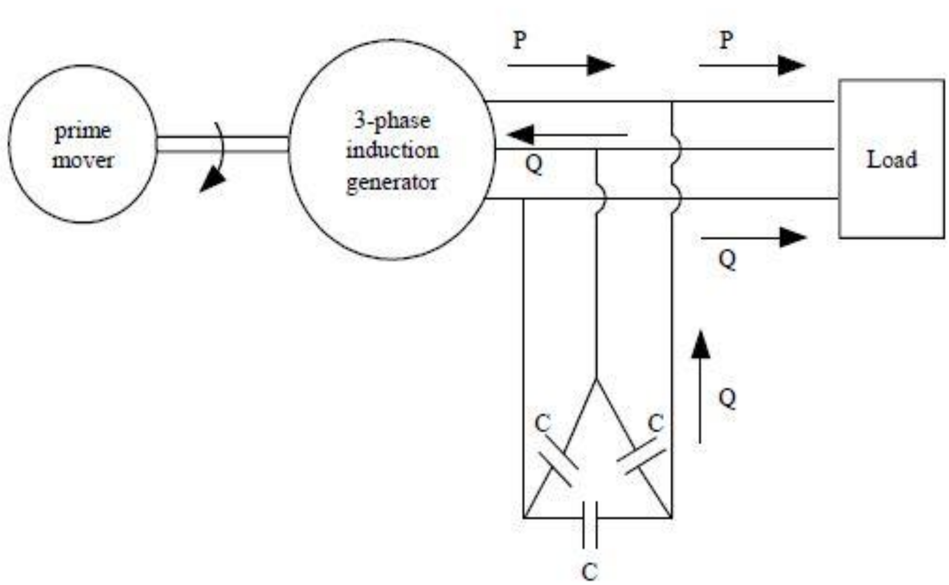

FIGURE 1.8 Self excited Induction generator

Constant speed constant frequency [CSCF] :

In Constant speed constant frequency scheme, by continuously adjusting the blade pitch and/or generator characteristics the prime mover speed is made constant. At a slip of 1% to 5% above the synchronous speed, an induction generator can operate on an infinite bus bar. Induction generators have many advantages like they are easier to operate, control, maintain, and do not have any synchronization problems.

Variable speed constant frequency [VSCF]:

The variable-speed operation of wind electric system yields higher output for both low and high wind speeds. This results in higher annual energy yields per rated installed capacity. Both horizontal and vertical axis wind turbines exhibit this gain under variable-speed operation.

Variable-Speed Variable Frequency [VSVF]:

The performance of synchronous generators can be affected with variable prime mover speed. For variable speed corresponding to the changing derived speed, SEIG can be conveniently used for resistive heating loads, which are essentially frequency insensitive. This scheme is gaining importance for stand-alone wind power applications

1.5 THESIS OBJECTIVE:

Induction generators are mostly used now-a-days in wind based power generation system and market of micro electric energy generation unit system. But in market induction machines are only available as induction motors. The catalogues only tell about rating, efficiency of induction motor. Hence there is no information about efficiency, looses of the induction generators.

The objective of this thesis is to calculate the losses, efficiency of induction machine for both motoring mode and generating mode. A comparative analysis between the motoring and generating mode will be done. So the generating mode ratings can be calculated from the induction motor catalogue.

1.6 ORGANIZATION OF THESIS:

Chapter 1: This chapter entitled as "Introduction". It includes different types of electrical motors, construction, working principle of 3-Φ induction motor and induction generator.

Chapter 2: This chapter entitled as "Induction machine and its energy efficiency" include the detail information about losses and efficiency of induction machine, its equivalent circuit.

Chapter 3: This chapter entitled as "Analysis of induction machine during motoring mode" include the induction motor performance analysis, calculation of losses and efficiency, no load test, blocked rotor test, power flow diagram of induction motor.

Chapter 4: This chapter entitled as "Analysis of induction machine during generating mode" include the magnetization characteristic, voltage build up in induction generator, its efficiency and power flow diagram for different modes.

Chapter 5: This chapter entitled as "Experimental analysis and comparative study" include the experimental set up different test, the observation tables, calculation of losses and efficiency of induction machine for motoring and generating mode.

Chapter 6: This chapter entitled as "Conclusion and future work" include the conclusion and future scopes of this project.

CHAPTER 2

Induction machine and its energy efficiency

2.1 INTRODUCTION:

The cost and availability of the electric energy can vary so the energy saving policies are more important. For these reasons, electric energy consumers are interested to use apparatus with high efficiencies. Due to the introduction of new materials like new electrical steels which have reduced losses, electrical machines have advanced significantly in recent years and rare-earth permanent magnet materials have provided a 'lossless' source of magnetic flux. Recent advances in construction methods have reduced winding losses, so there is a continued trend to increase efficiency.

Induction machines are mostly used as motors. Three phase induction motors can be found from a few hundred watts up to several megawatts. The induction motors are characterized by data provided by the manufacturer as rated speed, power, voltage, current and efficiency. With the growing emphasis on energy conservation and the increasing energy prices, the efficiency value has become very important. The efficiency values given by the manufacturer are measured or calculated according to certain standards. The efficiency values can differ significantly for motor and generator mode.

2.2 ENERGY EFFICIENCY:

Induction machines are two types (squirrel cage rotor & wound rotor) depending upon the type of rotor. Squirrel cage induction machines are mostly used due to some advantages like simplest, most rugged construction and low maintenance. Induction machine (the stator) gets supply from a single ac source; rotor receives energy from stator by induction. Hence no separate excitation is required for rotor and no slip rings are required creating low maintenance cost. Induction machines can be used as both motor and generator. The efficiency is different for motoring and generating mode.

The efficiency of a machine is the ratio of output power to input power, $\eta = \frac{P_{out}}{P_{in}}$

Efficiency can be determined by direct or indirect method. In direct method mechanical power is determined by accurate torque and speed measurement. This efficiency value depends upon ambient and motor temperature, which is not desirable for efficiency comparison. The indirect method is calculation of efficiency by segregation of losses, which allows correction for these temperature values to a specified ambient and reference motor temperature. Theoretically these losses are divided into fixed and variable losses. Fixed losses are magnetic core loss and friction & windage loss. Variable losses include stator and rotor copper loss. Beside these conventional losses induction machines have another power loss component called "stray load loss" caused by non-ideal nature of practical machines.

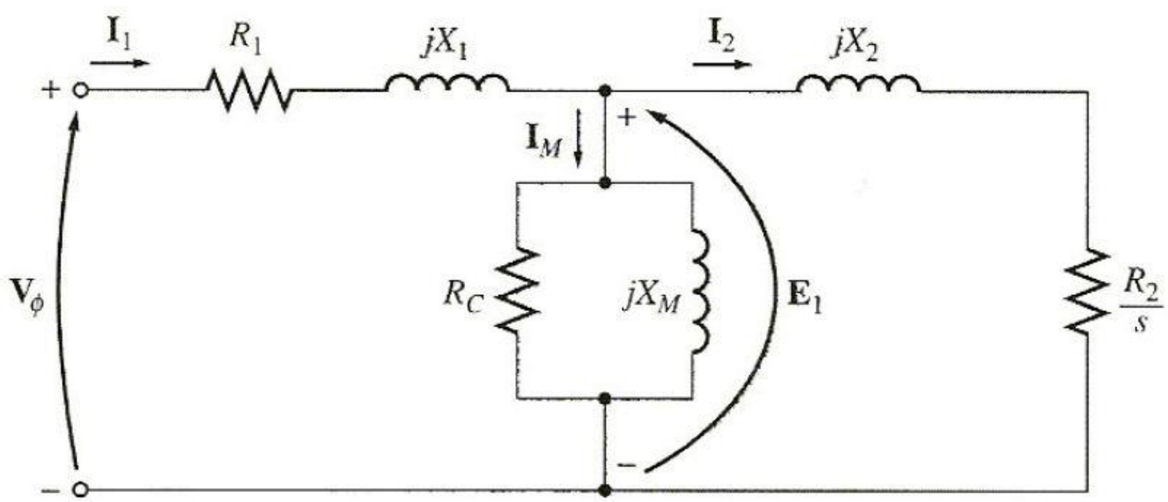

FIGURE 2.1 Equivalent circuit of induction machine

As said above the calculation of efficiency of an induction machine in convenient method is based on segregation of losses. The fixed losses or rotational losses (friction, windage loss and core loss) can be calculated by practical no load test of induction machine. These losses are assumed constant for both motoring and generating mode. The stator copper loss can also be calculated from no load test. Rotor copper loss is equal to slip fraction of air gap power i.e. power transferred from stator to rotor through air gap.

From no load test rotational loss, $P_R = W_o - I_o^2 R_o$

where W_o, I_o are wattmeter and ammeter reading respectively in no load test of the induction machine.

Stator copper loss = $I_o^2 R_o$

Rotor copper loss = $I_2^2 R_2 = sI_2^2 \frac{R_2}{s} = sP_g = s \times$ air gap power

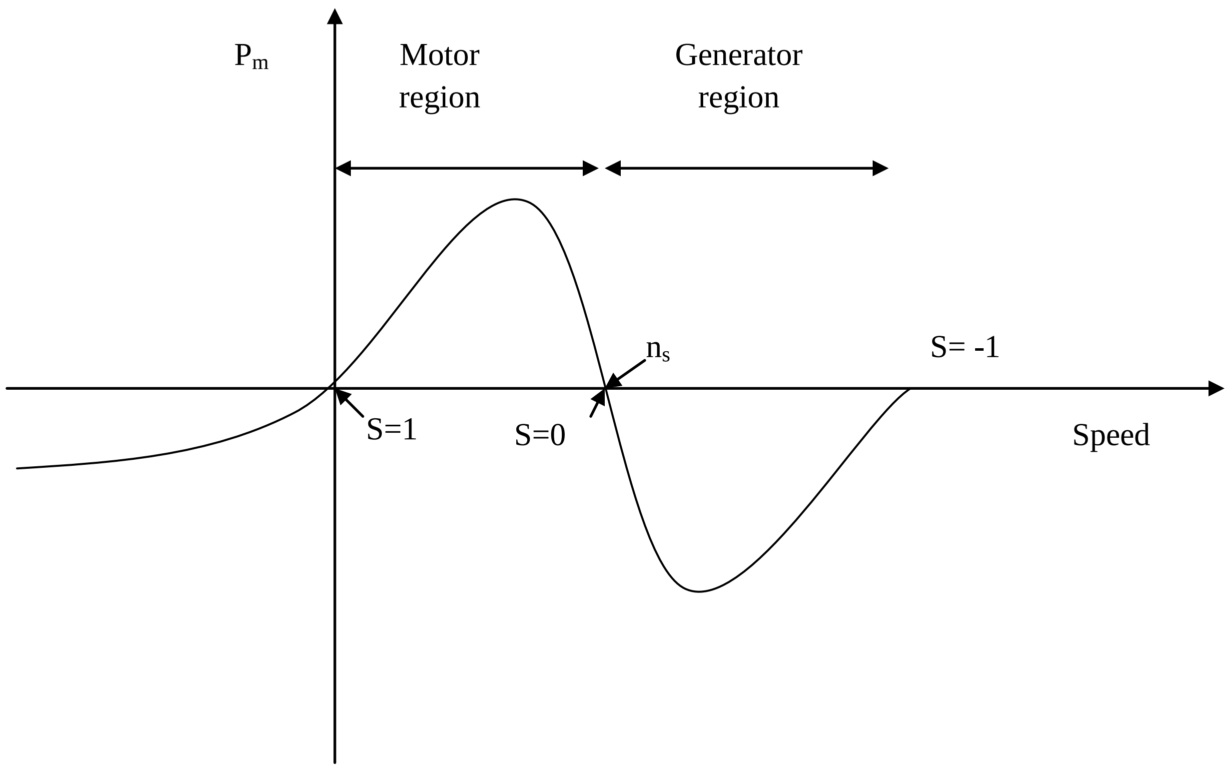

FIGURE 2.2 Power-slip characteristics of induction machine

From the Fig. 2.1 we can see the mechanical power is negative for generating mode of induction machine. The slip is negative for induction generator. At starting the starting torque is not zero but the mechanical power developed is zero for induction machine.

The energy efficiency for motoring mode and generating mode are given as:

1. MOTORING MODE:

In motoring mode the rotor of induction machines revolves in direction of rotating field at speed below the synchronous speed. Here the slip is in between 1 and 0. The efficiency of induction motor is given by $\eta_m = \frac{P_{mech}}{P_{el}} = 1 - \frac{P_{loss}}{P_{el}}$

The air gap power of induction motor is $P_g = P_{el} - P_{stator} - P_{Fe}$

For motoring mode, the stator current and stator voltage drop increase with load. Hence the air gap voltage (induced emf) decreases and so the magnetizing current and core losses also decrease. In grid connected induction motor the core losses are supplied by the grid where as the self excited induction motor gets reactive power from a capacitor bank.

2. GENERATING MODE:

In generating mode of induction machine, the rotor revolves at speed more than synchronous speed. The slip varies from 0 to -1 for induction generator. The efficiency of induction motor is given by $\eta_g = \frac{P_{el}}{P_{mech}} = \frac{P_{el}}{P_{el}+P_{loss}}$

The air gap power of induction motor is $P_g = P_{el} + P_{stator} + P_{Fe}$

In induction generator the air gap voltage will increase due stator voltage drop. So the magnetizing current and core losses will increase. The effect will be more if the machine is already in saturation and the stator resistance is not negligible. In induction generator the core losses are supplied by mechanical driver.

CONCLUSION:

Efficiency in motoring and generating modes have been studied in this chapter which depend on the iron loss, stator and rotor loss, friction and winding loss and stray load loss. By assuming equal active electrical power, the stator loses in generator loses will be larger than in motor mode so the efficiency in motor mode will be higher than in generator mode. In electrical machines, efficiency gains will result from the development of new materials and construction techniques.

CHAPTER 3

Analysis of Induction Machine during Motoring mode

3.1 INTRODUCTION:

Induction machines are mostly used in motoring mode. So detail information about equivalent circuit, losses and efficiency are available for motoring mode. There are many methods for calculating the efficiency of induction motor. The equivalent circuit parameters, losses and efficiency of induction motor can be calculated from the No load test, Blocked rotor test, DC test and Load test. The objective of this chapter is to describe the methods of determining the equivalent circuit parameters, losses and efficiency from these tests and discuss about induction motor performance.

3.2 DC TEST:

The dc stator resistance per phase is calculated from this test. The circuit connection is shown in Fig

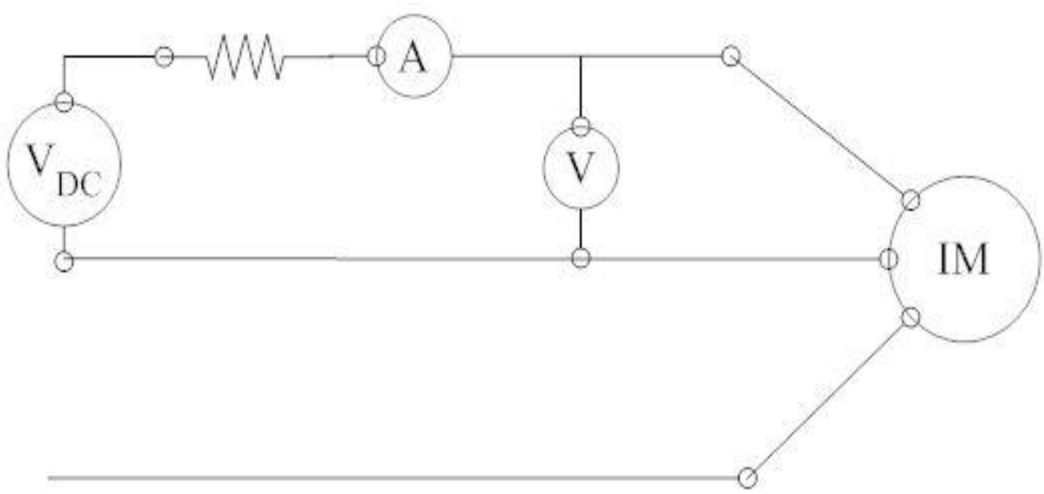

FIGURE 3.1: DC load test on 3-Φ induction motor

R = $\frac{1}{2}\frac{V_{DC}}{I_{DC}}$

3.3 NO LOAD TEST:

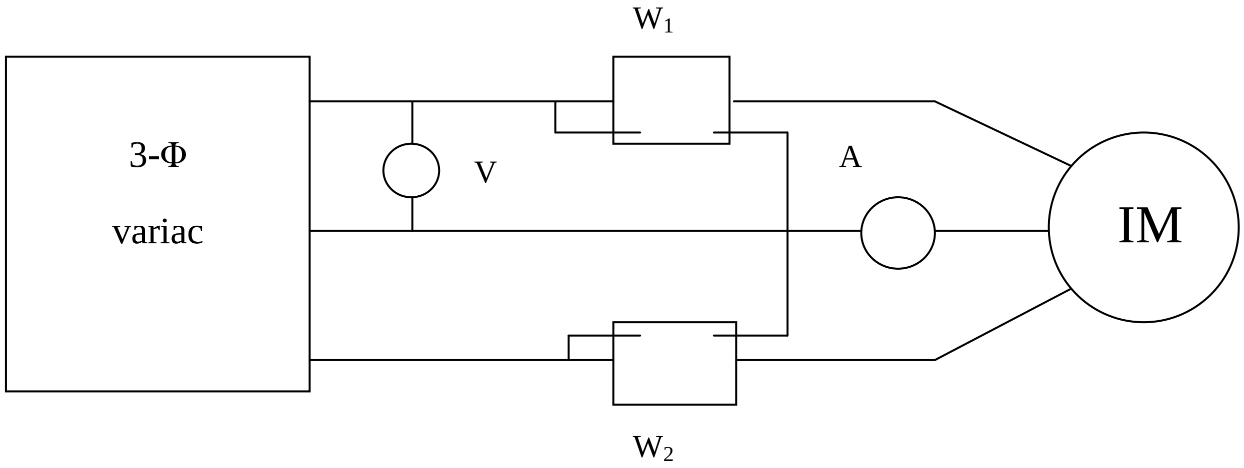

FIGURE 3.2: No load test of 3-Φ induction motor

- This test is also called Open circuit test.
- The induction motor is run at no load. Friction and windage are the only load.
- The motor is run at rated voltage and frequency.
- Slip (s_{nl}) is very small
- The per phase applied voltage V_{nl}, input current I_{nl}, input power P_{nl} are recorded from the voltmeter, ammeter, and wattmeters as shown in Fig.
- As slip is very small, r_2/s_{nl} in Fig. is very large compared to X_m. Hence resultant of parallel branches is almost equal to jX_m.
- So no load reactance from the stator terminals, $X_{nl} = x_1 + X_m$
- Stator no load impedance, $Z_{nl} = \frac{V_{nl}}{I_{nl}}$
- Stator no load resistance, $R_{nl} = \frac{P_{nl}}{I_{nl}^2}$
- $X_{nl} = \sqrt{(Z_{nl}^2 - R_{nl}^2)}$
- The fixed losses or rotational losses P_R consist of core loss and friction & windage loss is calculated from the relationship

$$P_R = m\,(P_{nl} - I_{nl}^2 r_1)$$

m = no. of stator phases

r_1 = stator resistance per phase

- So we get no load stator reactance and rotational losses from the no load test.

The equivalent circuit of Induction Motor for No load test is given below:

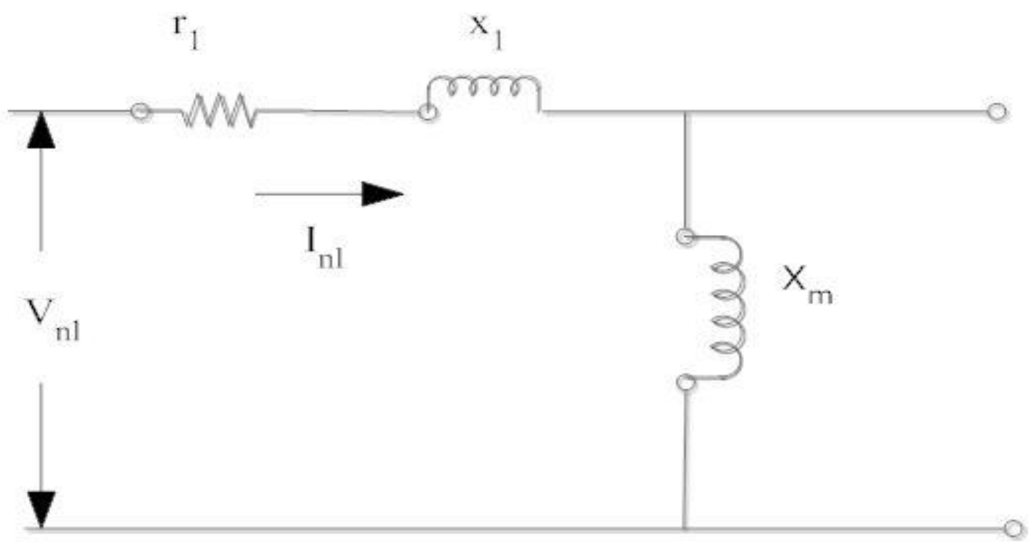

FIGURE 3.3: Equivalent circuit of 3-Φ induction motor for No load test

3.4 BLOCKED ROTOR TEST:

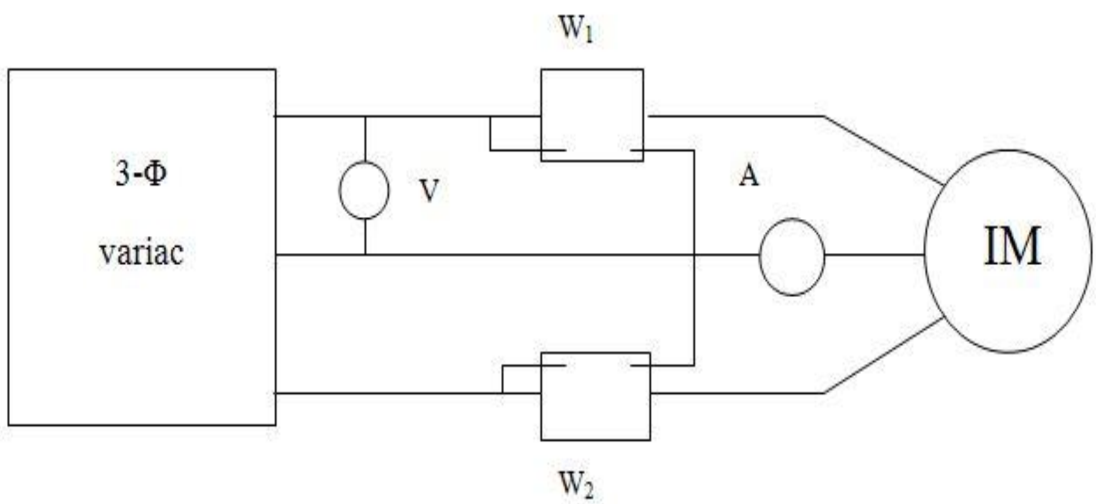

FIGURE 3.4: Blocked rotor test on 3-Φ induction motor

- Blocked rotor test is performed to determine the leakage impedance
- The rotor shaft is blocked by external means.
- Voltage is applied till rated current flows in the stator winding.
- Per phase values of applied voltage V_{br}, input current i.e. rated current I_{br} and the input power P_{br} .
- In this test the voltage input is very small, so the core loss.
- Hence the input power P_{br} is nearly equal to both stator and rotor winding copper loss.
- Equivalent circuit parameters of induction motor can be calculated from no load test and blocked rotor test results.

The equivalent circuit diagram for blocked rotor test is given below:

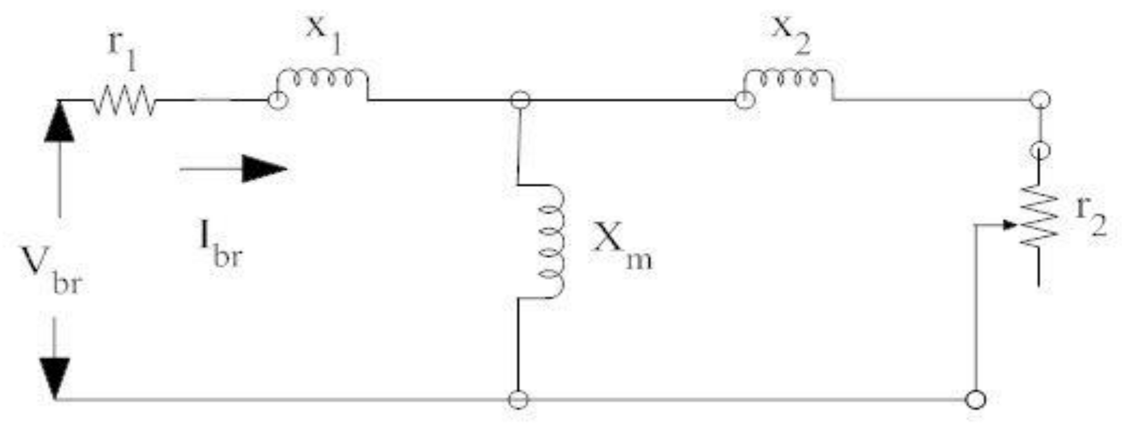

FIGURE 3.5: Equivalent circuit of 3-Φ induction motor for blocked rotor test

From this test:

Blocked rotor impedance, $Z_{br} = \frac{V_{br}}{I_{br}}$

Blocked rotor resistance, $R_{br} = \frac{P_{br}}{I_{br}^2}$

Blocked rotor reactance, $X_{br} = \sqrt{Z_{br}^2 - R_{br}^2}$

$X_{br} = x_1 + x_2$

Generally $x_1 = x_2 = \frac{1}{2}X_{br}$

From the observations of no load test, blocked rotor test and DC test we get X_{nl}, x_1, x_2, r_1.

$X_m = X_{nl} - x_1$

$r_2 = (R_{br} - r_1)(\frac{X_2}{X_m})^2$

3.5 PERFORMANCE ANALYSIS:

Induction machine is a classical asynchronous machine and mostly used due to its better performance than other electric motors. Squirrel cage induction motors are used more due some advantages like cheap, robust and low maintenance. Induction motor performance depends on rotor resistance, air gap length, shape of both stator and rotor slots. The objective of this chapter is discuss about performance and operating characteristics of induction motor and the factors affecting them.

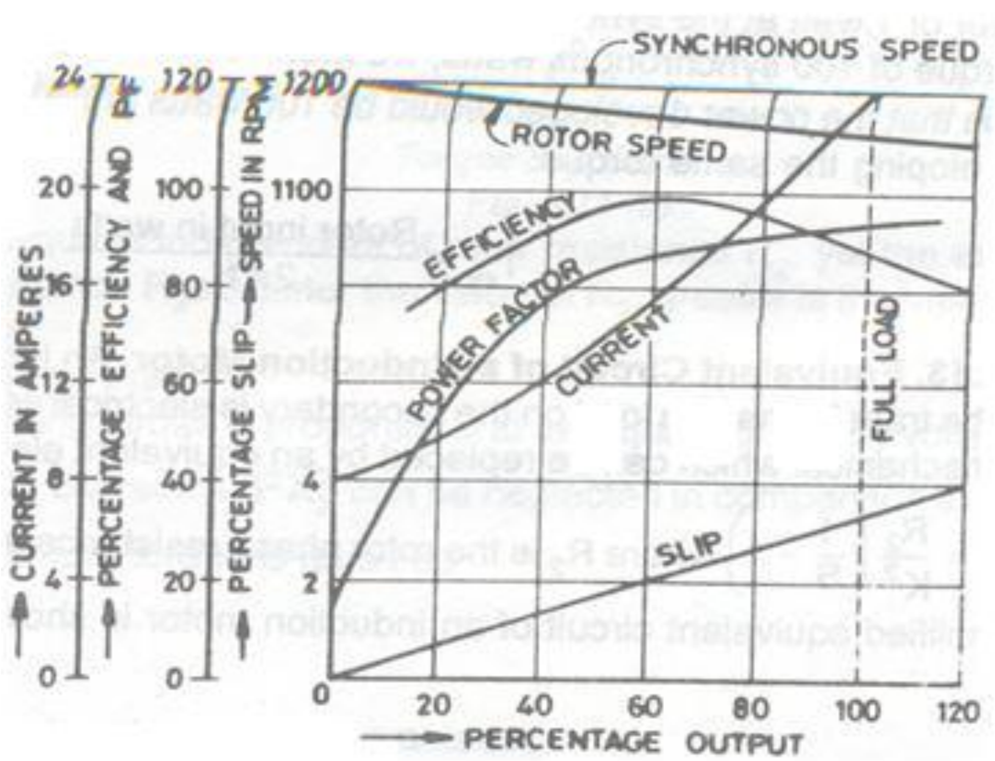

FIGURE 3.6: Operating characteristics of an induction motor

At no load, the speed of rotor is close to synchronous speed. Hence the no load slip is very small. No load torque is very small and sufficient to overcome friction and windage loss. So the rotor current is also small. As mechanical load are added, the load torque increases, the rotor speed decreases and the slip increase. The decrement in rotor speed from no load to full load is 2%-5% of rated speed.

The stator power factors is very low (nearly in range 0.1-0.3) at no load condition of induction motor, because the current drawn by induction motor is largely magnetizing current. As load increase, the active component of no load current increases, the power factor angle decrease and the power factor improves. The power factor is 0.85 to 0.88 at 80% - 90% of full load output. Power factor decreases slightly beyond this load because of the dominant effect of stator and rotor leakage reactance drops.

The no load stator current is about 30% - 50% of rated current. As mechanical load is added, the rotor speed decreases increasing rotor current. Therefore the counter e.m.f. decreased allowing more stator current to flow.

The induction machine variable losses and efficiency increase with load and efficiency becomes maximum when fixed losses and variable losses are equal. Generally maximum efficiency occurs at 80% to 95% of rated output. Beyond this load, the variable losses increase rapidly than output resulting decrement in efficiency.

The air gap flux remains constant for constant supply voltage in induction motors. So if air gap length is increased, then more magnetizing current is required for constant flux. This leads to decrease in no load and full load power factor of the induction motor. Thus the air gap length should be kept as small as possible for better power factor of induction motor.

The slot leakage flux is directly depends upon the slot depth. So induction motors with deeper slots have more leakage reactance, low starting torques, low maximum torque and low slip at maximum torque.

3.6 POWER FLOW DIAGRAM:

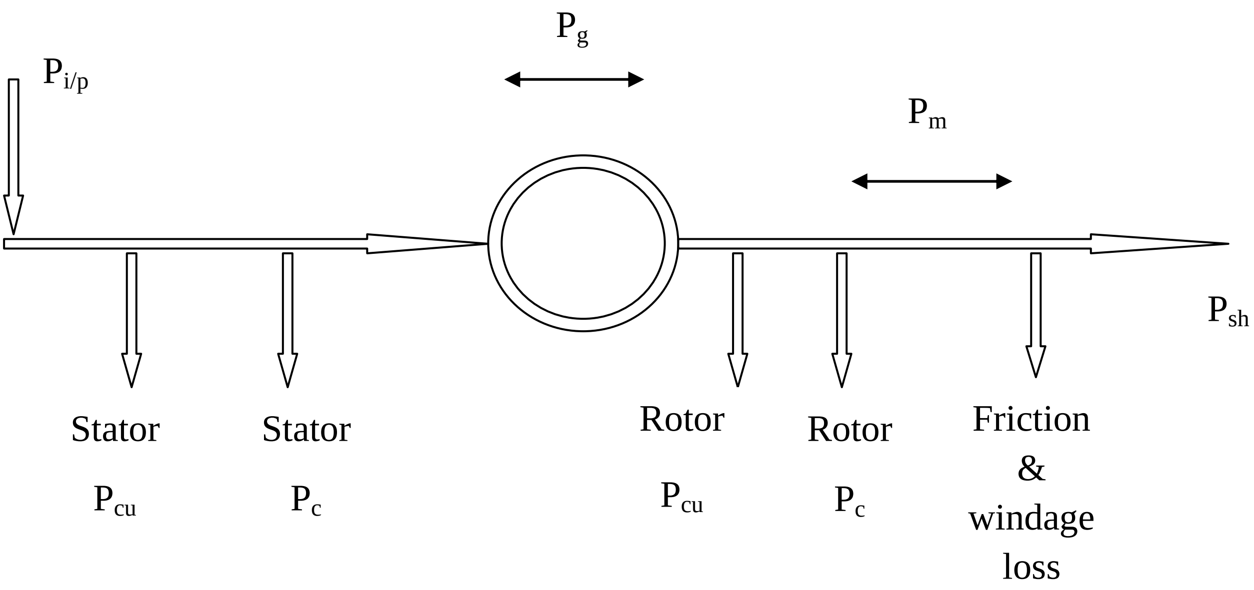

FIGURE 3.7: Power flow diagram of a 3-Φ induction motor

Where

$P_{i/p}$ = Power input

P_{cu} = Copper loss or I^2R loss

P_c = Core loss

P_g = Air gap power

P_m = Mechanical power

P_{sh} = Output shaft power

3.7 EFFIENCY CALCULATION:

Efficiency calculation of electrical machines need input power, output power and losses. For 3-Φ induction motor the input power is 3-Φ electrical power and output power is rotor shaft power. The losses in an induction motor are two types:

i. Fixed losses
ii. Variables losses

Fixed losses consist of core loss and losses due to friction and windage. Normally these losses are taken as constant for induction motor. Fixed losses (also called Rotational losses) can be calculated from observations of no load test.

Variable losses consist of stator ohmic loss, rotor ohmic loss and stray losses. Total ohmic loss or copper loss can be determined by performing blocked rotor test on induction motor. The stator copper loss and rotor copper loss can be calculated directly if stator and rotor windings ac resistances are known. Stray load loss occurs in iron as well as in conductors.

$$\eta = \frac{\text{Output power}}{\text{Input power}} = \frac{\text{Shaft power}}{\text{Electrical power}} = \frac{P_{sh}}{P_{el}}$$

Input power = Output power + losses

Mechanical power, P_m = mechanical power developed in rotor

Air gap power, P_g = power transferred from stator to rotor through air gap

Shaft power, $P_{sh} = P_m$ – friction and windage loss

$$P_g = I_2^2 \frac{r_2}{s} = I_2^2 r_2 + I_2^2 r_2 (\frac{1-s}{s})$$

= rotor ohmic loss + mechanical power developed in rotor

= sP_g + (1 – s) Pg

$P_m = (1- s) P_g$

Rotor ohmic loss = $P_m(\frac{s}{1-s})$

$P_g = P_{el}$ – stator ohmic loss – stator core loss

CHAPTER 4

Analysis of Induction Machine during generating mode

4.1 INTRODUCTION:

Induction machines acts as a generator when the slip of machine is negative i.e. the rotor rotates with speed above synchronous speed. When slip is negative, the rotor e.m.f., rotor current and power becomes negative. Under such condition, the electric torque developed is negative (opposite to prime mover) and the machine delivers power to supply mains. Induction generator is also called asynchronous generator. The induction generators are two types depending upon the source of magnetizing current:

i. Self-excited induction generator
ii. Separately-excited induction generator

4.2 MAGNETIZATION CHARACTERISTICS:

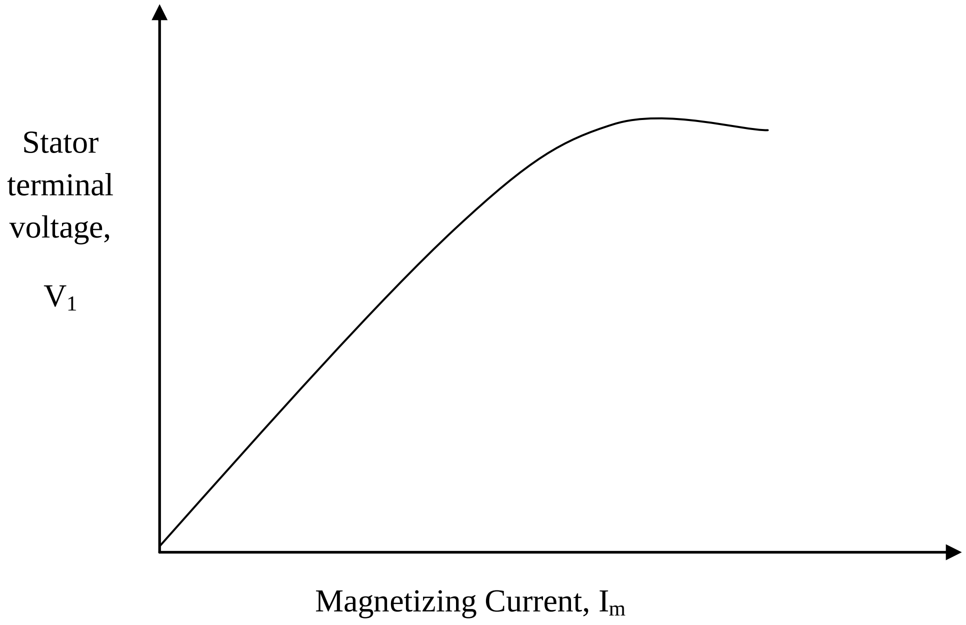

FIGURE 4.1: Magnetizing characteristics of induction generator

The magnetization characteristic of self excited induction generator is same as self excited DC generator. When the stator current is zero, there is some e.m.f. in the stator terminal. This is due to residual magnetism present in rotor. Then the curve becomes linear for some range and then it deviates from linear relationship. When magnetic saturation occur the stator terminal voltage does not increase with stator current.

4.3 VOLTAGE BUILDUP PROCESS:

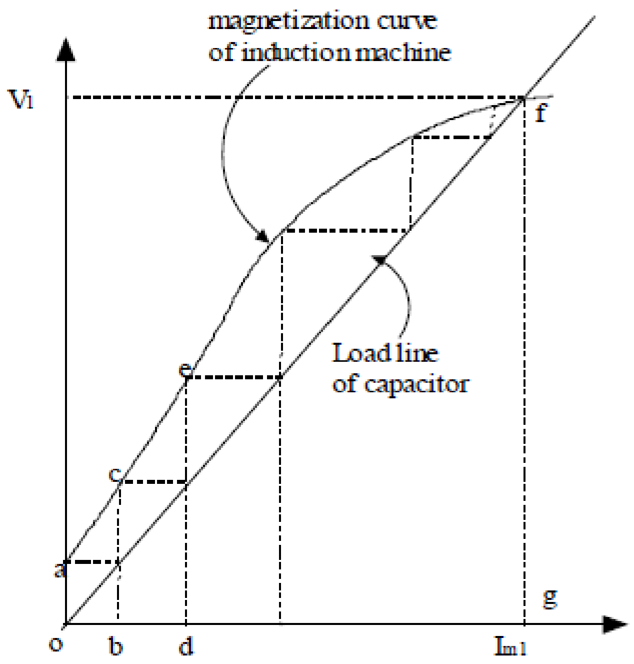

FIGURE 4.2: Voltage build-up process in 3-Φ induction generator

When the rotor of induction generator is run, the residual magnetism present in rotor iron creates a small e.m.f. oa across stator terminals. This voltage causes a capacitor current ob. The flux due to current ob is added with residual flux and generates a stator terminal voltage bc. This voltage produces current od in capacitor bank which then generates voltage de. This cumulative process continues till the intersection point f between saturated magnetization curve and capacitor load line. The intersection point f gives no load generated e.m.f. gf at the magnetizing current I_{m1}.

The induction generator will not build up if there is no residual flux present in rotor iron. To overcome this problem the induction machine is run in motoring mode for some time to create residual magnetism. This voltage build up process is similar to that of dc shunt generator.

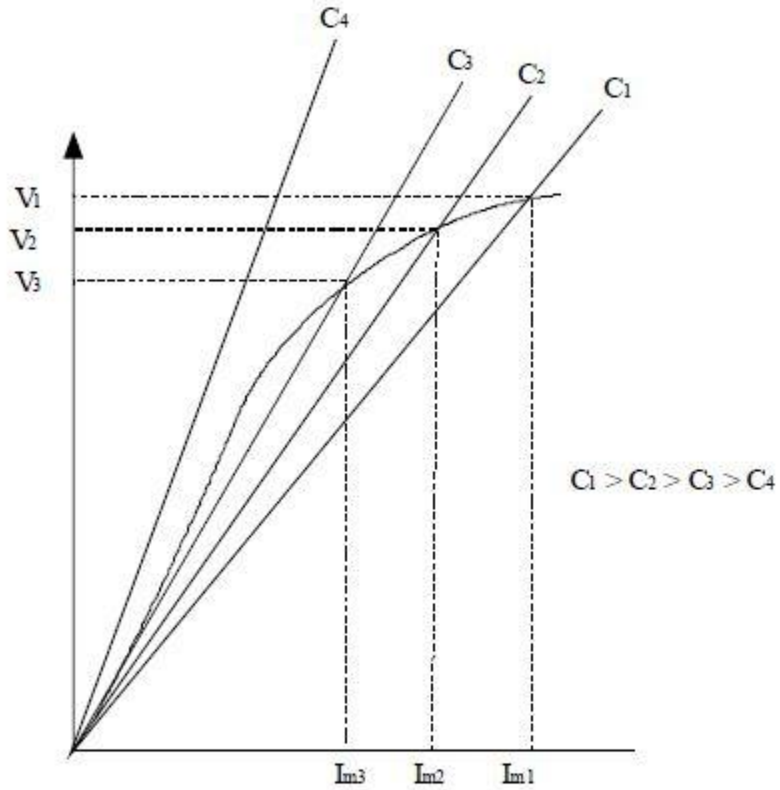

FIGURE 4.3: Effect of capacitance on voltage build up process in 3-Φ induction generator

The voltage build process depends upon the capacitor value. Higher the value of capacitance, greater is the voltage build up, as shown in Fig. 4.3. If the capacitor load line does not intersect the magnetization of induction generator, there would be no voltage build up. In Fig.4.3 for capacitor C_4, the voltage build up does not occur.

4.4 POWER FLOW DIAGRAM:

Induction generators can be divided into two types depending upon the speed of rotor:

i. Super-synchronous generator
ii. Sub-synchronous generator

The power flow diagrams of both generators are different.

4.4.1 SUPER-SYNCHRONOUS GENERATOR:

$s < 0$ (negative)

For generating mode,

P_m = negative

P_g = negative

$P_m = (1 - s) P_g$

- ⇨ $|P_m| > |P_g|$

sP_g = positive

- ⇨ $P_2 + P_{2cu}$ = positive
- ⇨ As P_{2cu} is always positive, hence P_2 is also positive

P_{2cu} = Rotor copper loss

P_2 = Electrical power output from rotor terminals

P_{1cu} = Stator copper loss

P_c = Core loss

So net electrical power output = $P_1 + P_2$

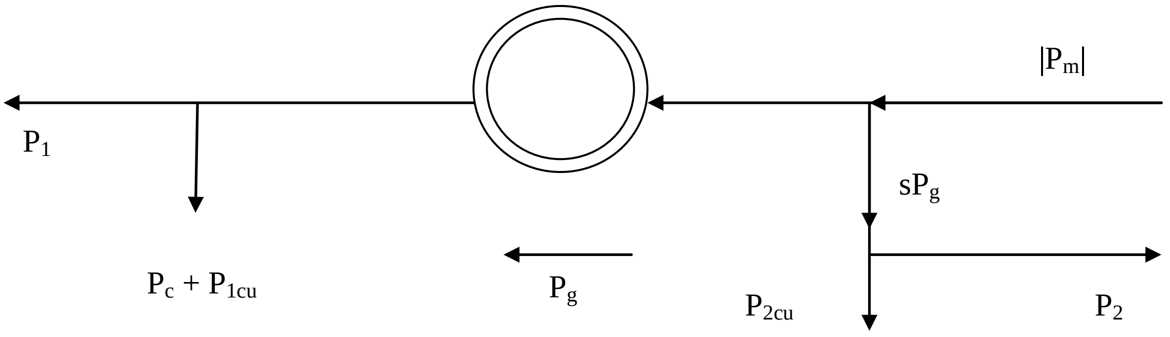

FIGURE 4.4 Power flow diagram of super-synchronous induction generator

4.4.2 SUB-SYNCHRONOUS GENERATOR:

$0 \le s \le 1$

For generating mode,

P_m = negative

P_g = negative

sP_g = negative

- ⇨ $P_2 + P_{2cu}$ = negative
- ⇨ P_2 is negative

$|P_m| < |P_g|$

Net electrical power output = $P_1 - P_2$

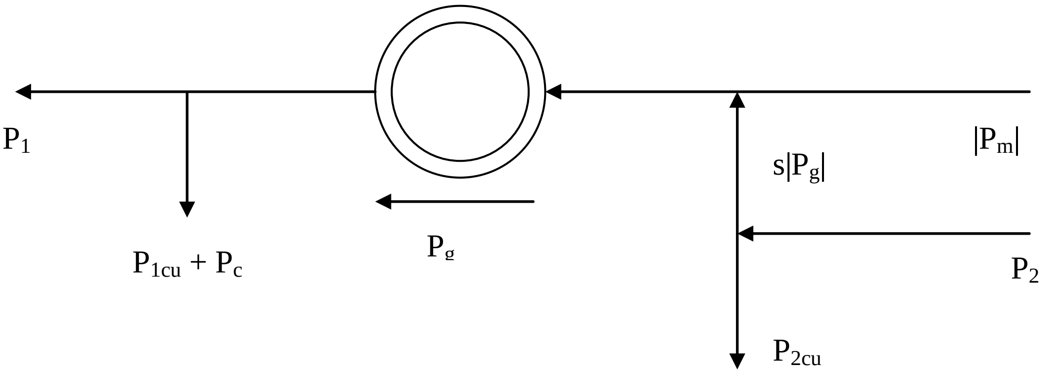

FIGURE 4.5 Power flow diagram of sub-synchronous induction generator

4.5 EFFIECIENCY CALCULATION:

For generating mode of induction machine input power is mechanical power and output power is electrical power. As shown above the output power in super-synchronous induction generator is greater than sub-synchronous induction generator. So efficiency is higher in case of super-synchronous induction generator.

$$\eta = \frac{P_{el}}{P_{mech}} = \frac{P_{el}}{P_{el} + \text{loss}}$$

For generating mode the losses will be same as of induction motor i.e. fixed loss (core loss and friction and windage loss) and variable loss (stator and rotor ohmic loss).

4.6 CONCLUSION:

So induction machines can be used as generator by increasing the rotor speed above synchronous speed. The reactive power can be supplied from external supply or by connecting capacitor bank (self excitation). In self excited induction generator the voltage build up is same as the dc shunt generator. The power flow diagram and efficiency are discussed for induction generator. The comparison between motoring mode and generating mode characteristics and efficiency will be discussed in next chapter.

CHAPTER 5

Experimental Analysis and comparative study

5.1 INTRODUCTION:

For induction motor and induction generator the output power is different. The losses in both the modes will be different. In this chapter a comparative analysis between motoring mode and generating mode of a 3-Φ induction machine is discussed by doing practical experiment.

The determination of efficiency of an induction machines is carried out by calculating different losses. The rotational loss or fixed loss is calculated from the no load test of the induction machine. The ohmic losses can be calculated from blocked rotor test on induction machine. The rotor loss is calculated from slip fraction of the power transferred from stator to rotor through air gap i.e. air gap power. The air gap power is given by:

$P_g = P_{el} – P_{stator} - P_{core}$ ------------------- Motoring mode

$P_g = P_{el} + P_{stator} + P_{core}$ ------------------ Generating mode

In induction motor the core loss is supplied by the connected grid where as in induction generator it is supplied by mechanical driver. In self-excited induction generator the reactive power is supplied by the capacitor bank connected.

5.2 MEASUREMENT SETUP AND EXPLANATION:

For determining and comparing the losses and efficiency of motoring and generating mode of induction machine, a 3-Φ squirrel cage induction machines is subjected to no load test, blocked rotor test and load test both under motoring and generating mode. The circuit connection for no load test and blocked rotor test is shown in Fig 5.1 on next page. In no load test the rotor is open circuited and in blocked rotor test the rotor is blocked by means of some external force. The ac voltmeter and ac ammeter ratings are different for these tests.

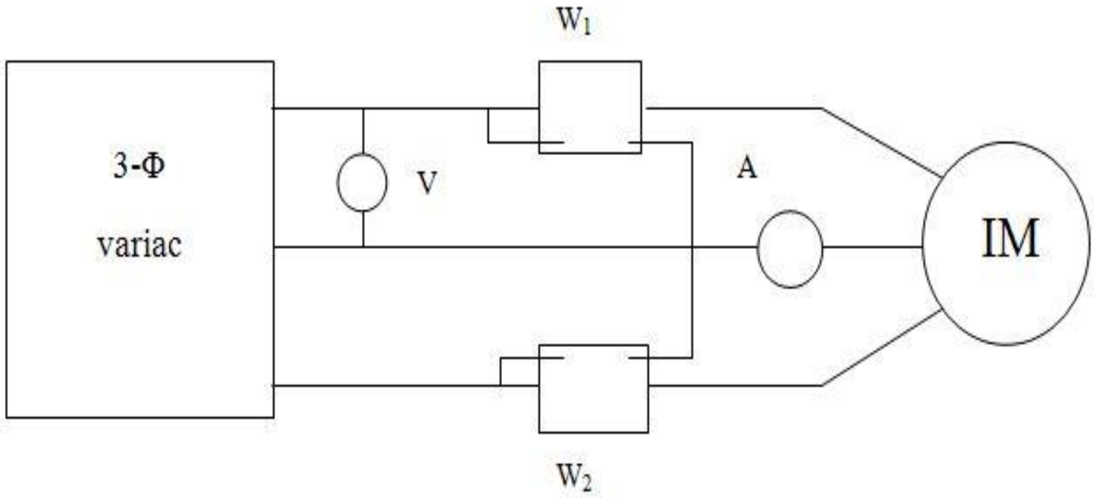

FIGURE 5.1: Experimental setup for 3-Φ induction machine testing

For No load test:

Voltmeter rating = 0 – 600V

Ammeter rating = 0 – 5A

For blocked rotor test:

Voltmeter rating = 0 – 100V

Ammeter rating = 0 – 30A

From load test we calculated the stator and rotor ohmic losses, power factor, output power and efficiency for different input powers. Then from these readings we plotted power factor characteristics, graph between output power and efficiency, output power and stator and rotor ohmic loss, graph between stator current and efficiency using Microsoft Excel. Similarly no load characteristic is plotted from observations of no load test.

For induction generator the rotor is rotated at speed above synchronous speed. The induction machine is coupled with a DC motor. The rotor speed of induction machine is varied by controlling the speed of DC motor. For self excitation a group of capacitors is connected at stator side of the induction machine.

FIGURE 5.2: 3-Φ Induction Machine coupled with DC motor

FIGURE 5.3 Experimental setup of induction machine

5.3 EXPERIMENTAL RESULTS AND COMPARATIVE STUDY:

TABLE 1: No Load Test of Induction Motor

Current(Amp)	Voltage(Volt)	Power(Watt)
8.9	415	1020
8.5	400	1000
8.2	380	960
7.8	360	910
7.5	340	870
7.2	320	820
6.9	300	750

Blocked Rotor Test: 90V, 15A, 1450W

TABLE 2: Load test on Induction Generator

Current	Voltage	Power	cosΦ	P_{stator}	P_{rotor}	$P_{o/p}$	Ƞ(%)
12A	420V	6538.42W	0.749	172.8W	226.5W	5630W	85.21
11.3A	415V	5507.02W	0.668	153.3W	137.1W	4726W	84.32
10.6A	410V	4561.66W	0.606	134.8W	82.7W	3832W	83.22
9.8A	410V	3083.01W	0.443	115.2W	38.3W	2553W	81.43

TABLE 3: No Load Test on Induction Generator

Current(A)	Voltage(V)	Power(W)
7	415	920
6.9	400	880
6.8	380	860
6.6	360	800
6.4	340	720
6.2	320	640

TABLE 4: Load Test on Induction Motor

Current(A)	Voltage(V)	Power(W)	P_{stator}(W)	P_{rotor}(W)	cosΦ	$P_{o/p}$(W)	Ƞ(%)
12	390	6430	172.8	78	0.793	5440	84.57
13	385	7355	202.8	165`	0.848	6244	85.12
14	385	8115	235.2	262.5	0.869	6937	85.48
14.5	380	8420	252.3	315	0.882	7220	85.73
15	380	8800	270	382.5	0.891	7550	85.22

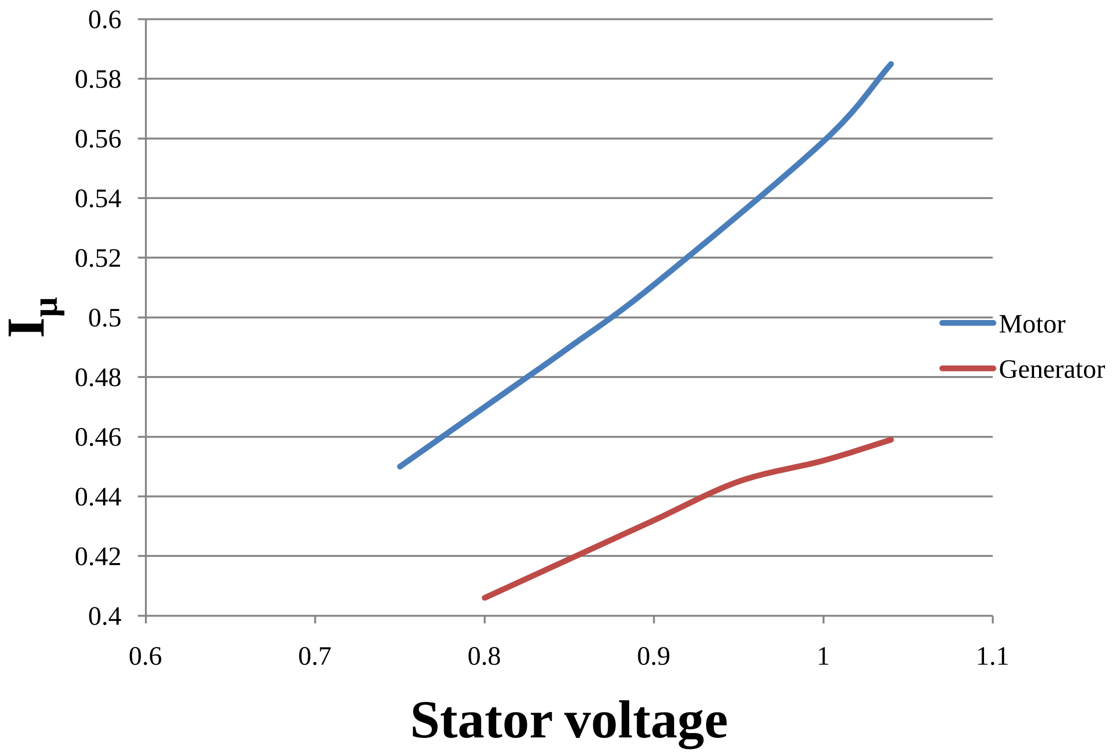

FIGURE 5.4: I_μ vs Stator voltage for a 3-Φ induction machine

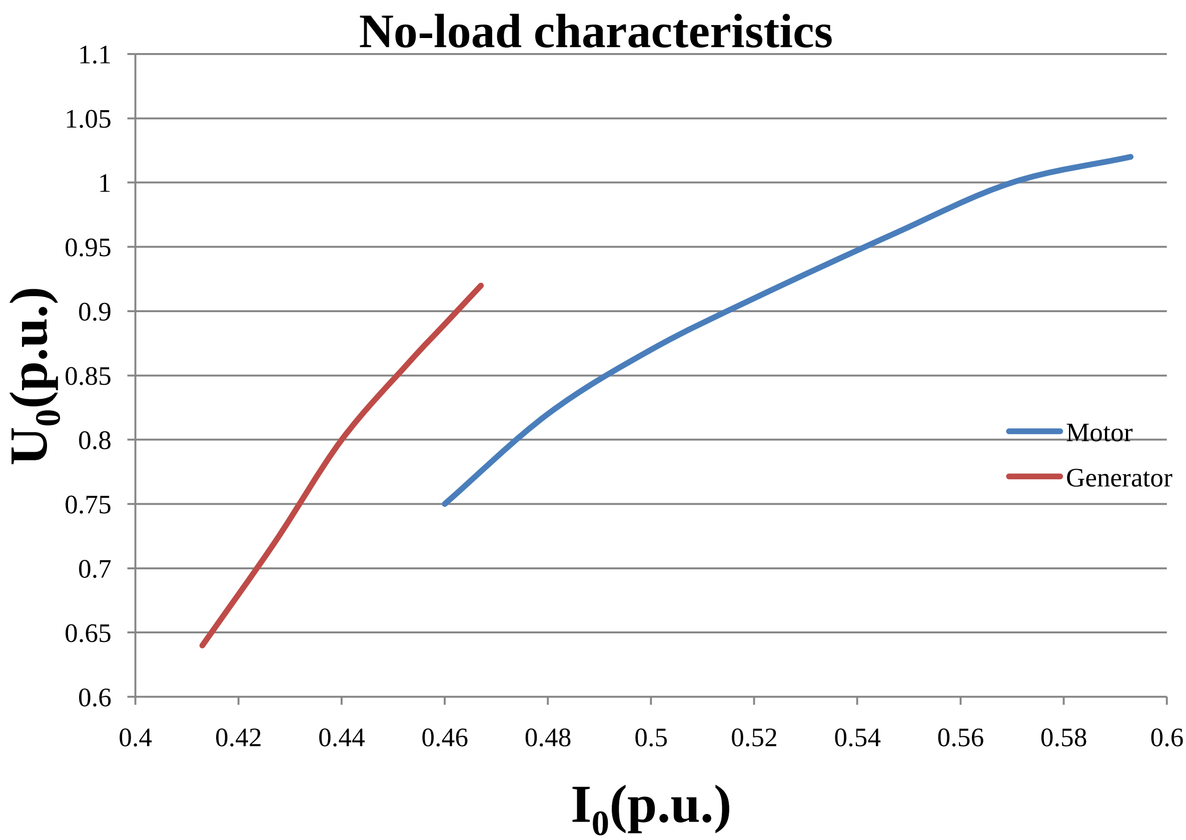

FIGURE 5.5: No load characteristics of 3-Φ induction machine

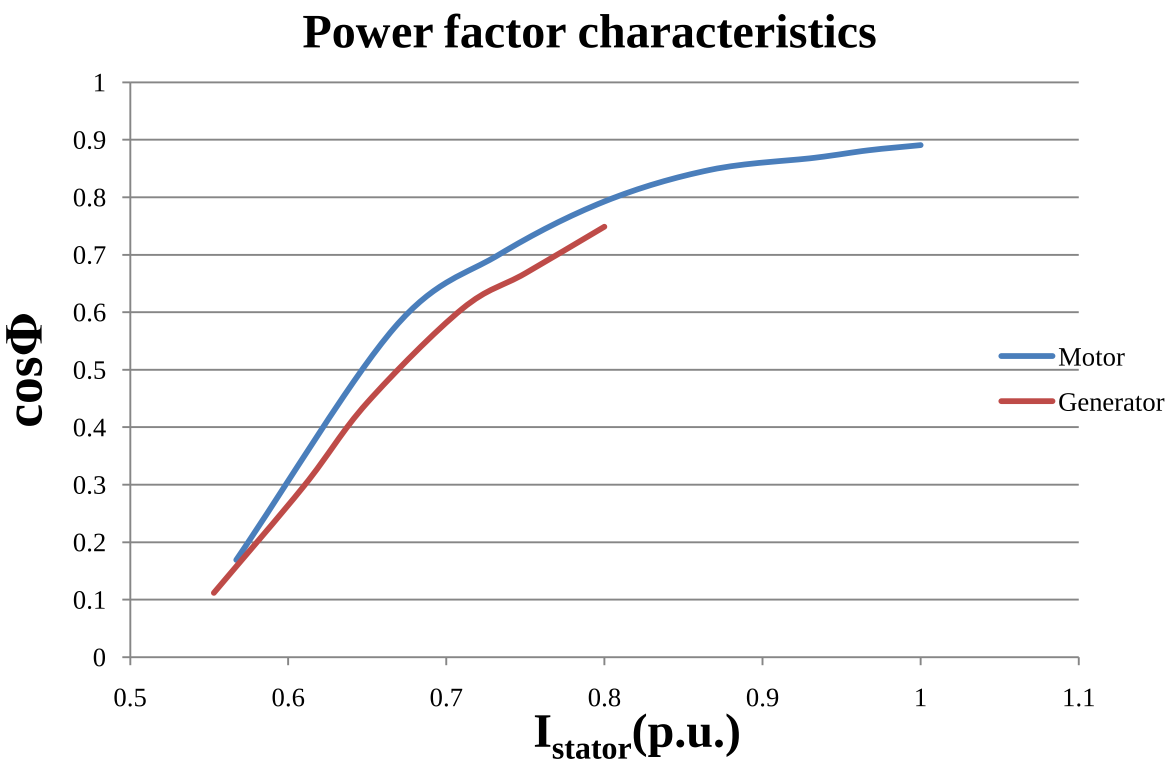

FIGURE 5.6: Power factor characteristics of a 3-Φ induction machine

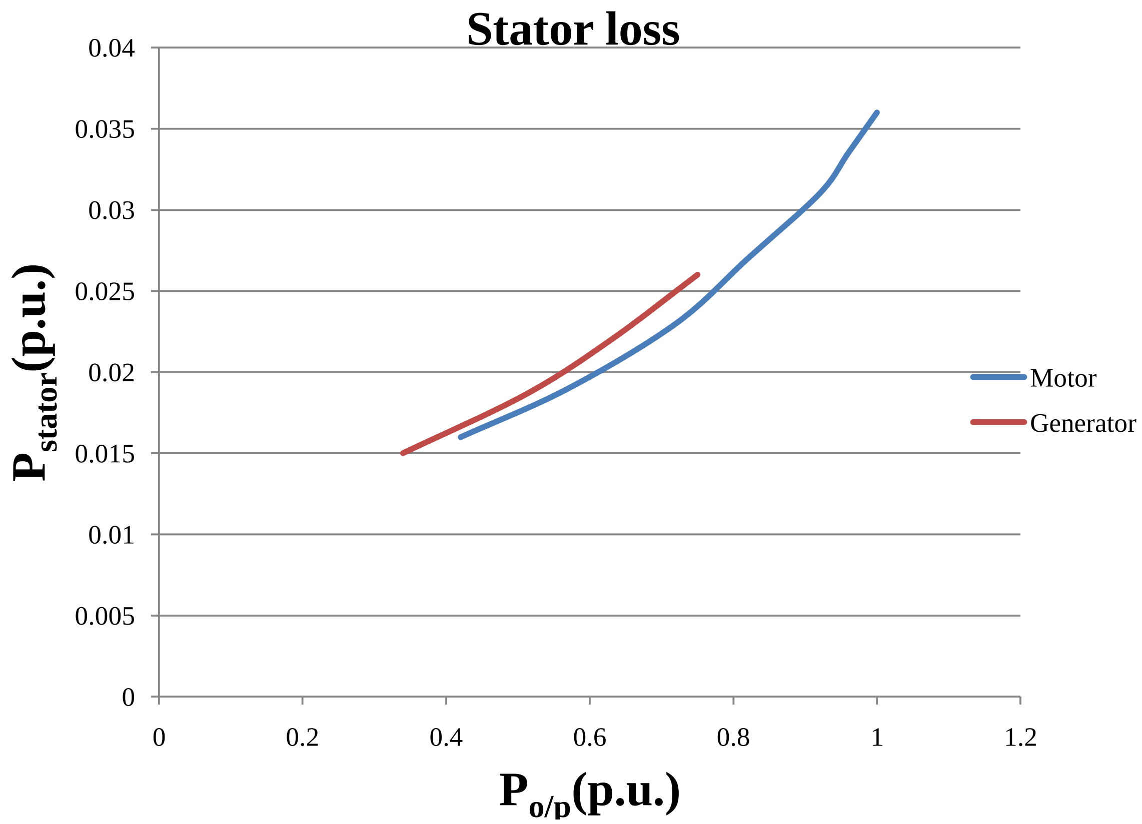

FIGURE 5.7: Stator losses vs output power of a 3-Φ induction machine

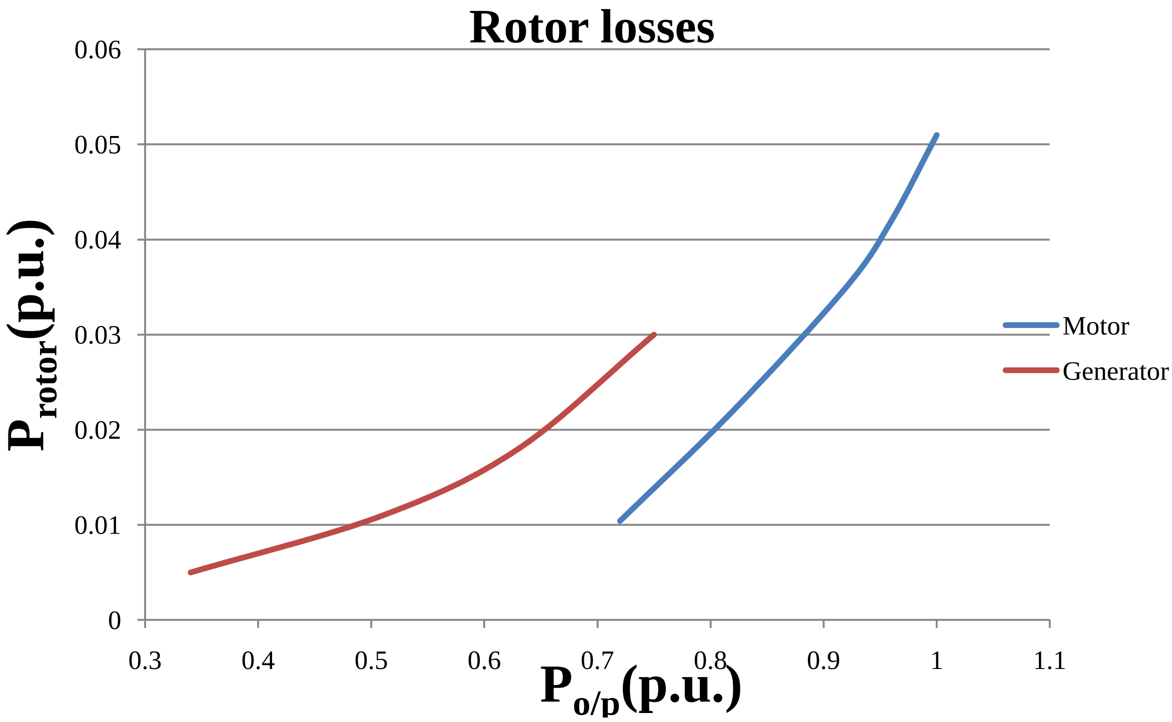

FIGURE 5.8: Rotor losses vs output power of a 3-Φ induction machine

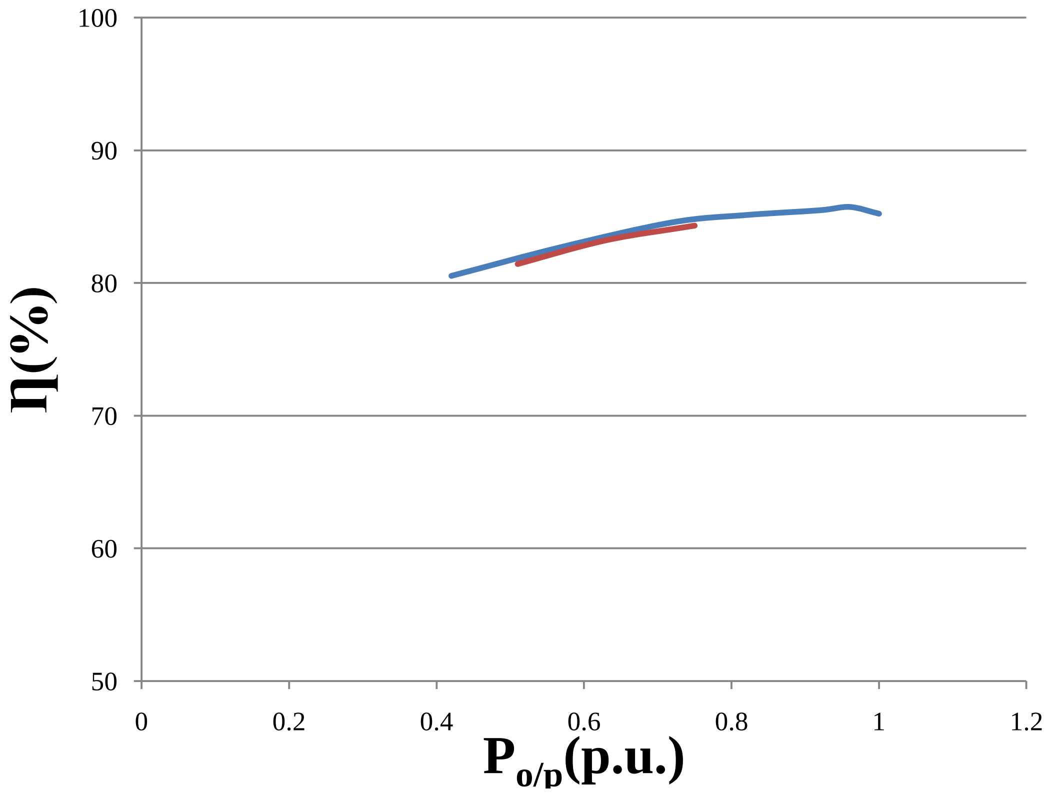

FIGURE 5.9: Efficiency vs output power of a 3-Φ induction machine

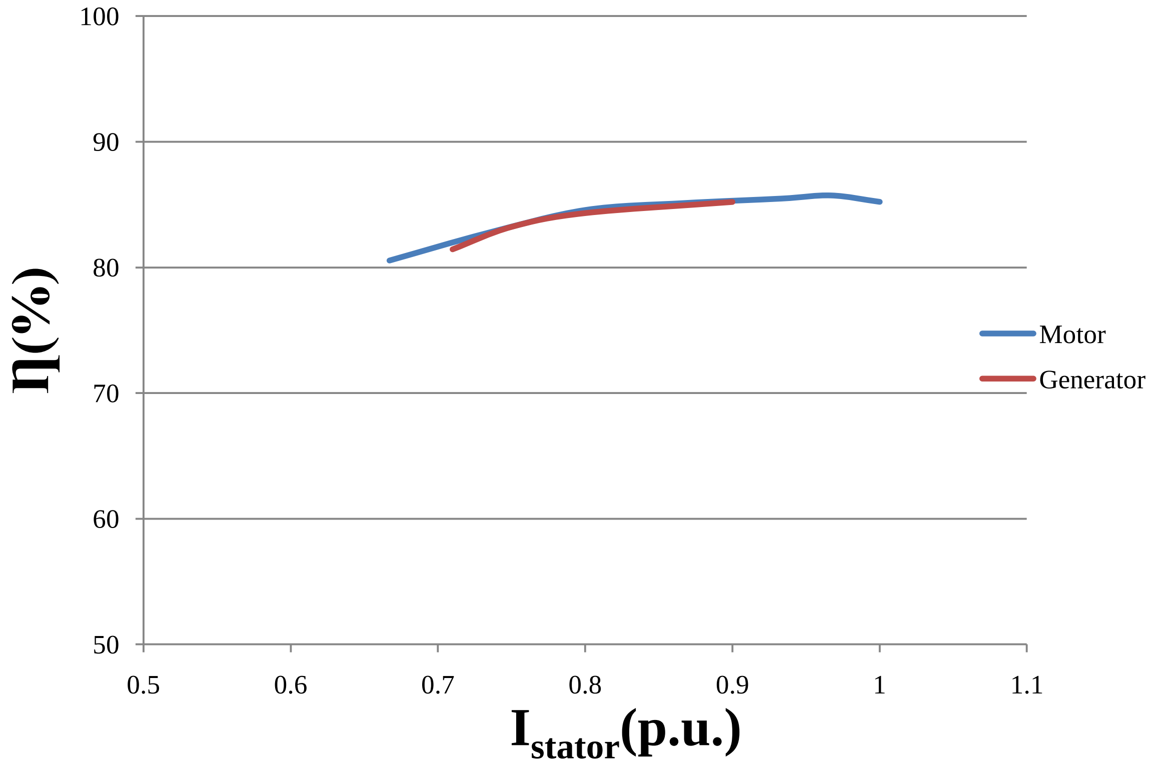

FIGURE 5.10: Efficiency vs Stator current of a 3-Φ induction machine

The efficiency is calculated by segregation of losses. No load test gave rotational loss or fixed losses where as blocked rotor test gave copper losses. In this paper the losses and efficiency are compared for motoring and generating mode.

In Fig. 5.5 No load characteristics of a 3-Φ induction machine is given for both motoring and generating mode. From this graph we can see the rotational loss is more in case of generating mode than that of motoring mode. This is because, with increase in stator current the air gap flux decreases a little where as it increases with stator current in case of generator. Hence in generating mode the core loss is more.

Fig. 5.6 shows the power factor characteristics of a 3-Φ induction machine. The induction machine has low power factor in case of generating mode than that of motoring mode. This shows that in generating mode, the stator current is much more reactive due to saturation effect.

Fig. 5.7 shows the graph between stator loss vs output power. This show the stator losses are higher in generating mode. This is due to voltage drop in stator and the saturation level. This leads to larger air gap flux, higher magnetizing current and more core loss. So the stator loss is more.

Fig. 5.8 shows the plot between rotor loss vs output power. As the stator loss and core loss is higher, the rotor loss is more in generating mode than motoring mode due to saturation effect. Rotor losses are determined from air gap power and slip. As we discussed above the air gap power is more in case of generating mode.

Fig. 5.9 and fig. 5.10 show about efficiency comparison. This shows the efficiency of induction machine is higher is motoring mode than that of generating mode. This is because the induction generator has more losses than induction motor.

5.4 CONCLUSION:

For motoring mode the stator current increases with the load. The air gap voltage and the air decreases a slight with load and so the core loss. But in induction generator the air gap voltage and air gap flux increases with stator current and load. Hence the stator losses and rotor losses in generating more are higher than the motoring mode. So the efficiency of induction machine is higher in motoring mode than generating mode.

CHAPTER 6

Conclusion & Future work

Induction machines are used as induction machine most of the time. They can be used as generator by rotating the rotor the above the synchronous speed. In this report, a high rated 3-Φ induction machine is compared for its motoring mode and generating mode. So for high rated induction machines the stator and rotor losses are quite high for generating mode than motoring mode. So the efficiency of induction machines is high in motoring mode.

But for efficiency of other class or rated induction machines are not studied. Hence the future work of this project is to calculate the efficiencies for motoring and generating mode for lower rated induction machines and compare them.

Hence information about generating mode can be determined from the catalogue of induction motors. But this comparison cannot be applied to induction machine for calculating efficiency of induction generator always.

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APPENDIX-I

3-Φ Induction Machine Details:

7.5KW

10HP

400V

50Hz

N_r = 1420 rpm

N_s = 1500 rpm

I_s = 15A

I_r = 27A