WASIT UNIVERSITY
COLLEGE OF ENGINEERING
ELECTRICAL ENGINEERING DEPARTMENT
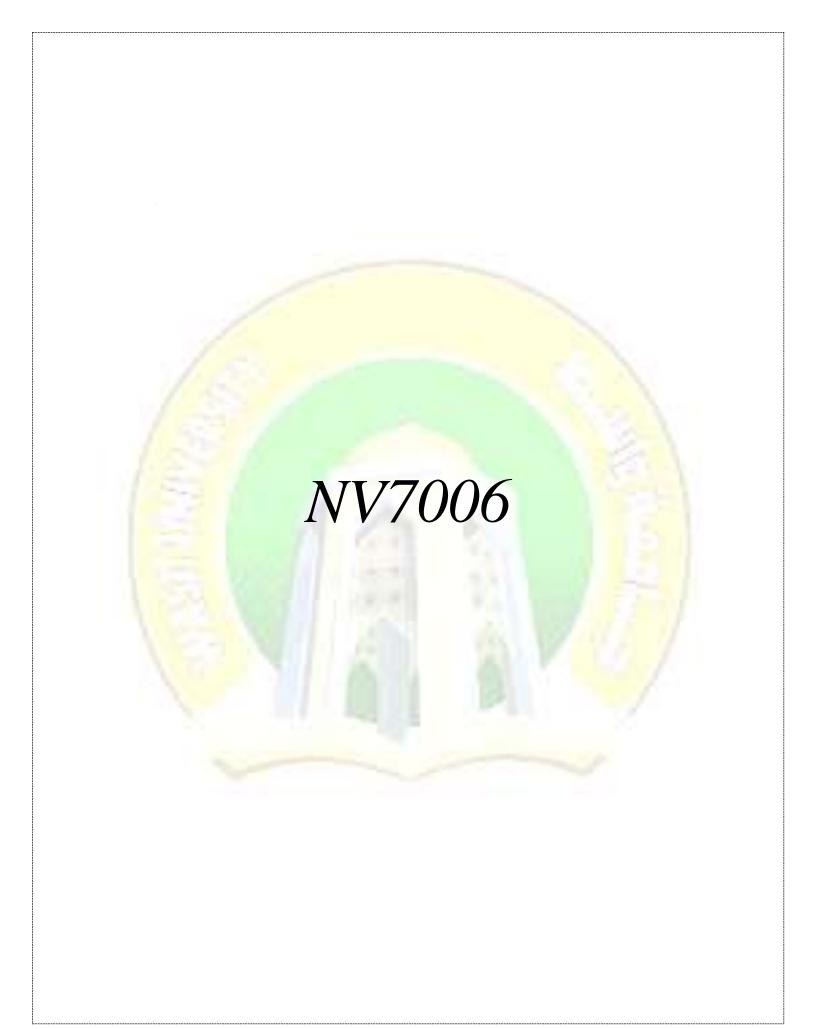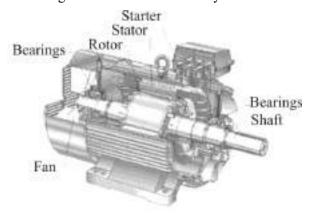# ELECTRICAL MACHINES LABORATORY
THIRD CLASS

FIRST SEMESTER

NV7006

Theory

The Induction motor is a single phase and three phase AC motor and is the most widely used machine. These motors are probably the simplest and most rugged of all electric motors. The supply is connected to the stator and the rotor power is received by induction caused by the stator rotating flux, hence the motor obtains its name induction motor. Its characteristic features are:

1. Simple and rugged construction.

2. Low cost and minimum maintenance.

3. High reliability and sufficiently high efficiency.

4. Needs no extra starting motor and need not be synchronized.

Open view of Three Phases Induction Motor
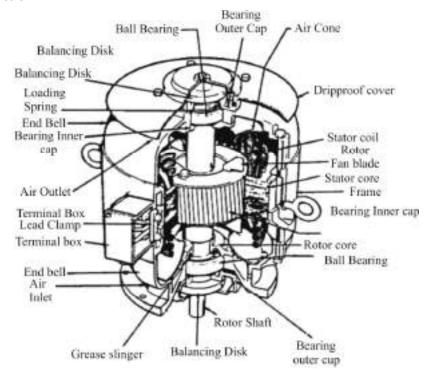

Three Phase Induction Motor

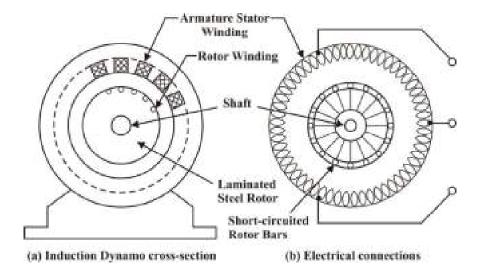**Induction Motor Basics: Name Plate Parameters:**

- A typical nameplate of an induction motor lists the following parameters:

- Rated terminal supply voltage in Volts.

- Rated frequency of the supply in Hz. (Hertz)

- Rated current in Amps. (Amperes)

- Speed in RPM. (Rotation Per Minute)

- Power rating in Watts or Horsepower (HP).

- Rated torque in Newton meters or Pound-inches.

- Winding insulation type - Class A, B, F or H.

- Type of stator connection (for 3-phase only), star (Y) or delta (Δ).

When the rated voltage and frequency are applied to the terminals of an induction motor, it draws the rated current (or corresponding power) and runs at base speed and can deliver the rated torque.

Construction

Construction view of Three Phase Induction Motor

(a) Induction Dynamo cross-section   **(b) Electrical connections**
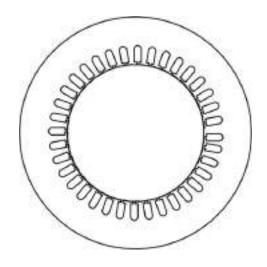
An Induction Motor has basically two parts:

●   Stator

●   Rotor

The Stator and the Rotor are electrical circuits that perform as electromagnets. In the three phase induction motor, the windings of the rotor are not connected to a power supply, but are essentially short circuits.
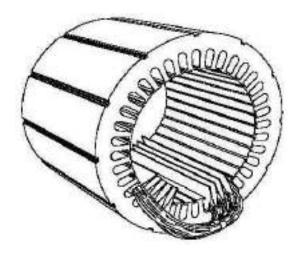
The Stator is the stationary electrical part of the motor. The Stator is made up of a number of stampings with slots to carry three phase windings. It is wound for a definite number of poles. The windings are geometrically spaced 120° apart. The stator consists of a cylindrical laminated and slotted core placed in a frame of rolled or cast steel. The frame provides mechanical protection and carries the terminal box and the end covers with bearings.
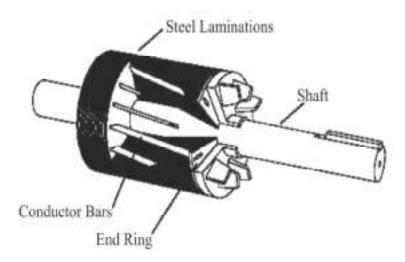
Stator Core

In the slots of a 3-phase winding of insulated copper wire is distributed which can be wound for 2, 4, 6 etc. poles. The stator is the outer body of the motor which houses the driven windings on an iron core. In a single speed three phase motor design, the standard stator has three windings, while a single phase motor typically has two windings. The stator core is made up of a stack of round pre-punched lamination pressed into a frame which may be made of aluminum or cast iron.

The laminations are basically round with a round whole inside through which the rotor is positioned. The inner surface of the stator is made up of a number of deep slots or grooves right around the stator. It is into these slots that the windings are positioned. The arrangement of the windings or coils within the stator determines the number of poles that the motor has a standard bar magnet has two poles, generally known as North and South. Likewise, an electromagnet also has a North and a South pole. As the induction motor, stator is essentially like one or more electromagnets depending on the stator windings, it also has poles in multiples of two. i.e., 2 poles,4 poles, 6 poles etc. The winding configuration, slot configuration and lamination steel all have an effect on the performance of the motor. The voltage rating of the motor is determined by the number of turns on the stator and the power rating of the motor is determined by the losses which comprise copper loss and iron loss, and the ability of the motor to dissipate the heat generated by these losses. The stator design determines the rated speed of the motor and most of the full load, full speed characteristics.

Stator winding of Induction Motor

Rotor

Rotor

The rotor consists of a laminated and slotted core tightly pressed on the shaft. Two types of rotors are used in Induction Motors - Squirrel-Cage Rotor and Wound Rotor. The rotor comprises a cylinder made up of round laminations pressed onto the motor shaft, and a number of short-circuited windings. The rotor windings are made up of rotor bars passed through the rotor, from one end to the other, around the surface of the rotor. The bars protrude beyond the rotor and are connected together by a shorting ring at each end. The bars are usually made of aluminum or copper, but sometimes made of brass. The position relative to the surface of the rotor, shape, crosses - sectional area and material of the bars determine the rotor characteristics. Essentially, the rotor windings exhibit inductance and resistance, and these characteristics can effectively be dependent on the frequency of the current flowing in the rotor.
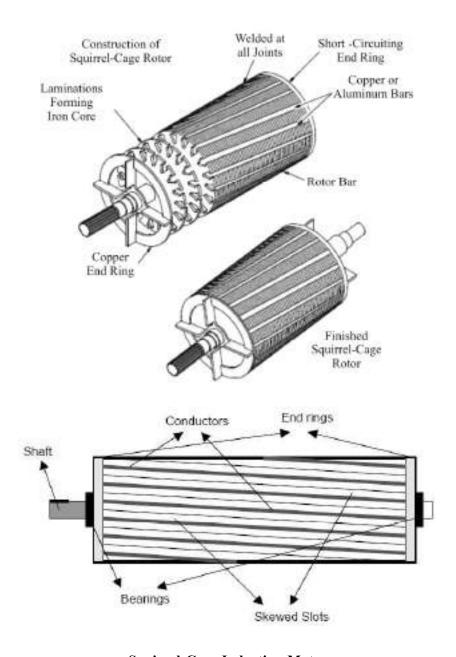
A bar with a large cross sectional area will exhibit a low resistance, while a bar of a small cross sectional area will exhibit a high resistance. Likewise a copper bar will have a low resistance compared to a brass bar of equal proportions. Positioning the bar deeper into the rotor, increases the amount of iron around the bar, and consequently increases the inductance exhibited by the rotor. The impedance of the bar is made up of both resistance and inductance, and so two bars of equal dimensions will exhibit different AC impedance depending on their position relative to the surface of the rotor. A thin bar which is inserted radial into the rotor, with one edge near the surface of the rotor and the other edge towards the shaft, will effectively change in resistance as the frequency of the current changes. This is because the AC impedance of the outer portion of the bar is lower than the inner impedance at high frequencies lifting the effective impedance of the bar relative to the impedance of the bar at low frequencies where the impedance of both edges of the bar will be lower and almost equal. The rotor design determines the starting characteristics.

There are two general types of Rotors:

- The Squirrel-Cage Rotor,

- The Wound (or slip ring) Rotor.

The Squirrel-Cage Rotor:

In the squirrel-cage rotor, the rotor winding consists of single copper or aluminum bars placed in the slots and short-circuited by end-rings on both sides of the rotor. In the wound rotor, an insulated 3-phase winding similar to the stator winding and for the same number of poles is placed in the rotor slots. The ends of the star-connected rotor winding are brought to three slip rings on the shaft so the connection can be made to it for starting or speed control.

Squirrel Cage Induction Motor

Most common AC motors use the Squirrel Cage Rotor, which will be found in virtually all domestic and light industrial alternating current motors. The squirrel cage takes its name from its shape - a ring at either end of the rotor, with bars connecting the rings running the length of the rotor.

It is typically cast aluminum or copper poured between the iron laminates of the rotor, and usually only the end rings will be visible. The vast majority of the rotor currents will flow through the bars rather than the higher-resistance and usually varnished laminates. Very low voltages at very high currents are typical in the bars and end rings; high efficiency motors will often use cast copper in order to reduce the resistance in the rotor.
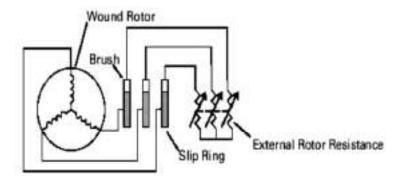
In operation, the squirrel cage motor may be viewed as a transformer with a rotating secondary - when the rotor is not rotating in sync with the magnetic field, large rotor currents are induced; the large rotor currents magnetize the rotor and interacts with the stator's magnetic fields to bring the rotor into synchronization with the stator's field. An unloaded squirrel cage motor at synchronous speed will consume electrical power only to maintain rotor speed against friction and resistance losses; as the mechanical load increases, so will the electrical load - the electrical load is inherently related to the mechanical load. This is similar to a transformer, where the primary's electrical load is related to the secondary electrical load.

This is why, as an example, a squirrel cage blower motor may cause the lights in a home to dim as it starts, but doesn't dim the lights when its fan belt (and therefore mechanical load) is removed. Furthermore, a stalled squirrel cage motor (overloaded or with a jammed shaft) will consume current limited only by circuit resistance as it attempts to start. Unless something else limits the current (or cuts it off completely) overheating and destruction of the winding insulation is the likely outcome.

In order to prevent the currents induced in the squirrel cage from superimposing itself back onto the supply, the squirrel cage is generally constructed with a prime number of bars, or at least a small multiple of a prime number (rarely more than 2). There are an optimum number of bars in any design, and increasing the number of bars beyond that point merely serves to increase the losses of the motor particularly when starting.

Virtually every washing machine, dishwasher, standalone fan, record player, etc. uses some variant of a squirrel cage motor. In squirrel cage motors, the motor speed is determined by the load it drives and by the number of poles generating a magnetic field in the stator. If some poles are switched in or out, the motor speed can be controlled by incremental amounts.

Wound Rotor:

Wound Rotor Induction Motor

Compared to squirrel cage rotors, wound rotor motors are expensive and require maintenance of the slip rings and brushes, but they were the standard form for variable speed control before the advent of compact power electronic devices. Transistorized inverters with variable-frequency drive can now be used for speed control, and wound rotor motors are becoming less common. (Transistorized inverter drives also allow the more-efficient three-phase motors to be used when only single- phase mains current is available, but this is never used in household appliances, because it can cause electrical interference and because of high power requirements).

Several methods of starting a polyphase motor are used. Where the large in rush current and high starting torque can be permitted, the motor can be started across the line, by applying full line voltage to the terminals (Direct-on-line, DOL). Where it is necessary to limit the starting inrush current (where the motor is large compared with the short-circuit capacity of the supply), reduced voltage starting using series inductors, an autotransformer, thyristors or other devices are used. A technique sometimes used is (Star-Delta, YΔ) starting, where the motor coils are initially connected in Y for acceleration of the load, then switched to delta when the load is up to speed. This technique is more common in Europe than in North America. Transistorized drives can directly vary the applied voltage as required by the starting characteristics of the motor and load.

This type of motor is becoming more common in traction applications such as locomotives, where it is known as the asynchronous traction motor. In wound-rotor motors, the impedance of the rotor windings can be altered externally, which changes the current in the windings and thus affords continuous speed control.

Advantage of Wound Rotor Motor

- High starting torque with low starting current by inserting an external resistance in each phase of the rotor circuit.

- Speed can be controlled easily.

- No abnormal heating during starting.

- Smooth acceleration during heavy load.

Disadvantage of Wound Rotor Motor

- Lower efficiency and low power factor.

- Speed regulation is poor.

- Initial and maintenance costs are more due to slip ring brushes etc.

Principle

Where a polyphase electrical supply is available, the three-phase (or polyphase) AC induction motor is commonly used, especially for higher-powered motors. The phase differences between the three phases of the polyphase electrical supply, create a rotating electromagnetic field in the motor. Through electromagnetic induction, the time changing and reversing (alternating in direction polyphase currents) rotating magnetic field induces a time changing and reversing (alternating in direction) current in the conductors in the rotor; this sets up a time changing and counter balancing moving electromagnetic field that causes the rotor to turn in the direction of the rotating field. The rotor always moves (rotates) slightly behind the phase peak of the primary magnetic field of the stator and is thus always moving slower than the rotating magnetic field produced by the polyphone electrical supply.
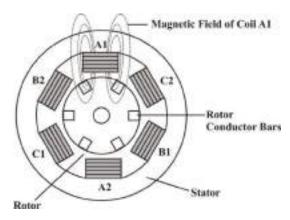
The principle of the revolving magnetic field is the key to the operation of the AC motor. Induction motors rely on revolving magnetic fields in their stators (stationary windings) to cause their rotors to turn. Stators themselves do not turn. Stators are permanently attached to the inside of the motor housing in the same manner that the stationary windings in the generator are connected to the main frame. The revolving magnetic fields created in the stator windings provide the necessary torque to move the rotor. The idea behind it is that a magnetic field in a stator can be made to appear to rotated electrically, around the inner periphery of the motor housing. This is done by overlapping several different stator windings. A magnetic field is developed in each different stator winding at a different time. Just before the magnetic field of one winding decays, the winding overlapping it develops the same magnetic polarity. As this second magnetic field decays in the second winding, another overlapping winding develops a magnetic field of the same polarity, and the sequence repeats itself. Successive stator windings develop magnetic fields in an orderly procession and appear to progressively move around the inside of the motor housing. These individual magnetic fields are the property of current flow in the motor stator. This current flow comes from the three individual phase currents of the three-phase generator output.

The figure shows the three single-phase voltages/currents that develop in the generator main armature completing individual circuits. Circuit A-B in the generator armature has a like A-B winding in the motor's stator. Each of the three circuit combinations (A-B, B-C, and C-A) are developed independently in the generator over a short period of time. The generator circuits are then completed through the motor's stator windings in a similar manner. As long as the current and magnetic field develops and decays in an orderly, progressive manner around the periphery of the motor frame, a revolving magnetic field exists. A revolving magnetic field in the stator is only part

of the operation. Another magnetic field needs to be created in the rotor so that the torque and rotation can develop using the principles of magnetic attraction and repulsion. The magnetic field developed in the rotor is a product of induction. As soon as the stator and the rotor windings develop their magnetic affiliation, torque will develop, and the rotor will turn.

The rotor can never rotate at the synchronous speed because there would be no relative motion between the magnetic field and the rotor windings and no current could be induced. The induction motor has a high starting torque.

Induction Motor Principle

The speed at which the magnetic field rotates is the synchronous speed of the motor and is determined by the number of poles in the stator and the frequency of the power supply.

$$Ns = \frac{120\ f}{P}$$

Where,
N_S = synchronous

speed, f = frequency,

P = number of poles,

Synchronous speed is the absolute upper limit of motor speed. At synchronous speed, there is no difference between rotor speeds and rotating field speed, so no voltage is induced in the rotor bars, hence no torque is developed. Therefore, when running, the rotor must rotate slower than the magnetic field. The rotor speed is just slow enough to cause the proper amount of rotor current to flow, so that the resulting torque is sufficient to overcome windage and friction losses, and drive the load. This speed difference between the rotor and magnetic field called Slip.

Actual speed for an induction motor will be less than this calculated synchronous speed by an amount known as slip, that increases with the torque produced. With no load, the speed will be very close to synchronous. When loaded, standard motors have between 2-3% slip, special motors may have up to 7% slip, and a class of motors known as torque motors are rated to operate at 100% slip (0 RPM/full stall).

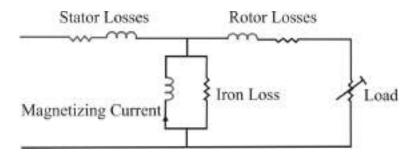The slip of the AC motor is calculated

by: $S = (N_S - N_r) / N_S$

Where,

N_r = Rotational speed, in revolutions per

minute. S = Normalized Slip, 0 to 1.

Equivalent Circuit

The induction motor can be treated essentially as a transformer for analysis. The induction motor has stator leakage reactance, stator copper loss elements as series components, and iron loss and magnetizing inductance as shunt elements. The rotor circuit likewise has rotor leakage reactance, rotor copper (aluminum) loss and shaft power as series elements. The transformer in the centre of the equivalent circuit can be eliminated by adjusting the values of the rotor components in accordance with the effective turn's ratio of the transformer. From the equivalent circuit and a basic knowledge of the operation of the induction motor, it can be seen that the magnetizing current component and the iron loss of the motor are voltage dependant, and not load dependant.

Additionally, the full voltage starting current of a particular motor is voltage and speed dependant, but not load dependant. The magnetizing current varies depending on the design of the motor. For small motors, the magnetizing current may be as high as 60%, but for large two pole motors, the magnetizing current is more typically 20 - 25%. At the design voltage, the iron is typically near saturation, so the iron loss and magnetizing current do not vary linearly with voltage with small increases in voltage resulting in a high increase in magnetizing current and iron loss.

Equivalent Circuit of Three Phase Induction Motor

Starting of Induction Motor

In a three phase induction motor, the induced emf in the rotor circuit depends on the slip of the induction motor and the magnitude of the rotor current depends upon this induced emf. When the motor is started, the slip is equal to 1 as the rotor speed is zero, so the induced emf in the rotor is large. As a result, a very high current flows through the rotor. This is similar to a transformer with the secondary coil short circuited, which causes the primary coil to draw a high current from the mains. Similarly, when an induction motor starts, a very high current is drawn by the stator, on the order of 5 to 9 times the full load current. This high current can damage the motor windings and because it causes heavy line voltage drop, other appliances connected to the same line may be affected by the voltage fluctuation. To avoid such effects, the starting current should be limited. A starter is a device which limits the starting current by providing reduced voltage to the motor. Once the rotor speed increases, the full rated voltage is given to it.

Methods of Starting

There are two important factors to be considered in starting of induction motors:

1. The starting current drawn from the supply, and
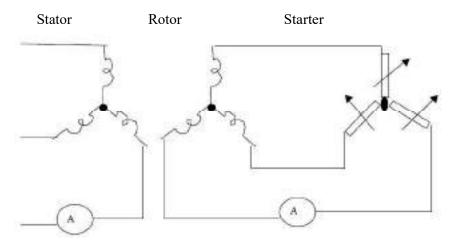
2. The starting torque.

The starting current should be kept low to avoid overheating of motor and excessive voltage drops in the supply network. The starting torque must be about 50 to 100% more than the expected load torque to ensure that the motor runs up in a reasonably short time.

The most usual methods of starting 3-phase induction motors are

1. For Slip-Ring Motors

   ● Rotor resistance starting

2. For Squirrel-Cage Motors

   ● Direct-on -line starting (starting from the fixed voltage).

   ● Star-delta starting (starting from the fixed voltage).

   ● Autotransformer starting.(starting from the lower voltage to higher voltage).

● **Rotor Resistance Starting**

By adding external resistance to the rotor circuit any starting torque up to the maximum torque can be achieved; and by gradually cutting out the resistance a high torque can be maintained throughout the starting period. The added resistance also reduces the starting current, so that a starting torque in the range of 2 to 2.5 times the full load torque can be obtained at a starting current of 1 to 1.5 times the full load current.
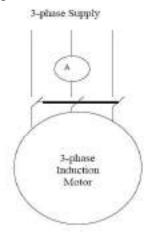
Rotor Resistance Starting

● **Direct-On-Line Starting**

This is the most simple and inexpensive method of starting a squirrel cage induction motor it is switched on directly to full supply voltage. The initial starting current is large, normally about 5 to 7 times the rated current but the starting torque is likely to be 0.75 to 2 times the full load torque. To avoid excessive supply voltage drops because of large starting currents the method is restricted to small motors only. To decrease the starting current cage motors of
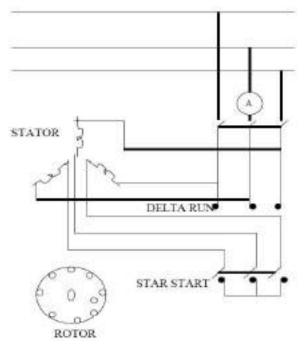
medium and larger sizes are started at a reduced supply voltage. The reduced supply voltage starting is applied in the next two methods.

Direct On Line Starting

- **Star-Delta Starting**
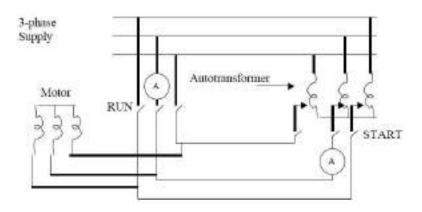
This is applicable to motors designed for delta connection in normal running conditions. Both ends of each phase of the stator winding are brought out and connected to a 3-phase change -over switch. For starting, the stator windings are connected in star and when the machine is running the switch is thrown quickly to the running position, thus connecting the motor in delta for normal operation. Phase voltages & the phase currents of the motor in star connection are reduced to $1/\sqrt{3}$ of the direct -on -line values in delta. The line current is 1/3 of the value in delta. A disadvantage of this method is that the starting torque (which is proportional to the square of the applied voltage) is also reduced to 1/3 of its delta value.

Star Delta Starting

- **Auto-Transformer Starting**

This method provides the lower initial voltage applied to the motor with the help of autotransformer and therefore the starting current and torque. The motor, which can be connected permanently in delta or in star, is switched first on reduced voltage from a 3-phase tapped autotransformer and when it has accelerated sufficiently, it is switched to the running (full voltage) position. The principle is similar to star/delta starting and has similar limitations. The advantage of the method is that the current and torque can be adjust.

Auto Transformer Starting

Slip of Induction Motor

There must be a relative difference in speed between the rotor and the rotating magnetic field. If the rotor and the rotating magnetic field were turning at the same speed no relative motion would exist between the two, therefore no lines of flux would be cut, and no voltage would be induced in the rotor. The difference in speed is called slip. Slip is necessary to produce torque. Slip is dependent on load. An increase in load will cause the rotor to slow down or increase slip. A decrease in load will cause the rotor to speed up or decrease slip. Slip is expressed as a percentage and can be determined with the following formula.

% Slip = (Ns - Nr) x 100/Ns where,

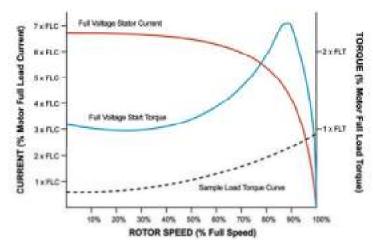Ns = synchronous speed

Nr = rotor speed

Characteristic of Induction Motor

Starting Characteristics

In order to perform useful work, the induction motor must be started from rest and both the motor and load accelerated up to full speed. Typically, this is done by relying on the high slip characteristics of the motor and enabling it to

provide the acceleration torque. Induction motors at rest, appear just like a short circuited transformer, and if connected to the full supply voltage, draw a very high current known as the "Locked Rotor Current". They also produce torque which is known as the "Locked Rotor Torque". The Locked Rotor Torque (LRT) and the Locked Rotor Current (LRC) are a function of the terminal voltage to the motor, and the motor design. As the motor accelerates, both the torque and the current will tend to alter with rotor speed if the voltage is maintained constant. The starting current of a motor, with a fixed voltage, will drop very slowly as the motor accelerates and will only begin to fall significantly when the motor has reached at least 80% full speed.

The actual curves for induction motors can vary considerably between designs, but the general trend is for a high current until the motor has almost reached full speed. The LRC of a motor can range from 500% Full Load Current (FLC) to as high as 1400% FLC. Typically, good motors fall in the range of 550% to 750% FLC.

The starting torque of an induction motor starting with a fixed voltage, will drop a little to the minimum torque, known as the pull up torque, as the motor accelerates and then rise to a maximum torque, known as the breakdown or pull out torque at almost full speed and then drop to zero at synchronous speed. The curve of start torque against rotor speed is dependant on the terminal voltage and the motor/rotor design. The LRT of an induction motor can vary from as low as 60% Full Load Torque (FLT) to as high as 350% FLT. The pull-up torque can be as low as 40% FLT and the breakdown torque can be as high as 350% FLT. Typical LRTs for medium to large motors are in the order of 120% FLT to 280% FLT. The power factor of the motor at start is typically 0.1 - 0.25, rising to a maximum as the motor accelerates, and then falling again as the motor approaches full speed.

A motor which exhibits a high starting current i.e., 850% will generally produce a low starting torque, whereas a motor which exhibits a low starting current, will usually produce a high starting torque.

This is the reverse of what is generally expected. The induction motor operates due to the torque developed by the interaction of the stator field and the rotor field. Both of these fields are due to currents which have resistive or in phase components and reactive or out of phase components. The torque developed is dependent on the interaction of the in phase components and consequently is related to the I^2R of the rotor. A low rotor resistance will result in the current being controlled by the inductive component of the circuit, yielding a high out of phase current and a low torque.

Figures for the locked rotor current and locked rotor torque are almost always quoted in motor data, and certainly readily available for induction motors. Some manufactures have been known to include this information on the motor name plate. One additional parameter which would be of tremendous use in data sheets for those who are engineering motor starting

applications, is the starting efficiency of the motor. By the starting efficiency of the motor, I refer to the ability of the motor to convert amps into Newton meters. This is a concept not generally recognized within the trade, but one which is extremely useful, when comparing induction motors. The easiest means of developing a meaningful figure of merit is to take the locked rotor torque of the motor (as a percentage of the full load torque) and divide it by the locked rotor current of the motor (as a percent age of the full load current).i.e.,

Starting efficiency = Locked rotor torque / Locked rotor current

If the terminal voltage to the motor is reduced while it is starting, the current drawn by the motor will be reduced proportionally. The torque developed by the motor is proportional to the current squared, and so a reduction in starting voltage will result in a reduction in starting current and a greater reduction in starting torque. If the start voltage applied to a motor is halved, the start torque will be a quarter; likewise a start voltage of one third will result in a start torque of one ninth.

Running Characteristics

Once the motor is up to speed, it operates at low slip, at a speed determined by the number of stator poles. The frequency of the current flowing in the rotor is very low. Typically, the full load slip for a standard cage induction motor is less than 5.

The induction motor draws a magnetizing current while it is operating. The magnetizing current is independent of the load on the machine, but is dependent on the design of the stator and the stator voltage. The actual magnetizing current of an induction motor can vary from as low as 20% FLC for large two pole machines to as high as 60% for small eight pole machines. The tendency is for large machines and high speed machines to exhibit a low magnetizing current, while low speed machines and small machines exhibit a high magnetizing current. A typical medium sized four pole machine has a magnetizing current of about 33% FLC. A low magnetizing current indicates a low iron loss, while a high

magnetizing current indicates an increase in iron loss and a resultant reduction in operating efficiency.

The resistive component of the current drawn by the motor while operating, changes with load, being primarily load current with a small current for losses. If the motor is operated at minimum load i.e., open shaft, the current drawn by the motor is primarily magnetizing current and is almost purely inductive. Being an inductive current, the power factor is very low, typically as low as 0.1. As the shaft load on the motor is increased, the resistive component of the current begins to rise. The average current will noticeably begin to rise when the load current approaches the magnetizing current in magnitude. As the load current increases, the magnetizing current remains the same and so the power factor of the motor will improve. The full load power factor of an induction motor can vary from 0.5 for a small low speed

motor up to 0.9 for a large high speed machine. The losses of an induction motor comprise: iron loss, copper loss, windage loss and frictional loss. The iron loss, windage loss and frictional losses are all essentially loading independent, but the copper loss is proportional to the square of the stator current. Typically the efficiency of an induction motor is highest at 3/4 load and varies from less than 60% for small low speed motors to greater than 92% for large high speed motors. Operating power factor and efficiencies are generally quoted on the motor data sheets.

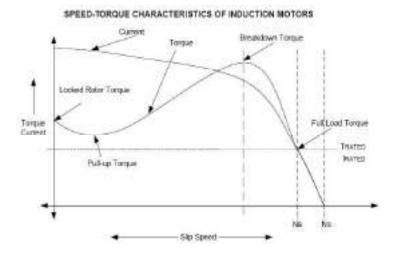## Speed Torque Characteristics of an Induction Motor

Figure shows the typical speed-torque characteristics of an induction motor. The X-axis shows speed and slip. The Y-axis shows the torque and current. The characteristics are drawn with rated voltage and frequency supplied to the stator. During start-up, the motor typically draws up to seven times the rated current. This high current is a result of stator and rotor flux, the losses in the stator and rotor windings, and losses in the bearings due to friction. This high starting current overcomes these components and produces the momentum to rotate the rotor. At start- up, the motor delivers 1.5 times the rated torque of the motor. This starting torque is also rotor torque (LRT). As the speed increases, the current drawn by the motor reduces slightly (see the current drops significantly when the motor speed approaches
~80% of the rated speed).

At base speed, the motor draws the rated current and delivers the rated torque. At base speed, if the load on the motor shaft is increased beyond its rated torque, the speed starts dropping and slip increases. When the motor is running at approximately 80% of the synchronous speed, the load can increase up to 2.5 times the rated torque. This torque is called breakdown torque. If the load on the motor is increased further, it will not be able to take any further load and the motor will stall. In addition, when the load is increased beyond the rated load the load current increases following the current characteristic path. Due to this higher current flow

in the windings, inherent losses in the windings increase as well. This leads to a higher temperature in the motor windings.

Motor windings can withstand different temperatures, based on the class of insulation used in the windings and cooling system used in the motor. Some motor manufacturers provide the data on over load capacity and load over duty cycle. If the motor is overloaded for longer than recommended then the motor may burn out. As seen in the speed-torque characteristics, torque is highly nonlinear as the speed varies. In many applications, the speed needs to be varied, which makes the torque vary. We will discuss a simple open loop method of speed control called, Variable Voltage Variable Frequency (VVVF or V/f) in this application note.

SPEED-TORQUE CHARACTERISTICS OF INDUCTION MOTORS

Advantage of AC over DC Motor

Most of the power-generating systems produce AC. For this reason, a majority of the motors used, operate on AC. There are other advantages for using AC. In general, AC motors are less expensive and easier to maintain than DC machines. An AC motor is particularly well suited for constant speed operations. This is because its speed is determined by the frequency of the power source and the number of poles constructed in the motor alternating current motors is built in different sizes, shapes, and ratings for many different applications. It is impossible to address all forms of AC motors in this text. This article will address only the squirrel cage induction motor.

Note:

No load current of Induction Machine:

It is to be declared that there is some permissible percentage value of no load current for Induction Machine since it depends upon type, size and design of the Induction Machine. Higher the rating of the machine lesser will be the magnitude of no load current of Induction Machine.

For small size Induction Machine, magnitude of no Load Current may varies under range of 40 to 60% of the rated current of the machine which will reduces as the size of the Induction Machine Increases

Reference Table

While performing Load test it is to be noted that armature current should not exceed to below current listed in tabular form for different Machines rating or else Machines winding may get heat up and finally damage.

Machines Rating	Maximum permissible current
1 HP	2.1 Amp
2HP	4 Amp
3 HP	6 Amp

Experiment 1

Objective
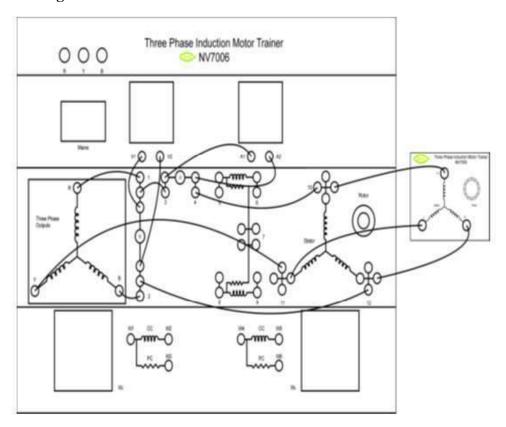Study of the Running and Reversing of Three Phase Induction Motor

Items Required

- Connecting Leads
- Tachometer

Circuit Diagram

Procedure

1. First of all make sure that the earthing of your laboratory is proper and it is connected to the terminal provided on back side of the panel.

2. Before starting experiment keep in mind that the belt of motor must be loose so that motor can run freely.

3. Make sure that the Three Phase Mains and the MCB of panel is at off position.

4. Connect terminal R of Three Phase Outputs to terminal 1 and B to terminal 2.

5. Connect terminal Y to directly terminal 11 of motor connection.

6. Connect terminal 1 to terminal 3 and terminal 2 to terminal 12.

7. Connect terminal 4 to terminal 10.

8. Connect terminals 10, 11 and 12 to terminals R, Y and B terminals of motor respectively.

9. Insert meters, for this connect terminals V1 and V2 to terminals 1 and 2 respectively and terminals A1 and A2 to terminals 3 and 4 respectively.

10. Compare your connections with the connections of Figure. If all the connections are proper then switch on the Three Phase Mains as well as the MCB of panel.

11. You will observe the motor suddenly starts running in a particular direction.

12. Observe its direction of rotation whether it is clockwise or anticlockwise.

13. Now switch off the MCB and interchange the any of the connections of terminals (Say R and Y) on the motor.

14. Switch on the MCB and you will see that the direction of rotation is reversed.

15. Switch off the MCB.

16. If you connect terminal R of motor to its terminal Y, terminal Y to terminal B and terminal B to terminal R. You will observe in this case direction of rotation does'nt change because phase reversal does'nt occur. Only the supply terminals have been rotated.

Theory of No Load Test

In this test, the motor is made to run without load that is no load conditions the speed of the motor is very close to the synchronous speed but less than the synchronous speed. The rated voltage is applied to the stator. The total input line current and total input power is measured. Two wattmeter method is to calculate the total input power.

As the motor is on No Load the power factor is very low which is less than 0.5 and one of the two wattmeter's read negative. It is necessary to reverse the connections of the current coil or pressure coil connections of such a wattmeter to read positive reading. This reading must be taken negative for the further calculations. The power input 'w' consists of following losses; stator copper losses, stator core losses iron losses friction and windage losses.

The no load rotor current is very small and hence the rotor copper loss is negligibly small the rotor frequency is 's' time the supply frequency and on no load it is very small. Rotor core losses are proportional to this frequency and hence negligibly small. Under no load I is very small and in many practical cases it is also neglected thus 'w' consists of stator iron loss and friction and windage loss which are constant for the entire load. Hence 'w' is said to give fixed losses of the motor.
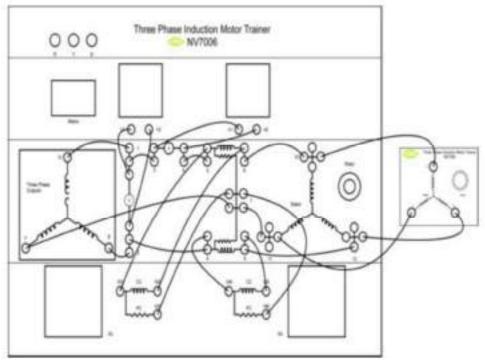
Experiment 2

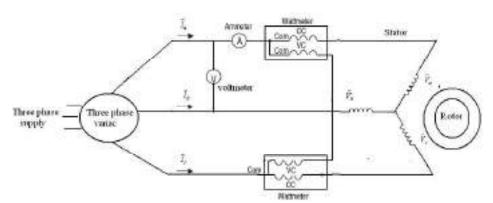**Objective**

Study of No Load Test in a Three Phase Induction Motor

Items Required

- Connecting Leads
- Tachometer

Circuit Diagram

Conventional Circuit Diagram of No Load Test

Procedure

1. First of all make sure that the earthing of your laboratory is proper and it is connected to the terminal provided on back side of the panel.

2. Before starting experiment belt of motor must be loose so that motor can run freely.

3. Make sure that the Three Phase Mains is off and the MCB of panel is also at off position.

4. Connect terminal R of Three Phase Outputs to terminal 1 and terminal Y to terminal 7.

5. Connect terminal B to terminal 2.

6. Connect terminal 1 to terminal 3 and terminal 2 to terminal 8.

7. Connect terminal 4 to terminal 5.

8. Connect terminal 6 to terminal 10, terminal 9 to terminal 12 and terminal 7 to terminal 11.

9. Connect motor to the trainer, for this connects terminals 10, 11 and 12 to terminals R, Y and B on the motor respectively.

10. Now insert meters in the circuit for this connect terminals V1 and V2 to terminals 1 and 2 respectively.

11. Similarly connect ammeter terminals A1 and A2 to terminals 3 and 4 respectively.

12. Now connect wattmeter, for this connect terminal W1 to terminal 5, terminal W2 to terminal 6 and terminal W3 to terminal 7.

13. Similarly connect second wattmeter, for this connect terminal W4 to terminal 8, terminal W5 to terminal 9 and terminal W6 to terminal 7.

14. Compare your connections with the connections shown in Figure . If all connections are proper then switch on the Three Phase Mains as well as the MCB of the panel.

    15. You will observe that the motor starts running and meters show some deflection.

16. Observe the readings of voltmeter, ammeter and both wattmeters and record into the observation table as V_0 (V_L), I_0 (I_L), W_A and W_B respectively.

    Note: If one of the wattmeter reads negative (needle goes in opposite direction), just reverse the connections of its current coil and read reading as negative.

17. Switch off the supply.

Observation Table

S. N.	Voltmeter Reading V_0 (volt)	Ammeter Reading I_0 (amp)	Wattmeter Reading W_A (watt)	Wattmeter Reading W_B (watt)	No load input power W_0 = W_1 + W_2 (watt)	Power Factor cos Φ= $(W_A+W_B)/$ $\sqrt{3}V_0I_0$
1. 2. 3.						

Calculations

As,

I_0 = No load line current

V_0 = No load rated line voltage

W_0 = No load input power

$Cos\Phi_0$ = Power factor

I_C = Active component of no load current

I_M = Magnetizing component of no load current

R_0 = No load branch resistance

X_0 = No load branch reactance Hence,

$Cos\Phi_0$ = $W_0 / \sqrt{3} (V_0 I_0)$

W_0 = $\sqrt{3} (V_0 I_0 Cos\Phi_0)$

From the knowledge of I_0 and Φ_0 the parameters of the equivalent circuit can be obtained as

I_C = $I_0 Cos\Phi_0$

I_M = $I_0 Sin\Phi_0$

R_0 = V_0 / I_C (per phase)

X_0 = V_0 / I_M (per phase).

Theory of block rotor test

In this test the rotor is locked and not allowed to rotate. Thus the slip is 1. The situation is exactly similar to the short circuit test on transformer. If under short circuit condition the primary is excited with rated voltage a large short circuit current can flow which is dangerous to the winding point of view so similar to the transformer short circuit test the reduced voltage (about 10 to 5 % of full load voltage) is just enough such that the stator carries the rated current is applied. During this test the stator carried the rated current, hence the stator copper loss is also dominated similarly the rotor also carried the short circuit current to produce the rotor losses the voltage is reduced the iron loss which is proportional to voltage is small enough the motor is at standstill hence mechanical loss that is friction and windage loss is absent.
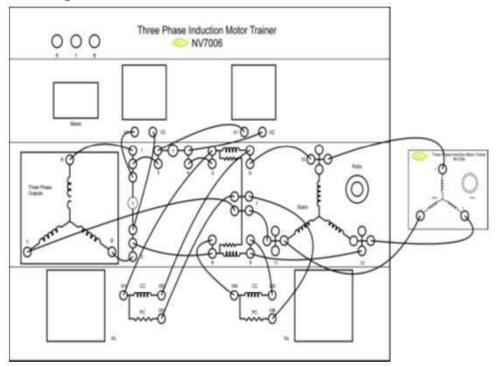
Experiment 3

Objective

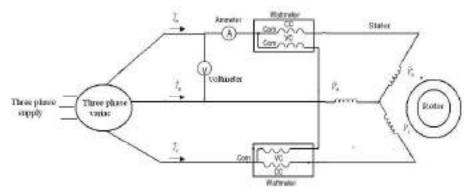Study of the Block Rotor Test of Three Phase Induction
Motor

Items Required

- Connecting Leads

- Tachometer

- Three Phase Variac (Can be arranged from your
  laboratory)

Circuit Diagram

Conventional Circuit Diagram of Block Rotor Test

Procedure

1. First of all make sure that the earthing of your laboratory is proper and it is connected to the terminal provided on back side of the panel.

2. Before starting experiment belt of motor must be tight so that motor can not run freely.

3. Make sure that the Three Phase Mains is off and the MCB of panel is also at off position.

4. Connect Three Phase Supply through a three phase Variac to the trainer with knob of Variac at zero position.

5. Connect terminal R of Three Phase Outputs to terminal 1 and terminal Y to terminal 7.

6. Connect terminal B to terminal 2.

7. Connect terminal 1 to terminal 3 and terminal 2 to terminal 8.

8. Connect terminal 4 to terminal 5.

9. Connect terminal 6 to terminal 10, terminal 9 to terminal 12 and terminal 7 to terminal 11.

10. Connect motor to the trainer, for this connects terminals 10, 11 and 12 to terminals R, Y and B on the motor respectively.

11. Now insert meters in the circuit for this connect terminals V1 and V2 to terminals 1 and 2 respectively.

12. Similarly connect ammeter terminals A1 and A2 to terminals 3 and 4 respectively.

13. Now connect wattmeter, for this connect terminal W1 to terminal 5, terminal W2 to terminal 6 and terminal W3 to terminal 7.

14. Similarly connect second wattmeter, for this connects W4 to 8, W5 to 9 and W6 to 7.

15. Now block the rotor of motor by the module provided with motor.

16. Compare your connections with the connections shown in Figure. If all connections are proper then switch on the Three Phase Mains as well as the MCB of the panel.

17. Slowly increase the input voltage through Variac, so that motor attains its rated current (2.1A for 1HP Motor) **see reference table given before experiments for different machines rating**, this will be Isc. Record voltage (Vsc) in voltmeter corresponding to this condition.

18. Similarly record the readings of wattmeters W_A and W_B.

Note: If one of the wattmeter reads negative (needle goes in opposite direction), just reverse the connections of its current coil and read reading as negative.

19. Switch off the supply.

20. **Observation Table**

S. N	Voltmeter Reading V_{SC} (volt)	Ammeter Reading I_{SC} (amp)	Wattmeter Reading W_A(watt)	Wattmeter Reading W_B (watt)	Short circuit input power W_{SC} = WA+WB	Power Factor $\cos\Phi$ = (W_A+W_B) /$\sqrt{3}$VscIsc
1.						
2.						
3.						
4.						

Calculations

As,

I_{SC} = Short circuit current per phase

V_{SC} = Short circuit voltage per phase

W_{SC} = Short circuit input power per phase

$\cos\Phi_{SC}$ = Short circuit Power factor

R_{1E} = Equivalent resistance referred to stator

X_{1E} = Equivalent reactance referred to stator

Z_{1E} = Equivalent impedance referred to stator

Hence,

W_{SC} = $\sqrt{3}$ ($V_{SC} I_{SC} Cos\Phi_{SC}$) (Per phase)

X_{1E} = $\sqrt{(Z_{1E})^2 - (R_{1E})^2}$

$Cos\Phi_{SC}$ = $W_{SC} / \sqrt{3}$ ($V_{SC}I_{SC}$)

R_{1E} = $W_{SC} / 3 (I_{SC})^2$ (Per phase)

Z_{1E} = V_{SC} / I_{SC} (Per phase)

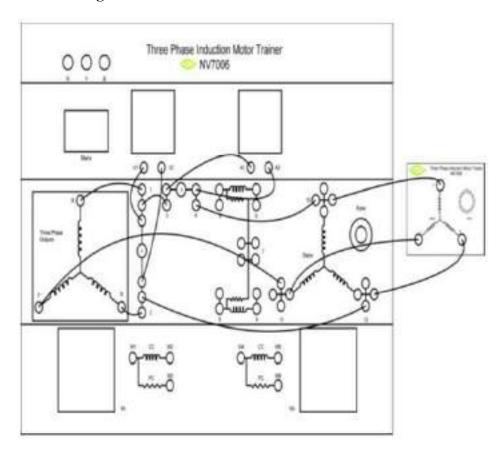<div align="center">**Experiment 4**</div>

Objective

Study and Measurement of slip in Three Phase Induction Motor

Items Required

- Connecting Leads
- Tachometer

Circuit Diagram

Procedure

1. First of all make sure that the earthing of your laboratory is proper and it is connected to the terminal provided on back side of the panel.

2. Before starting experiment belt of motor must be loose so that motor can run freely.

3. Make sure that the Three Phase Mains and the MCB of panel is at off position.

4. Connect terminal R of Three Phase Outputs to terminal 1 and B to terminal 2.

5. Connect terminal Y to directly terminal 11 of motor connection.

6. Connect terminal 1 to terminal 3 and terminal 2 to terminal 12.

7. Connect terminal 4 to terminal 10.

8. Connect terminals 10, 11 and 12 to terminals R, Y and B of motor respectively.

9. Insert meters, for this connect terminals V1 and V2 to terminals 1 and 2 respectively and terminals A1 and A2 to terminals 3 and 4 respectively.

10. Compare your connections with the connections of figure. If all the connections are proper then switch on the Three Phase Mains as well as the MCB of panel.

11. You will observe the motor suddenly starts running in a particular direction.

12. Now measure the speed of motor using Tachometer. Record this speed as N_R (rotor speed).

13. Calculate the speed of motor by following

   formula- $N_s = 120f / P$

   Where, f = frequency of input supply (50Hz)

   P = No. of Poles in motor (4 Poles in this case)

14. Now calculate the slip by relation-

   $\% S = (N_S - N_R) / N_S \times 100$

15. Switch off the MCB.

Experiment 5
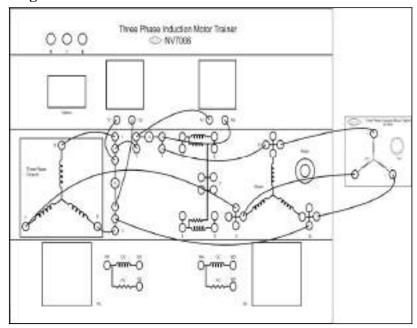
Objective

Study of Speed-Torque Characteristics of Three Phase Induction Motor

Items Required

- Connecting Leads
- Tachometer

Circuit Diagram

Procedure

1. First of all make sure that the earthing of your laboratory is proper and it is connected to the terminal provided on back side of the panel.
2. Before starting experiment belt of motor must be loose so that motor can run freely.
3. Make sure that the Three Phase Mains and the MCB of panel is at off position.
4. Connect terminal R of Three Phase Outputs to terminal 1 and terminal B to terminal 2.
5. Connect terminal Y to directly terminal 11 of motor connection.
6. Connect terminal 1 to terminal 3 and terminal 2 to terminal 12.
7. Connect terminal 4 to terminal 10.
8. Connect terminals 10, 11 and 12 to R, Y and B terminals of Motor respectively.

9. Insert meters, for this connect terminals V1 and V2 to terminals 1 and 2 respectively and terminals A1 and A2 to terminals 3 and 4 respectively.

10. Make sure that belt is loose so that motor can run on normal speed freely.

11. Compare your connections with the connections of Figure . If all the connections are proper then switch on the Three Phase Mains as well as the MCB of panel.

12. Measure the number load speed (RPM) of motor using Tachometer, record your observation into the observation table.

13. Now slowly tighten the load so that speed of motor reduces.

14. Measure the speed again a record into the table.

15. Calculate torque on belt, for this first observe the readings of spring balances.

16. Now if reading of first spring balance is W1 and that of second one is W2 then the overall force on the pulley will be W = W1-W2 & calculate the torque into the observation table for the corresponding speed by using of below formula-

$$T = F \ r \ 9.8 \ Nm$$

Where,
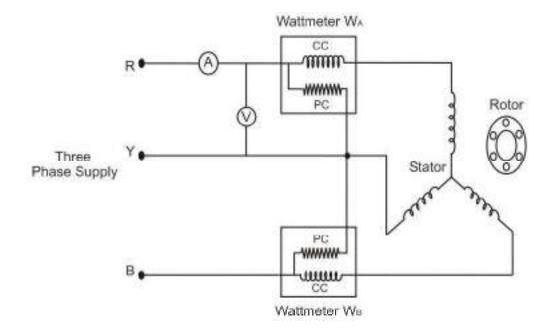
  F = Force on the pulley
  r = Radius of the pulley

17. Increase the load up to current specified (**see reference table given before experiments for different machines rating)** and take no. of readings of N and T.

18. Draw a graph between these two parameters, this graph is nothing but Speed-Torque characteristics or the load characteristics of Three Phase Induction Motor.

Observation Table

S. No.	W1 in Kg	W2 in Kg	Speed (N) in RPM	Torque T In Nm

Warranty

1) We warranty the product against all manufacturing defects for 24 months from the date of sale by us or through our dealers. Consumables like dry cell etc. are not covered under warranty.

2) The warranty will become void, if

   a) The product is not operated as per the instruction given in the learning material.

   b) The agreed payment terms and other conditions of sale are not followed.

   c) The customer resells the instrument to another party.

   d) Any attempt is made to service and modify the instrument.

3) The non-working of the product is to be communicated to us immediately giving full details of the complaints and defects noticed specifically mentioning the type, serial number of the product and date of purchase etc.

4) The repair work will be carried out, provided the product is dispatched securely packed and insured. The transportation charges shall be borne by the customer.

Note:

- **Measuring instruments (Voltmeter, Ammeter & Wattmeter) do not include under warranty after first installation.**

- **The Tachometer is not covered in the warranty.**

List of Accessories

1. 4mm Patch Cords 8" (Red)..5 Nos.

2. 4mm Patch Cords 8" (Black) ....5 Nos.

3. 4mm Patch Cords 8" (Yellow)...5 Nos.

4. 4mm Patch Cords 8" (Blue)..5 Nos.

5. 4mm Patch Cords 24" (Red)..2 Nos.

6. 4mm Patch Cords 24" (Black) ....2 Nos.

7. 4mm Patch Cords 24" (Yellow)…………………………………………….. 2 Nos.

8. 4mm Patch Cords 24" (Blue)…………………………………………2 Nos.

9. Tachometer ....1 No.

10. Learning Material CD ....1 No.

11. Three Phase Mains Socket..1 No.

NV7012

Experiment 1

Object :
Study of the polarity test with two single phase transformers.

Equipments Needed :

1. Connecting leads

Circuit Diagram
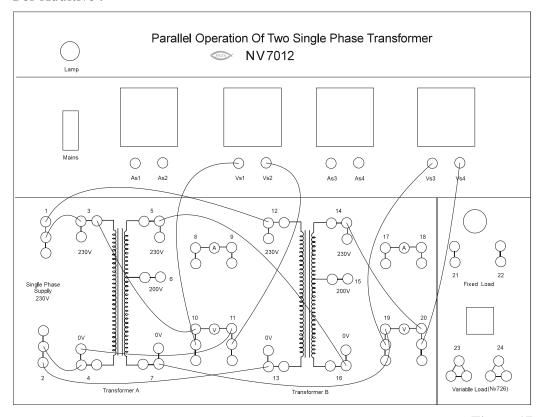
For Additive :
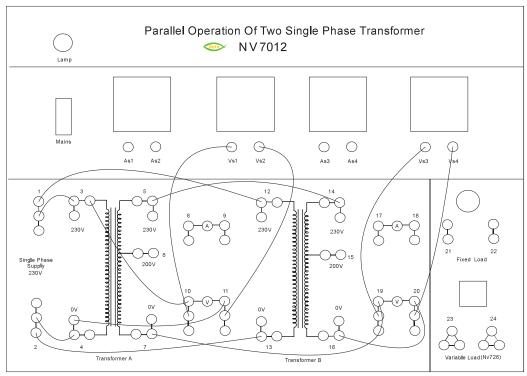

Figure 17

For Subtractive :

Figure 18

Procedure :

Before performing any experiment make sure that earthing of your laboratory is proper and it is properly connected to the back side of the panel.

For Additive :

1.   First make sure that the mains supply is 'Off'.

2.   Connect terminals 1 to 3 and 2 to 4.

3.   Now to connect the meter in the circuit, connect terminals 3 to 10 and 4 to11

4.   Connect terminals 10 to Vs1, 11 to Vs2.

5.   Now connect terminals 1 to 12 and 2 to 13.

6.   Connect terminal 5 to 16.

7.   Now to connect the meter in the circuit, connect terminals 7 to 19 and 14 to 20.

8.   Connect terminals 19 to Vs3 and 20 to Vs4.

9.   Switch 'On' AC supply.

10.   Record the voltmeters reading.

11.   Switch 'Off'the mains supply.

For Subtractive :

1. First make sure that the mains supply is 'Off'.

2. Connect terminals 1 to 3 and 2 to 4.

3. Now to connect the meter in the circuit, connect terminals 3 to 10 and 4 to11.

4. Connect terminals 10 to Vs1, 11 to Vs2.

5. Now connect terminals 1 to 12 and 2 to 13.

6. Connect terminal 5 to 14.

7. Now to connect the meter in the circuit, connect terminals 7 to 19 and 16 to 20.

8. Connect terminals 19 to Vs3 and 20 to Vs4.

9. Switch 'On' AC supply.

10. Record the voltmeters reading.

11. Switch 'Off'the mains supply.

Observation Table :

S.No.	V1	V2	Additive / Subtractive
1.			
2.			

Results :

You will observe that reading of one of the voltmeter is twice the reading of another voltmeter in case of Additive Polarity, and 0 in case of Subtractive Polarity.

SECOND SEMESTER

MG5212

2. Starting Characteristics & SLIP of Squirrel-Cage Induction Motor

<Preliminary Knowledge>

The single-phase induction motors have an auxiliary winding for starting torque, that is, start winding, besides the main stator winding wire. This produces the starting torque by giving a phase difference to two winding currents. The split-phase motor produces a rotating field, thus, starting by using a phase difference of induced current. And when its speed reaches about 70% of the normal speed, the start winding becomes open by means of the centrifugal switch, and the motor continues to revolve as the rotating field is generated from the main stator winding between main stator winding and rotator.

When the speed of the capacitor starting motor reaches about 70% of its normal speed, the start winding and capacitator get removed by the centrifugal switch, and the main stator winding is used to drive the motor, instead. Here, if the motor starts driving, the split motor or condenser-starting motor has a high inductance, too. For that reason, the motor comes to have a lower power factor.

In this case, you are going to have a practice with the capacitor starting motor with the excellent motive power. This motor connects the capacitor serially with start winding. Then, the current flowing at the start winding gets about 45° ahead of the voltage. In result, the start winding current has about 90° phase angle with the main stator winding current. In other words, those with the two phase power will amount to the same status, obtaining the start rotating field.

In this practice, you should measure the starting characteristics and learn how to do so. However, the starting current decreases right after starting. If you stop the rotator by force, the motor will burn out as over current flows to the starting winding. In that case, you should measure a voltage and current at the very moment of starting the motor while starting it at the lowest possible voltage. Then, you can calculate the resulting numbers as follows and obtain a normal starting current at a normal input voltage.

Starting input voltage : Starting current measured = Normal input voltage :
Normal starting current

Therefore,

$$\text{normal starting current} = \frac{\text{Starting current measured} \times \text{Normal Input voltage}}{\text{Starting input voltage}}$$

A general induction motor has a synchronous speed, which is the maximum speed theoretically by the AC input frequency. However, it should be designed to have a speed lower than the synchronous speed in order to obtain an actual rotating torque. At this time, the difference between synchronous speed and actual motor speed is called the slip speed of the motor, as shown in the following example.

- If a north pole and a south pole are considered as 1-pair, the four-pole motor has 2-pair, producing the number of motor rotations (synchronous speed) at 60Hz.

    Frequency(Hz)×60/Number of pairs of pole

    =60×60/2=1,800 RPM .... Synchronous speed

    In this case, if a motor speed is 1,725 RPM,

    the ship speed becomes,

        1800−1725=75 RPM.

- The motor's slip date is,

        indicated as $\dfrac{\text{Slip speed}}{\text{Synchronous speed}} \times 100(\%)$.

At the very moment when the motor starts, the slip is "1" (in other words, the slip rate is 100%) and the induction current of rotator becomes 60Hz, the maximum like the stator frequency. And the Inductive Reactance [XL=2πfL] of a rotator conductor reaches the maximum, and the voltage at the both ends of the conduct becomes the maximum, increasing the primary (stator) power supply accordingly.

At this time, the starting torque is as follows.

$Ts = K\phi I_R \cos\theta$, in this case, K : Constant (vary depending on Air-Gap)

ϕ : Intensity of stator magnetic field

I_R : Rotator current

<Preparation for Operation>

Equipment: MG-5212

[Caution] When it comes to the motor's no-load starting characteristics, it may require only the motor to run on principle. In this case, however, considering that your main purpose is to learn how to measure it, you will have a no-load practice on motor with the no-load generator connected.

1. First of all, check if the motor of the practice equipment MG-5212 is connected to the generator properly, and turn OFF the main switch and motor switch.

2. Connect the M-1, M-2 and Wattmeter of the motor circuit to each terminal indicated.

3. Connect the AC 0~110V source terminal to the input terminal by using the connecting cord. And connect the J3~J4 and the J5~J6 as shown in dotted lines so that the main winding of the motor circuit can be connected to the circuit.

4. Connect the M-1, M-2, M-3 and M-4 meters of the generator to each terminal.

5. Place the RH-1 of the generator circuit in the middle position between right and left, and turn the knob of the exciting source DC 0~120V to the minimum in the counterclockwise direction. And turn OFF the exciting switch.

6. Turn ON the main and motor switches, turn the AC 0~110V source voltage control knob beside the left side of the equipment to reach about 100V, and turn OFF the motor switch.

7. Turn OFF the load switch S-1~S-4 and output switch of the generator circuit.

8. Check if there is any obstacle to the motor and generator circuit and check if the circuit configuration is normal, again.

<Operation & Measurement>

1. To check if the motor rotates normally, you should turn ON the main and motor switches, press the button and adjust the AC source so that the motor can rotate at the rated RPM(1725). Stop the motor by pressing the Normal Stop button, and turn the AC source voltage control knob to the minimum (0V) position.

2. Press the Start button for the motor. While lifting the AC source knob slowly, read the ammeter (M-2) and voltmeter (M-1) indicators right before the motor starts running, and record results to the table 2-1. And stop the motor by pressing the Stop button.

   [Caution] Carry out measuring within the shortest time possible (about five seconds).

<Table 2-1>

	Measured Value	Calculated Value
Starting Current (I_S)		
Starting Voltage (V_S)		110V

3. Based on the measured values, you should calculate the starting current at the normal input voltage (AC 110V) and record results to the table 2-1. The starting current right before the motor starts rotating increases in proportion to the motor input voltage.

4. Turn the AC source voltage control knob to the AC 110V, run the motor by pressing the Start button, read the input current (M-2), input voltage (M-1) and motor speed (RPM) indicators, and record results to the No-Load box of the table 2-2.

5. Turn ON the generator's output switch and load switch S-1~S-4 all together, read the following input current, input voltage and RPM indicators, and record

results to the Full Load of the table 2-2.

<Table 2-2>

	No-Load	Full Load
Input Current (I)		
Input Voltage (V)	110 V	110 V
Rotation Speed (RPM)		

6. After finishing measurement, stop the motor by pressing the Stop button, and turn OFF the motor switch and generator output switch. In case of not continuing this practice, turn OFF the main switch.

<Practice Evaluation>

1. According to the data in the table 2-1, you should calculate how many times the calculated starting current is bigger than the input current in the table 2-2. And describe the reason why the starting current is larger than that of the normal rotation.

2. According to the data in the table 2-2, calculate the slip speed in time of no-load and full-load. The synchronous speed of the motor used in this practice is 1800 RPM.

\<Summary\>

1. As the slip rate in time of starting is 100%, the maximum voltage of the frequency like the stator current is induced at the squirrel-cage rotator, and the stator current increases accordingly. This state is just as the second transformer has a short circuit. When the starting current continues, the motor will burn out.

2. In case of most induction motors, their slip speed increases more during load than no-load. Therefore, the input current increases during load and the rotation torque rises accordingly.

3. Changing Rotational Direction of Squirrel-Cage Induction Motor

<Preliminary Knowledge>

As mentioned briefly in the preliminary knowledge above, the capacitor-starting mode can obtain the start rotating field by producing a current phase difference between main winding and start winding. In other words, when you make a serial connection between start winding and capacitor, the phase of start winding current is slightly behind the main winding current, so the rotator rotates from the main pole to the direction of starting pole. However, when you change the wiring from the direction of normal rotation to the opposite way of the main winding or start winding, the motor will rotate in the reverse direction. Considering that the Fig.3-1 shows the direction of normal rotation, the Fig.3-2 indicates the reverse direction by connecting the main winding in the opposite way.
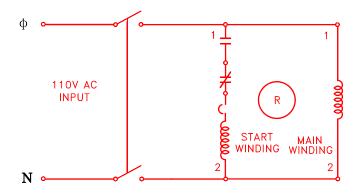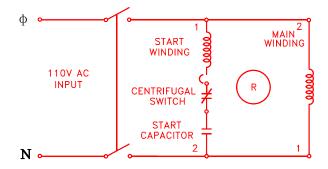

Fig. 3-1   Normal Rotation

Fig. 3-2   Reverse Rotation

<Preparation for Operation>

Equipment : MG-5212 Set

1. Execute the No.(1)~(3) and (5)~(6) of the preparation for operation in the "2. Starting characteristics & Slip of squirrel-cage induction motor."

2. Check if there is any obstacle to the motor and generator rotating part, and check if the circuit configuration is normal, again.

<Operation & Measurement>

1. Turn ON the Motor switch, press the Start button, and check if the motor starts rotating. And record its rotation direction to the Normal Rotation Direction box of the Table 3-1.

2. Stop the motor by pressing the Stop button, and turn OFF the Motor switch for a while. And connect the main winding in a reverse direction as shown in the Fig. 3-2. (In other words, connect the terminal J3-J6 and J5-J4.)

3. Turn ON the Motor switch again, press the Start button, and check if the motor starts running. And indicate its rotation direction to the Reverse

Rotation Direction box of the Table 3-1.

<Table 3-1>

Normal Rotation Direction	Reverse Rotation Direction

4. After finishing measurement, stop the motor by pressing the Stop button, and turn OFF the Motor switch. And connect the reversely connected main winding of the motor in a normal way again as shown in the Fig. 3-1. In case of not continuing this practice, turn OFF the main switch.

<Practice Evaluation>

Omitted

<Summary>

1.In case of some machines connected to the motor axis, you must not change their rotational direction in the opposite way. Therefore, if you are to conduct a rotation test on the motor in the reverse direction, you should separate the load device connected to the motor before conducting an experiment. And after finishing an experiment, make sure that you connect it back to the normal direction.

2.Some motors cannot produce their normal performance, if they rotate in the reverse direction. Therefore, you should consider this aspect when purchasing the motor for the normal and reverse directions.

4. Load Characteristics & Torque of Induction Motor

<Preliminary Knowledge>

The single-phase induction motor is mainly used in the minimum output (under some HP). In particular, it is used mainly for home appliances like electric fan, fan-heater, water pump, washing machine and air conditioner. The 220V motor is used in various manufacturing facilities in factories, too.

The performances of the motor are indicated by the output (kW or HP), number of rotations (RPM), Torque(N. m), efficiency (%), power factor (%), input voltage and input current. However, we are going to have a practice on how the torque, number of rotations, output and speed are changed according to the motor loads. In general, the relationship between speed change, efficiency and torque is as follows.

- Speed variance (%) $= \dfrac{No-load\ speed - Full-load\ speed}{Full-load\ speed} \times 100$

- Output P = Input power − No-load loss, or $P = 2\pi \dfrac{N}{60} T$ [W]

  In this case, N : Number of motor rotations (RPM)

  T : Torque (N · m)

- Efficiency $\eta = \dfrac{Output}{Input} \times 100$

\<Preparation for Operation\>

Equipment : MG-5212 SET

1. Execute the No.(1)~(8) of the preparation for operation in the "2. Starting characteristics & Slip of squirrel-cage induction motor."

\<Operation & Measurement\>

1. Turn ON the main and motor switches, and run the motor by pressing the Start button. And adjust the AC source to the rated speed 1725RPM(may differ within 1%).

2. Turn ON the Exciting and Output switches of the generator, and turn the Exciting Source DC 0~120V knob so that the output voltage can reach 120V.

3. In the status above, record the M-1, M-2, Wattmeter and RPM Meter indicators of the motor circuit to the no-load box of the Table 4-1. And, read the M-1~M-4 Meter indicators of the generation circuit, and record results to the no-load box of the generator in the Table 4-1.

4. Turn ON the generator load switch S-1 and S-2, carry out measurement as shown in the No.(4) above, and record results to the 1/4 load box of the motor and generator in the Table 4-1.

5. Then, turn ON the generator load switch S-1, S-2, S-3 and S-4 for 1/2 load and turn ON the S-1, S-2, S-3 and S-4 for the full load. Carry out measurement each time as shown in the No.(4) above and record results to the 1/2 load and full load of the motor and generator in the Table 4-1.

<Table 4-1>

		No-Load	1/4 Load	1/2 Load	Full Load
Motor	Input Voltage (V)				
	Input Current (I)				
	Wattmeter (W)				
	Speed (RPM)				
Generator	Output Voltage (V_o)				
	Load Current (I_L)				
	Torque (N. m)				

6. Stop the motor by pressing the Stop button, and turn OFF the Motor switch. Separate the mechanical connection between motor and generator.

[Caution] After separation, be careful not to lose parts like a rubber coupling.

7. Check if there is any obstacle to the motor rotation part, and run the motor by pressing the Start button. Then, read the input voltage & current and wattmeter indicators and record their results to the Table 4-2.

<Table 4-2 (Only motor runs.)>

Input Voltage (V)	Input Current (I)	Watts (W)

8. Stop the motor by pressing the Stop button again, and turn OFF the Motor switch. And connect the motor and the dynamometer again by using the rubber coupling.

9. Fix the motor and dynamometer with the clamp and rotate the connected part of the rotation axis by hands slowly. If there is any imbalance, you must fix it immediately.

10. In case of not continuing this practice, turn OFF the main switch.

\<Practice Evaluation>

1. Calculate a speed variance with the data in the Table 4-1. (At this time, however, the no load must be connected with the no-load generator.)

2. Calculate the maximum rated output (full load) of the motor by using the data in the Table 4-1 and 4-2. Then, with this results, you should calculate the full load and torque.

> [Note]   Output $P \fallingdotseq$ Full-load input power $-$ Input power with motor running only
>
> Torque $T = \dfrac{60}{2\pi} \cdot \dfrac{P}{N}$ In this case, N : Speed (RPM)

3. Calculate the outputs for 1/4 load and full load of the motor, and compare two results to find which has a higher efficiency. And describe the reason?

> [Note]   Efficiency of 1/4 load
>
> $$\eta \fallingdotseq \frac{\dfrac{1}{4}\,\text{load input power} - \text{Power with motor running only}}{\dfrac{1}{4}\,\text{load input power}} \times 100$$

\<Summary>

1. As far as the motor is concerned, its output increases almost in proportion to the load within the range of rated output. The motor output can be indicated as an electric value (kW) and a horsepower (HP). And the relationship is as follows.

$$0.7355 \text{ kW} = 75 \text{ kg} \cdot \text{m/s} = 1\text{HP}$$

2. The efficiency of the motor rises as its load approaches the rated load. That's because the fixed loss power at the P=Full-load input power−Loss power has no much difference no matter the load is small or large.

5. Measuring Power Factor of Induction Motor

<Preliminary Knowledge>

All the induction motors have the iron core and winding to obtain the magnetic field or rotating field. If AC current flows there, the circuit will have the AC resistance of Inductive Reactance XL(Ω). Because the current phase and voltage phase are not equal in such circuit, there will be the reactive power out of the power applied to the motor. At this time, considering that the active power is obtained by subtracting the reactive power from the input power, the proportion of the active power to the input power is called Power Factor (P.F). In other words, the P.F is as follows.

$$P.F = \frac{Active\ power}{Apparent\ power} \times 100 = \frac{Wattmeter\ indicator}{Input\ voltage \times Input\ current} \times 100$$

$$Or,\ P.F = \frac{VI\cos\theta}{VI} = \cos\theta$$

In this case, when the inductive current flows to the motor input, its P.F will amount to less than 1. The larger the inductive reactance (XL) is in comparison with R, the lower the P.F becomes. Please, see the Fig.5-1 for more details.
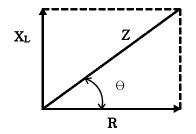

Fig. 5-1

Here, X_L ⋯ Inductive Reactance

R ⋯ Resistance

Z ⋯ Impedance

$Z = \sqrt{R^2 + X_L^2}$

Therefore, the P.F is $\cos\theta = \frac{R}{Z} = \frac{R}{\sqrt{R^2 + X_L^2}}$

In general, when it comes to the induction motors, the voltage of the frequency equal to the input frequency is induced to the rotator winding when it stops (right before starting). The closer it is to the rated speed, the more the frequency induced to the rotator approaches 0. Therefore, when starting, the P.F decreases more than normal rotation due to a growing XL.

<Preparation for Operation>

Omitted
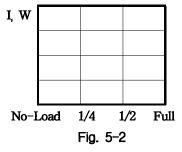
<Operation & Measurement>

Omitted

[Note] Refer to the Table 4−1 for the data from "4. Torque **Load characteristics & torque of induction motor.**"

<Practice Evaluation>

1. Calculate the P.F for no-load and full-load by using the data of the Table 4-1. And compare them to see which shows a more excellent P.F, and describe the reason.

2. Indicate the input current and wattmeter indicator for the load in the Fig. 5-2 by graph.

I, W

※ Wattmeter indicators are shown in dotted lines.

No-Load 1/4 1/2 Full

Fig. 5-2

<Summary>

1. In case of the single-phase induction motor, its P.F improves more when the load is heavy. Describe the reason?

   When a rotation speed decreases due to load, the slip data $\left(\dfrac{\text{Slip speed}}{\text{Sync. speed}} \times 100\right)$ increases accordingly. That's because the load inductance decreases in terms of power input.

MG-5214

SECTION 6.

SATURATION CURVE OF AN ALTERNATOR

< Basic theory >

In addition to the output voltage and load characteristics which have been the main performance parameters in a DC generator, the output frequency characteristic becomes an equally important element for an alternator, or an AC generator. Because the output frequency varies as the speed of the alternator changes, its necessary to synchronize the driving mechanical source (diesel engine, steam turbine, DC motor, etc) to the generator RPM. Therefore, this type of generator is identified as a synchronous alternator (generator).

The type of alternator used in MG-5214 is a three phase synchronous rotating field generator. The output of the generator is taken from a stator. The output voltage of the alternator is a function of the rotor speed and field strength. Therefore, when the rotor speed is held constant, the output will be a function of only the field current. In such a case, a maximum generator output at which any further increase of field current does not produce increased output is observed. Such a point is called the saturation point of the generator.

The rotating magnetic field in an alternator is essentially equivalent to a rotating permanent magnet. When the rotating speed is kept constant, the output is dependent only on the field strength of the magnet. The permanent magnet can be replaced by an electromagnet when a slip ring is added to the rotating shaft to allow DC current to flow through the field winding.

< Preparation >

Equipment : MG-5214 set

(1) Check the coupling between the motor and generator. Keep Main, Motor,

generator Output and load switches off.

(2) Connect meters M-1, M-2 and M-3 of the motor section, and M-1, M-2 and M-3 of the generator section to their specified terminals. Connect M-4 of the generator to any two terminals out of J3, J4 and J5.

(3) Turn RH-1 of motor fully counterclockwise, and RH-2 fully clockwise. Turn the Exciting Source DC 0~120V of the generator to MIN position. Keep Exciting switch off.

(4) Connect between DC 0~120V Source terminals and Input terminals of the motor using the provided cords. Also connect between J3 and J4, and J5 and J6 of the motor.

(5) Turn the Main and Motor switches on, and adjust DC 0~120V Source to obtain DC 60V. Turn the Motor switch off again.

(6) Make sure there is no objects in the rotating path of the motor. Verify all the connections.

< Operation and Measurements >

(1) Turn Motor switch on, and verify that the input is approximately 60V. Press Start button, and adjust DC Source for DC 115V.

(2) Turn RH-2 of the motor fully counterclockwise, and adjust RH-1 to obtain 1800 RPM motor speed.

(3) Turn the Output and Exciting switches of the generator on. Raise the Exciting Source DC 0~120V from 0V with 10V increment, and each time check the output voltage and plot the data on the chart in Figure 6-1 in solid line. Make sure the RPM is maintained at 1800 for each measurement. If not, adjust RH-1 to obtain 1800.

(4) Bring down the Exciting Source voltage to 0V. Turn the generator switches S-1, S-2 and S-3 on. Repeat the same measurements as in step

(3) above, and plot the data on the chart in Figure 6-1 in dotted line. Make sure the RPM is maintained at 1800 as before.

(5) When measurements are done, turn off all the switches.
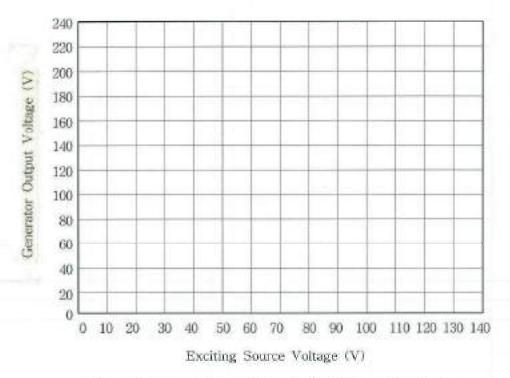

Figure 6-1   (Solid line : No load, dotted line : Full load)

< Experiment Review >

1. In Figure 6-1, find a range over which increasing the Exciting voltage does not increase the output.

2. Examine the difference in saturation characteristics between no load and full load. In case there are differences, explain why.

< Summary >

1. When the iron core inside the field winding reaches a saturation level, increasing the excitation current (field current) does not increase the flux in the core. Also, the generator output does not increase either. The sharpness of the saturation depends on the magnetization characteristics of the iron core.

2. As the load current is increased, the saturation point occurs at lower output voltage.

SECTION 8.

LOSS-EFFICIENCY OF AN ALTERNATOR

< Basic Theory >

When mechanical energy from a motor that drives a generator is converted to electrical energy by the generator, there is a certain amount of losses associated with the conversion process due to the non-ideal components in the system. The energy efficiency of a complete generator system can be defined as :

$$\text{Energy conversion efficiency (\%)} = \frac{\text{Generator output power}}{\text{Motor input power}} \times 100$$

By the same token, the efficiency of a generator itself can be defined as :

$$\text{Generator efficiency (\%)} = \frac{\text{Generator output power}}{\text{Generator loss} + \text{Generator output power}} \times 100$$

The generator loss is consisted of the following loss components :

- **Rotation loss (P_{RL})** : This is due to the mechanical friction in the rotating components. Also small amount of frictional loss due to the presence of air is included. This loss is equal to the motor input with the generator coupled, minus the motor input without the generator.

- **Field winding loss (P_{FL})** : This is the loss due to the rotating field winding resistance and the current in the winding. This loss is essentially a copper loss, and expressed as $P_{FL} = R_F \times I_F^2$.

- **Armature winding loss (P_{AL})** : This is the loss due to the winding resistance and the current in the armature winding. This is a copper loss, and expressed as $P_{AL} = R_A \times I_L^2$.

· **Core loss (P$_{CL}$)** : The core inside a stationary armature winding dissipates power because of the Eddy current and Hysteresis core losses. The core loss is due to the AC magnetization in the core, and is frequency dependent.

< Preparation >

Equipment : MG-5214 set, an Ohmmeter, or a multimeter

   [Note] For convenience, a DC shunt motor is used to drive the generator. The efficiency of the generator system, as well as the efficiency of the generator itself will be evaluated in this section.

(1) Keep Main and Motor switches off, and separate the coupling between the motor and the generator. Keep the rubber coupling for future use.

(2) Connect the meters M-1, M-2 and M-3 of the motor circuit to their specified terminals. Set M-3 for 10A range.

(3) Connect the meters M-1, M-2 and M-3 of the generator to their specified terminals, and connect M-4 to any of the two terminals out of J3, J4 and J5. Turn Exciting switch off.

(4) Turn the RH-1 of motor fully counterclockwise, and RH-2 fully clockwise.

(5) Connect between DC 0~120V Source terminals and Input terminals using a patch cord. Connect the Series field No.1 terminal to J4. (Do not connect J3 to J4). Connect J5 to J6.

(6) Turn Main and Motor switches on. Adjust DC 0~120V Source to obtain DC 60V. Turn motor switch off again.

(7) Make sure there is no objects in the rotating path of the motor, and re-verify all the connections. Also make sure the motor is in Shunt operation.

< Operation and Measurements >

(1) Turn the Motor switch on, and make sure the input voltage is DC 60V, Press Start button. Motor should turn.

(2) Turn RH-2 of motor fully counterclockwise, and adjust RH-1 to obtain 1800 RPM motor speed. Measure the input voltage, Shunt field current and the armature current, and fill in the information in Table 8-1 "MOTOR ONLY" section.

(3) Turn Motor and Main switches off. Couple the motor and generator using the rubber coupler.

(4) Place a clamp over the motor and generator, and tighten the clamp. Make sure the coupled shafts are in straight line.

Table 8-1   (1800 RPM)

	Motor Only	With No Load Generator	
		NO Exciting	Exciting
Input Voltage (E)			
Shunt Field Current (I_F)			
Armature Current (I_A)			

Table 8-2 (3 phase 60Hz generator)

	No Load	Full Load
Exciting Voltage (V_F)		
Exciting Current (I_F)		
Output Voltage (V_O)		
Load Current (I_L)		
Armature Winding Resistance (R_A)		

(5) Turn the generator load switches, Output switch, and the Exciting switches off. Press Start button, and adjust DC Source to DC 115V. Adjust RH-1 to obtain 1800 RPM. If needed, adjust DC 0~120V Source to obtain the RPM.

(6) Record the motor meter readings into Table 8-1 "WITH NO LOAD GENERATOR / NO EXCITING" section.

(7) Turn the generator Exciting and Output switches on, and adjust Exciting Source DC 0~120V to obtain 200V. Record the motor meter readings into Table 8-1 "WITH NO LOAD GENERATOR / EXCITING" section. Also record the generator meter readings in Table 8-2 NO LOAD section.

(8) Turn the generator load switches S-1, S-2 and S-3 on. Adjust RH-1 of the motor to obtain 1800 RPM. If needed, adjust DC 0~120V Source adjuster. Also adjust the Exciting Source DC 0~120V to get 200V at the output terminal.

(9) Record the generator meter readings into Table 8-2 "FULL LOAD" section.

(10) Press Stop button, and turn the motor off. Also, turn all the load switches off. Using an Ohmmeter or a multimeter, measure the winding resistance at J3 and J4. Record this value into Table 8-2 "Armature winding resistance." The measured value should be corrected by the following formula because it is a total resistance of the phase A and phase B.

$$\text{Three phase } R_A = \frac{\text{Measured resistance value}}{2} \times 3$$

(11) When all the measurements are done, turn off all the switches.

< Experiment Review >

1. Using the data in Table 8-1, find the rotation loss P_{RL}, and the total loss at no load P_{NLL}.

[Notes] • $P_{RL} = P_{MG} - P_M$

Where P_{MG} = Input power with a generator at no load and no exciting

$= E \cdot (I_F + I_A)$

P_M = Input power for motor only

$= E \cdot (I_F + I_A)$

• P_{NLL} = Motor input with a generator at no load and exciting, and is obtained from Table 8-1.

2. Using the data in Table 8-2, find the following parameters :

• Field winding loss : $P_{FL} = V_F \cdot I_F$
• Armature loss : $P_{AL} = R_A \cdot I_L^2$
• Core loss : $P_{CL} = P_{NLL} - P_{AL}$
• Total loss : $P_{TL} = P_{RL} + P_{FL} + P_{AL} + P_{CL}$

3. Find the generator efficiency with the generator at full load.

$$\text{Efficiency } \eta = \frac{\text{Generator output}}{\text{Generator total loss} + \text{Generator output}} \times 100$$

[Note] The measured generator voltage and current are the phase voltage and phase current of a three phase Y- system. Therefore, the three phase power output should be calculated by the following equation :

$$P_0 = V_D \times I_L \times \sqrt{3}$$

< Summary >

1. The efficiency of a generator system using a motor as a mechanical energy source can be defined as :

$$\text{Efficiency } \eta = \frac{\text{Generator output}}{\text{Motor input}} \times 100$$

2. To improve the efficiency of a generator system, not only the generator is required to be more efficient, but also the efficiency of the motor needs to be better.