# CYCLE-2:Experiment 1

## Steady- state performance of a 3-phase Induction Motor.

a) Obtain equivalent circuit parameter by conducting open circuit, short circuit and resistancemeasurement test,
b) Conduct load test and draw various performance characteristic i) speed vs. output power, ii) stator current vs. output power, iii) power factor vs. output power, iv) efficiency vs. output power.

**Motivation**

A large percentage of the electrical power generated in the world is consumed by induction motors, as they are the main drive motors used in the industries. Practicing engineers should be conversant with the performance characteristics. Equivalent circuit parameters of the machine should be accurately known for predicting the performance. While motor designer calculates the parameters using design details, measured values are preferable for prediction. All parameters would not be constant under all operating conditions, as they would be affected by temperature, winding currents, saturation, skin effect etc., and these have to be accounted for as far as practicable.

**Theory**

It can be shown by means of either traditional theory or generalized theory that the steady-state performance of poly-phase induction motor can be represented by equivalent circuit of Fig.1.1, which represents one phase of the machine. The symbols are:

$V_1$= input voltage per phase
$R_1$, $X_1$= resistance and leakage reactance of stator per phase
$R_2$, $X_2$= resistance and leakage reactance of rotor referred to stator
$X_m$= magnetizing reactance
Rc= core loss resistance
$I_1$, $I_2$= stator and rotor currents (referred to stator) per phase

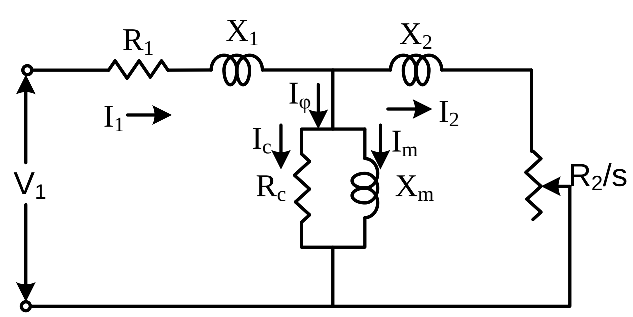


Fig.1.1

The developed torque is given by,

$$T = \frac{3I_2^{\,2}R_2}{(s\omega_s)} N.m.$$

Where

$\omega_s$ = synchronous speed in radians/sec.

s= p.u. slip.

It can be easily seen from the equivalent circuit that at constant voltage $V_1$, $I_2$ is dependent on the slip s. The developed torque will depend on the slip, supply voltage and the equivalent circuit parameters. The typical shape of the torque speed characteristic is shown in fig.1.2, where $T_s$, $T_m$ and $T_f$are starting torque, pull-out (maximum) torque and full load torque respectively. $s_f$ is the slip at full load torque, and $s_m$ is the slip at maximum torque. The stable and unstable operating regions are also indicated in the figure. Input current, power factor and developed power can be computed from the equivalent circuit. Thus all the performance characteristics will be available with the knowledge of parameters and the losses.

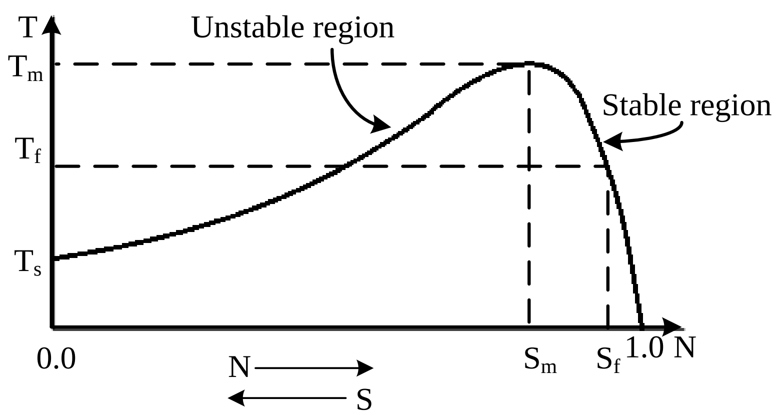


Fig.1.2

The parameters of the machine will not be constant under all operating conditions. Resistances are affected by temperature and ‘skin effect’. After calculating the hot d.c. resistance, a multiplication factor of the order of 1.5 should be used to determine the a.c. resistance. Considerable variation in rotor resistance with speed is observable especially in cage motors, since the rotor current is at supply frequency at starting and near zero frequency under running conditions. Appropriate value of $R_2$ should be taken for calculating the performance under these two different conditions. The leakage reactances $X_1$ and $X_2$ depends on the leakage fluxes produced by stator and rotor currents respectively. At high current some of leakage flux paths saturate leading to decrease of leakage reactance. Thus $X_1$ and $X_2$ would assume vastly different values at starting, running and pull out conditions. The magnetizing reactance $X_m$ and the core loss resistance $R_e$ depends on the operating mutual flux in the machine. Owing to magnetic saturation these also would vary with the air gap flux.

The parameters could be determined by 'no load' and 'blocked-rotor' tests, the former determines $R_c$ and $X_m$ while the latter yields $R_1$, $R_2$, $X_1$, $X_2$. Though no load test is sufficient to calculate $R_o$ and $X_m$ at rated voltage, a 'synchronous-speed' test adds to the accuracy, as it ensures zero slip. 'Blocked rotor' tests at different winding currents helps in evaluating leakage reactances at these currents which could be used for calculations.

The performance of the induction motor can be predicted using the parameters by different methods depending on the required accuracy. Following methods could be used:

a) The Thevenin's equivalent circuit, for the induction motor could be derived from which all the performance quantities such as current, torque, power, power factor etc. could be calculated for different speeds. Here core loss is generally neglected. Suitable parameters could be used at different speeds.

b) The circle diagram could be drawn using 'no load' and 'blocked rotor' test readings. This is likely to give inaccurate results as diameter of the circle being decided by the total leakage reactance will not be constant at all operating conditions. A circle of constant diameter would yield very approximate results.

c) For very accurate prediction, the performance equations in terms of input voltage, machine parameters and speed have to be simulated on a digital computer. A simple computer program would yield the results. Following equations could be used for simulation:

$$Z_1 = R_1 + jX_1$$

$$Z_2 = \frac{R_2}{s} + jX_2$$

$$Z_{\mathrm{m}} = \frac{jR_{\mathrm{c}}X_{\mathrm{m}}}{R_{\mathrm{c}} + jX_{\mathrm{m}}}$$

$$Z = Z_1 + \frac{Z_2 Z_{\mathrm{m}}}{Z_2 + Z_{\mathrm{m}}}$$

$$I_1 = \frac{V_1}{Z}$$

$$I_2 = \frac{I_1 Z_{\mathrm{m}}}{Z_{\mathrm{m}} + Z_2}$$

Torque, $T = \frac{3}{\omega_{\mathrm{s}}}(I_2^{\,2} R_2 / s)$

Power factor, $p.f. = \cos\left(\tan^{-1}\left(\frac{X}{R}\right)\right)$

Where R= real (Z)

X= imag (Z)

Input power $P_{in} = 3V_1I_1 \times p.f.$

Output power $P_o = (1 - s)\,\omega_s T$

Efficiency = $P_o/P_{in}$

**Equipments and Components**

a) A three phase induction motor (cage or wound rotor).
b) Three phase auto transformer.
c) Measuring instrument- ammeters, voltmeters, wattmeters and tachometer.

**Procedure, Connection Diagram, Experimentation and Precautions**

a) Note down the name plate details of the machine and observe the constructional features. Note the type of rotor used and the winding connections.

***b) Measurement of Stator Winding Resistance***

Make the connections as shown in fig.1.3 for a star-connected stator. Similar connections can be used for a delta-connected stator. Apply low voltage so that current through the winding is well below rated value.

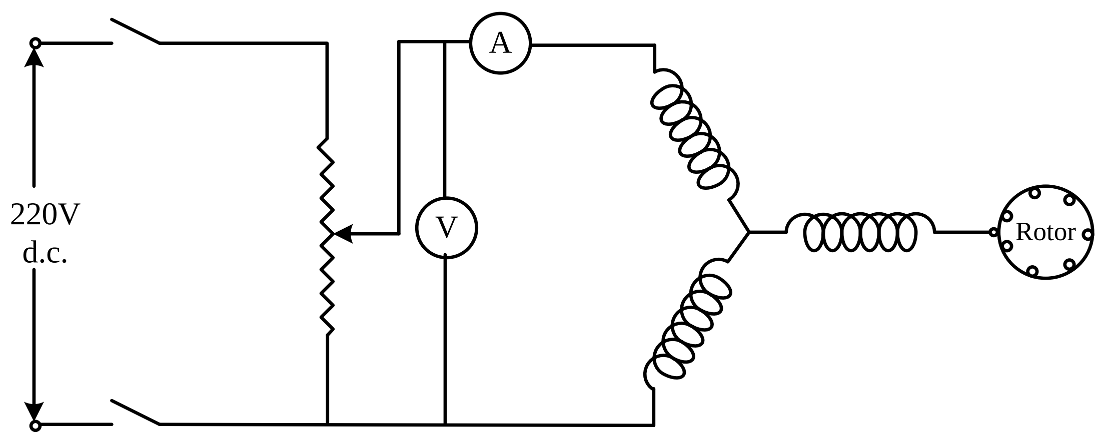


Fig.1.3

***c) Measurement of Rotor Winding Resistance***

If the machine has slip ring rotor, measure winding resistance of the rotor as in (b) above. (This test does not apply for squirrel cage motors).

***d) Light Running Test***

Connect the machine as shown in fig.1.4. Start the motor by applying the normal frequency reduced voltage to the stator and gradually increase the voltage to its rated value. In case of slip-ring motor short circuit the slip-rings before starting. Note down the readings of voltmeter, ammeter, wattmeters and tachometer at different voltages.

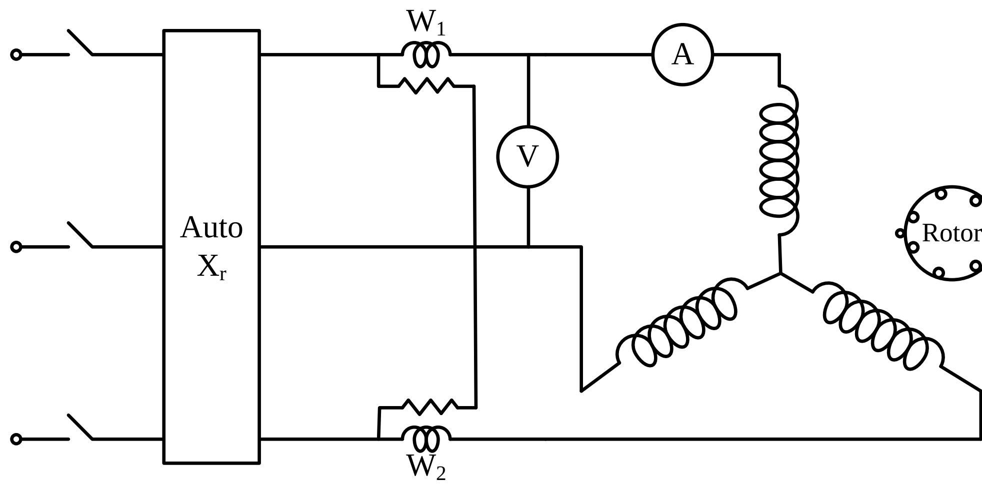


Fig.1.4

***e) Blocked Rotor Test***

With the above connections, keep the rotor blocked, and record the readings of various instruments for different steps of input current varying from zero to 1.5 p.u. If values changes noticeably for different rotor positions, an average set of readings should be taken. Since very low value of voltage can inject rated current under this condition precaution should be taken not to apply high voltages.

**Data Sheet***

***a) Name Plate Details of the Machine***

| | |
|---|---|
| Name of manufacturer: | Rated Output: |
| Rated voltage: | Supply frequency: |
| No. of phases: | Rated speed: |
| No. of poles: | Rated current: |
| Type of rotor: | Type of starting method: |
| Winding connections for stator/ rotor: | |

b) Average stator winding resistance/ phase= ……ohm

c) Average rotor winding resistance/ phase = ……ohm

Table. 1.1 Light running test

| S. No. | Input Voltage ($V_o$) | Input Current ($I_o$) | Input power $W_1 W_2 W_0 \left(= W_1 + W_2\right)$ | Speed (N) |
|---|---|---|---|---|
| | | | | |

Table. 1.2Blocked rotor test

| S. No. | Input Voltage ($V_o$) | Input Current ($I_o$) | Input power $W_1 W_2 W_{sh} \left(= W_1 + W_2\right)$ | Speed (N) |
|---|---|---|---|---|
| | | | | |

**Data Processing And Analysis**

***Parameters of the Equivalent Circuit***

The no load power input mainly represents core losses, as copper losses could be ignored.

$$R_c = V_o^2 / P_c$$

Now,

$$I_c = \frac{V_c}{R_c}$$

$$I_m^2 = I_o^2 - I_c^2$$

Knowing $I_m$, $X_m$ can be calculated from the relation,

$$X_m = V_o / I_m$$

In the case of blocked rotor test, the equivalent series impedance referred to stator is given by,

$$Z_{sc} = R_{sc} + jX_{sc} = \frac{\text{(Voltage per phase)}}{\text{(Short circuit current per phase)}}$$

The equivalent series resistance referred to stator is

$$R_{sc} = R_1 + R_2 = \frac{\text{(Input power per phase)}}{\text{(current per phase)}^2}$$

And $X_{sc} = X_1 + X_2 = \sqrt{Z_{sc}^2 - R_{sc}^2}$

The a.c. resistance $R_1$ is known by multiplying d.c. resistance by ‘skin effect’ factor.

Thus, $R_2$ can be evaluated. The separation of stator and rotor leakage reactance is difficult. For most machines of normal design it is sufficiently accurate to take

$$X_1 = X_2 = \frac{X_{sc}}{2}$$

In blocked-rotor test, the magnetizing branch has been neglected.

**Report**

a) Plot no load power input vs. applied voltage. Find out iron loss at rated voltage. Calculate $R_c$ and $X_m$ at different voltages and plot them vs. voltage.
b) Plot blocked rotor input power vs. input current. Calculate $R_{sc}$ and $X_{sc}$ and plot them vs. current.
c) Determine the parameters of the exact equivalent circuit at different conditions.
d) Predict the performance of the machine using the above parameters using the methods (a), (b), and (c) of the 'Theory' mentioned earlier

Plot a) Torque vs. speed

And b) Input current vs. speed, for braking, motoring and braking regions. Calculate the starting current, starting torque, pull-out torque and slip at pull-out.

For the stable region,

Plot

a) Torque
b) Speed
c) Power factor
d) Efficiency
e) Power Input
f) Input current

vs. Power output

**Experimental Quiz**

a) Why should there be a difference between d.c. and a.c. resistance?
b) Will the magnetizing branch parameters remain constant at all voltages? Explain.
c) Are the core loss and mechanical losses constant for all operating conditions? Comment.
d) How does the core loss vary with applied voltages and why?
e) Did the blocked rotor loss vary exactly proportional to square of the current? Explain the deviation if any.
f) What are the possible errors due to the approximate equivalent circuit?
g) Critically comment on the characteristics you obtained.
f) What will happen if one line of the supply is cut off (a) when the motor is supplying full load, (b) when the motor is at standstill?
g) What are the normal values of break down and locked rotor torques for general purpose motors?
h) Does the no load current steadily decrease as the supply voltage is reduced? If not, explain why?

**References**


a) Fitzgerald, Kingsley and Kusko, *Electric Machinery*, McGraw-Hill, (1971).

b) M.G. Say, *Performance and Design of A.C. Machines*, ELBS (1961).

c) V. Deltoro, *Electromechanical Devices for Energy Conservation and Control Systems*, Prentice Hall, India (1975).

d) Puchstein, Lloyd and Conard, *Alternating Current Machines*, Asia.

e) P.C.Sen Principles of Electrical machines and Power Electronics, John Wiley.

# CYCLE-2: Experiment 2

## Steady-state performance of a 1-phase squirrel cage Induction motor

(a) Obtain equivalent circuit parameter by conducting open-circuit, short-circuit and resistance measurement tests.
(b) Conduct load test and draw various performance characteristics: torque-vs.-speed, current-vs.-speed, current-vs.-output power etc.

**Motivation**

Single phase induction motors have many applications such as driving fans, blowers, compressors etc. Most of the fractional horse power motors are single phase induction motors. These account for millions of motors, about 20-30% of the total commercial value.

The knowledge of the performance of such a machine is thus essential.

**Theory**

***a) Principle of operation***

The behavior of a single phase induction machine can be studied by (i) double revolving field theory or (ii) cross field theory. As the double revolving field theory is simpler and gives a clearer physical concept, it is preferred for the analysis of single phase machines.

In double revolving field concept, a pulsating mmf produced by the stator (main) winding of a pure single phase machine can be resolved into two oppositely rotating mmf$F_f$ and $F_b$ of constant and equal magnitude which can be mathematically expressed by;

$$F = \frac{NI}{2}[\cos(\omega t - \theta) + \cos(\omega t + \theta)]$$
$$= F_f + F_b$$

Where N= effective number of turns for main winding.
I= main winding current.

However fluxes $\phi_f$ and $\phi_b$ produced by the mmf'$sF_f$ and $F_b$ respectively are of equal magnitude only at standstill. Under running condition (at all speeds) $\phi_f > \phi_b$. Each component of flux produces electromagnetic torque i.e. forward torque $T_f$ is produced by forward flux $\phi_f$ and backward torque $T_b$ by backward flux $\phi_b$. Net torque produced by induction machine being = $(T_f – T_b)$, which is positive along the direction of rotation.

The electromagnetically generated torque $J_f$ and $J_b$ can be mathematically expressed in term of induction machine equivalent circuit parameters as described later.

The behavior of single phase motor can also be explained using the symmetrical component theory by first deriving the equivalent circuit for three-phase induction motor connected to a single-phase supply as shown in Fig.2.1. Here the terminal relations are;

$V = V_a - V_c$ $\qquad$ $I_a + I_c = 0$ $\qquad$ $I_b = 0$

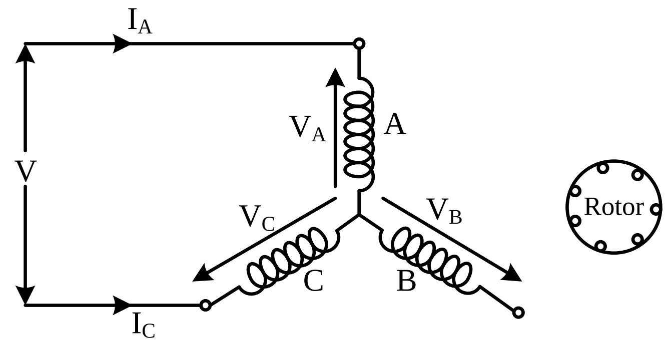


Fig.2.1.

Using symmetrical component relations it can be shown;

$$I_A = \frac{V}{Z_1 + Z_2}$$

Where $Z_1$ and $Z_2$ are the positive and negative sequence impedance of the induction motor. If only one phase is connected across the voltage source, the input current I would be given by;

$$I = \frac{V}{\frac{Z_1}{2} + \frac{Z_2}{2}}$$

Which verifies with the equivalent circuit.

***(b) Equivalent Circuit***

The equivalent circuit of a single phase induction machine as obtained by double revolving field theory is shown in Fig. 2.2. This equivalent circuit is drawn for any machine speed (corresponding slip being s). Here the core loss is neglected. The core loss can be taken into account by placing core loss resistor in parallel with the magnetizing reactance branch.

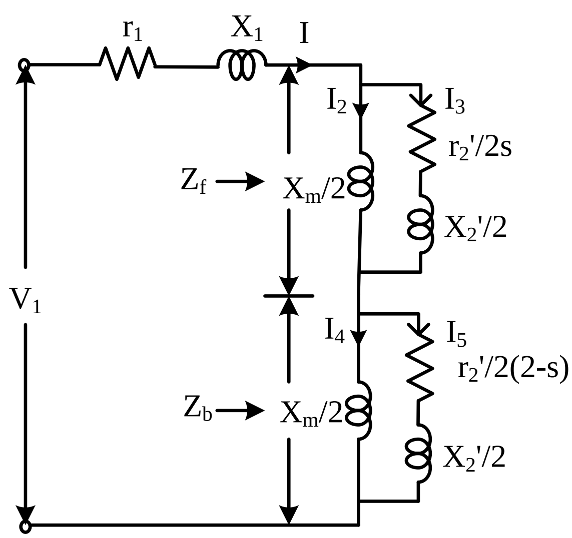


Fig.2.2. Equivalent circuit of a pure single phase induction Motor at any slip s.

From Fig.7.2 the forward impedance $Z_f$ and backward impedance $Z_b$ can be obtained.

$$Z_f = R_f + jX_f = \frac{j\frac{X_m}{2}(r_2'/2s + jX_2'/2)}{r_2'/2s + j\left(\frac{X_m + X_2'}{2}\right)}$$

$$= \left(\frac{r_2'}{2s} + \frac{jX_2'}{2}\right) \text{in parallel with} \left(\frac{jX_m}{2}\right)$$

$$Z_b = R_b + jX_b = \frac{j\frac{X_m}{2}(r_2'/2(2-s) + jX_2'/2)}{r_2'/2(2-s) + j\left(\frac{X_m + X_2'}{2}\right)}$$

$$= \left(\frac{r_2'}{2(2-s)} + \frac{jX_2'}{2}\right) \text{in parallel with} \left(\frac{jX_m}{2}\right)$$

Where $Z_f$ and $Z_b$ are complex impedances.

Therefore net impedance offered by single phase induction motor to supply is;

$$Z_{total} = Z_1 + Z_f + Z_b$$

The impedances are referred to stator. The impedance of rotor $r_2'$ and $X_2'$ are actual rotor values in stator terms, as used in transformer.

Fig2.3 and Fig.2.4 show the equivalent circuit at no load and blocked rotor conditions, respectively.

***(c) Stator current***

The motor current at any slip s will be

$$I = \frac{V}{Z_{total} \text{ at slip s}}$$

Where V is the supply voltage at given frequency.

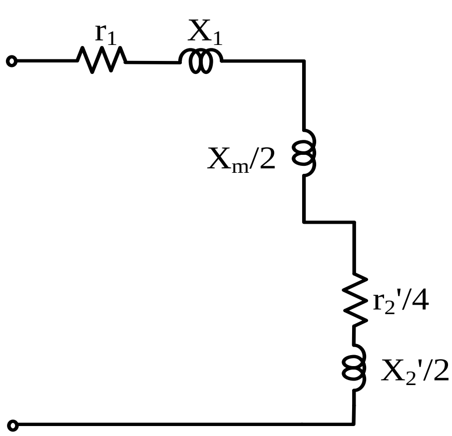


Fig.2.3. Equivalent circuit of a pure single phase induction motor under no load (s~0)

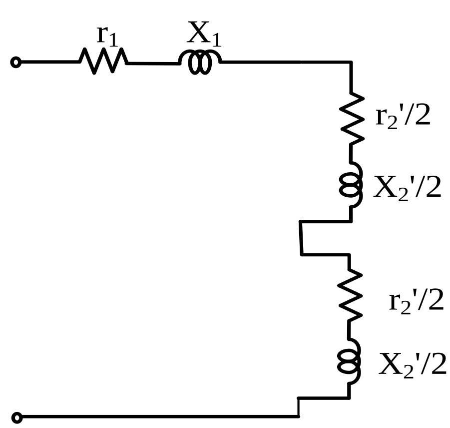


Fig.2.4. Equivalent circuit of an induction motor under blocked rotor condition (s=1)

***(d) Torques***

The forward torque $T_f$ in synchronous watts, following the reasoning results from polyphase induction machine analysis is.

$$T_f = I_3{}^2.r_2'/2s \text{ (synchronous Watts)}$$

The backward torque $T_b$ is;

$$T_b = I_5{}^2.r_2'/2(2-s) \text{ (synchronous Watts)}$$

Where $I_3$ and $I_5$ are as shown in Fig.2.2.

The torque speed characteristic of single phase induction motor due to each component field and their resultant have been shown in Fig.2.5 (corrected to actual flux condition).

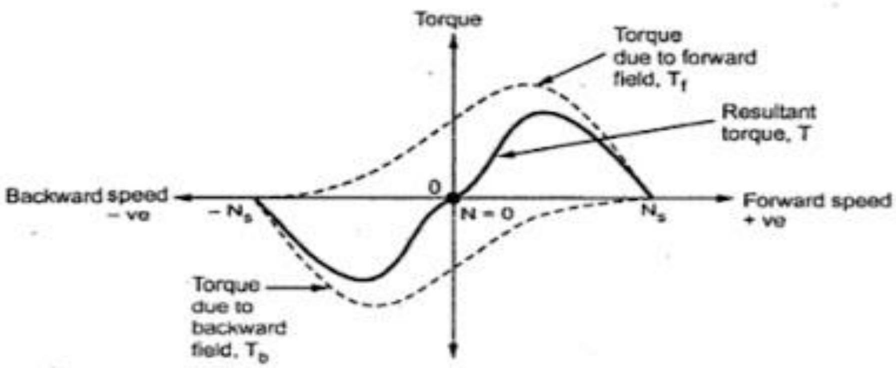


Fig.2.5.Complete torque speed characteristic of a single phase induction motor due to forward and backward fields.

***(e) Parameters of equivalent circuit***

(i) The a.c. values of the main winding resistance $r_1$ motor resistance $r_2$ and stator and rotor leakage reactances $X_1$ and $X_2$, are determined under blocked rotor condition (s=1), the equivalent can be approximated as shown in Fig.2.4 referred to stator.

Impedance referred to stator $Z_{bl}$ is given by

$$Z_{bl} = V_{bl}/I_{bl}$$

Equivalent resistance

$$r_e = (r_1 + r_2')$$

Where $V_{bl}$ = Blocked rotor voltage across stator main winding in volts.

$I_{bl}$ = Blocked rotor current into stator main winding, in amps.

$W_{bl}$ = Power input under blocked rotor condition in Watts.

$$\therefore r_2{}' = r_e - r_1$$

Where $r_1$ is measured by d.c. measurement $v_{dc}/I_{dc}$, where $v_{dc}$ is d.c. voltage across the main winding and $I_{dc}$ is winding current.

Equivalent leakage reactance

$$X_e = Z_{bl}{}^2 - r_e{}^2$$
$$= X_1 + X_2'$$

Assume

$$X_1 = X_2'$$

$$\therefore X_1 = X_2' = Xe/2$$

(ii) Determination of magnetization reactance $X_m$,

At no load, slip s=0 (approx.) equivalent circuit can be approximated as in Fig.2.3. No load power factor is given by;

$$\cos\phi_0 = \frac{W_{nl}}{V_{nl} * I_{nl}}$$

where $V_{nl}$ is no load voltage across the stator windings in volts,

$I_{nl}$ is no load current into stator winding in amps., and

$W_{nl}$ is no load power input in watts.

Voltage $V_{ab}$ across a and b is given by;

$$V_{ab} = V_{nl} - I_{nl}\{(r_1 + r_2'/4) + j(X_1 + X_2'/2)\}$$

Thus, $X_m = 2V_{ab}/I_{nl}$

***(f) Prediction of performance characteristics using the parameter***

Forward torque, $T_f = I^2.R_2'/2s$ synchronous Watts

Backward torque, $T_b = I^2. R_2'/2(2-s)$ synchronous Watts

Net torque developed, $T = T_f - T_b = W_{synch}$

Power output = (1-s) $W_{synch.}$

The air gap powers due to forward field and backward field are,

$$P_{gf} = I_1^2 R_f$$

$$P_{gb} = I_1^2 R_b$$

The corresponding torques are,

$$T_f = \frac{P_{gf}}{\omega_{synch}}$$

$$T_b = \frac{P_{gb}}{\omega_{synch}}$$

The resultant torque is,

$$T = T_f - T_b = \frac{I_1^2}{\omega_{synch}}(R_f - R_b)$$

The mechanical power developed is,

$$\begin{aligned} P_{mech} &= T\omega_m \\ &= T\omega_{synch}(1-s) \\ &= (P_{gf} - P_{gb})(1-s) \end{aligned}$$

Power input = V.I cosϕ

Efficiency = (1-s) $W_{synch.}$/ V.I cosϕ

**Equipment and Components**

(a) Single phase induction motor with proper starting arrangement.
(b) a.c. and d.c. ammeters and voltmeters.
(c) Single element wattmeter (i) low power factor (ii) ordinary.
(d) Stroboscope of tachometer.
(e) Rheostat of suitable rating.
(f) Single phase auto-transformer.

**Procedure, Connection Diagrams, Experimentation and Precautions**

(a) Note the name plate details and constructional feature. Study the motor starting arrangement.
(b) Measure the resistance of the stator winding (using d.c. measurements) and find the effective a.c. value after accounting for skin effect, temperature rise etc.
(c) *No load test*- Make connection as shown in Fig. 2.6. Apply 1.2 p.u. voltage to the machine and note the current, power and speed. Reduce the voltage in steps of 0.2 p.u. Measure corresponding input current, power and speed.
(d) *Blocked rotor test*- Disconnect the auxiliary winding and block the rotor. Apply a voltage such that 1.2 p.u. current flows in the stator winding and note the applied voltage and input power. Reduce the rotor current keeping the rotor blocked in steps of 0.2 p.u. Note the corresponding applied voltage and input power.
(e) *Direct load test*- Single phase motor can be directly loaded with mechanical load or using a d.c. dynamometer or a d.c. generator, as is done for three phase motor. The dynamometer is loaded using a loaded rheostat. Start the motor using the available starting method and bring it to rated speed at normal voltage. Gradually load the motor from no load to full load (i.e. when motor draws rated current) in regular steps. Measure input current, input power, speed, torque and output power at all loading conditions.

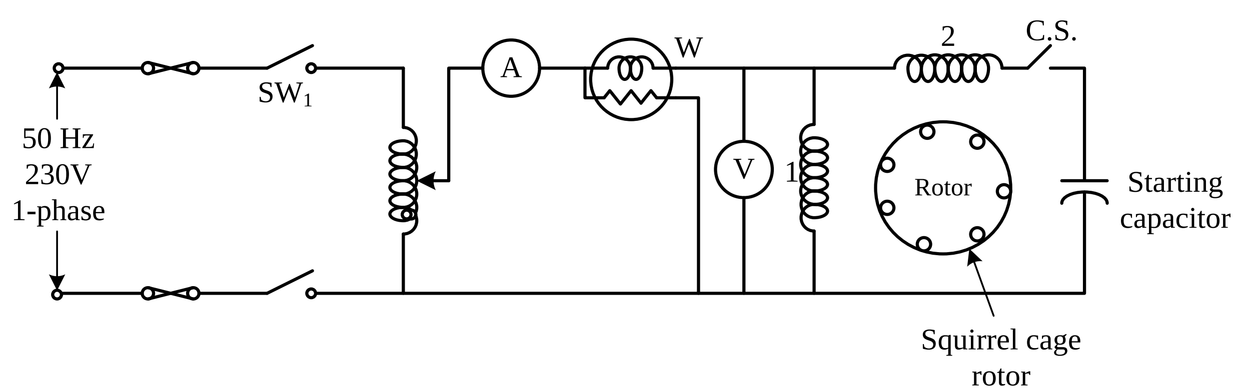


Fig.2.6. Connection diagram for blocked rotor and light run test on single phase IM
1. Main winding 2. Auxiliary winding C.S. Centrifugal switch

**Data Sheet**

(a) Name plate details of the machine,

(b) Main winding resistance (a.c. value), r1= …… ohms

Table.3.1 No-load test readings

| S.No. | Input voltage $V_1$ volts | Input current $I_1$ amps | Input power $W_1$ watts | Speed N rpm |
|---|---|---|---|---|
| | | | | |

Table.3.2 Blocked-rotor test readings

| S.No. | Input current $I_{sc}$ amps | Input voltage $V_{sc}$ volts | Input power $W_{sc}$ watts |
|---|---|---|---|
| | | | |

Table.3.3 Direct load test readings

| S.No. | Voltage applied V | Input current I | Input power W | Speed N | Output | Torque |
|---|---|---|---|---|---|---|
| | | | | | | |

**Data Processing and Analysis**

(a) Calculate impedance parameters of stator and rotor leakage.

(b) Calculate magnetizing reactance parameter.

(c) Predict performance characteristics using the parameters.

(d) Calculate performance from load test.

(e) Plot (i) efficiency (ii) power factor (iii) stator current (iv) input power (v) speed (vi) torque as a function of output power.

**Experimental Quiz**

(a) What are the approximations made while evaluating the equivalent circuit parameters? How are these approximations justified?

(b) While evaluating the performance from the equivalent circuit for different values of slip, the backward impedance $Z_b$, need only be found for one value of slip and the same can be assumed constant for normal other values of slips. Why?

(c) Comment on the agreement between the performance characteristics obtained theoretically and those obtained from the load test.

(d) How does the efficiency of the test motor compare with that of a three phase motor of same rating? Comment.
(e) Compare to the three phase induction motor, the single phase motor has a torque falling to zero at a speed slightly below synchronous speed, and slip tends to be greater. Why?
(f) What are the effects of the backward field on the performance of the test motor?
(g) A double frequency torque production results in higher noise in single phase motors. Explain.
(h) List various applications of single phase motors.

**Suggestions For Further Studies**

(a) Conduct suitable tests and obtain performance characteristics of;
    (i) Capacitor start and run motor.
    (ii) Split phase motor.
    (iii)Shaded pole motor.
(b) Determine the complete torque speed characteristics of the single phase motor using 'Ward-Leonard' method.
(c) Devise an experiment to study the air gap fields of single phase motor using stand still and running conditions.
(d) Study the behavior of three-phase induction motor fed from a single phase supply.

**References**


(a) A.F. Puchstein, T.C. Lloyd and A.G. Conrad, *Alternating Current Machines*, Asia, Third Ed.,(1968).
(b) V. Deltoro, *Electromechanical Devices for Energy Conversion and Control System*, Prentice-Hall (1975).
(c) C.G. Veinott, *Theory and Design of Small Induction Motors*, McGraw-Hill (1959).
(d) A. Fitzgerald, C. Kingsley and A. Kusko, *Electric Machinery*, McGraw-Hill, Third Ed.(1971).
(e) P.C.Sen Principles of Electrical machines and Power Electronics, John Wiley.

# CYCLE-2: Experiment 3

## Steady- state performance of a 3-phase alternator.

By conducting suitable tests (O.C.C., S.C.C, Load tests) obtain voltage regulation at different resistive loads.

**Motivation**

The terminal voltage of an alternator changes with load. The consumer's voltage, however, must be maintained within pre-specified limits. This demands that the machine be designed with low voltage regulation. But a machine with low voltage regulation is uneconomical and is subjected to much mechanical and electrical stresses in case of accidental short circuits. However, in most cases low voltage regulation is not necessary since automatic voltage control equipment is normally used to avoid voltage fluctuations with load. The voltage regulation is an important characteristics of an alternator and its predetermination is essential for its normal operation as well as for designing suitable excitation control schemes.

**Theory**

The voltage regulation of an alternator is the per unit voltage rise at its terminal when a given load at a given power factor is thrown off, the excitation and speed remaining constant. Regulation is governed by the armature resistance, leakage reactance and to a large extent by the armature reaction can be pre-determined by one of the following methods:

***Synchronous Impedance Methodfor calculating regulation***

The synchronous impedance method of determining regulation is based on the simple equivalent circuit and phasor diagram given in Figs.3.1 and 3.2 respectively. In this method the effect of armature reaction is expressed as voltage drop, $I_aX_{ar}$ ($X_{ar}$ is commonly called the armature reaction reactance). The leakage reactance and the armature reaction reactance combined together is called synchronous reactance of the machine, i.e. $X_s= X_l + X_{ar}$ ($X_{ar}$ is related to the mutual flux produced by the armature currents while $X_l$ relates to the leakage flux). The corresponding per phase impedance $Z_s= R_s+ jX_s$ is called the synchronous impedance of the machine where $R_s$ represents the effective resistance per phase. The determination of the synchronous impedance requires the knowledge of open circuit and short circuit characteristics.

If the generator is short circuited the whole voltage E is absorbed in the synchronous impedance of the machine, that is, $E= I_{sc}* Z_s$. Thus for a given field current, the ratio of open circuit armature voltage to the short circuit current gives the synchronous impedance of the machine. From the nature of open circuit and short circuit characteristics, it is obvious that the value of synchronous reactance is not constant but decreases as the saturation sets in. since $Z_s$is

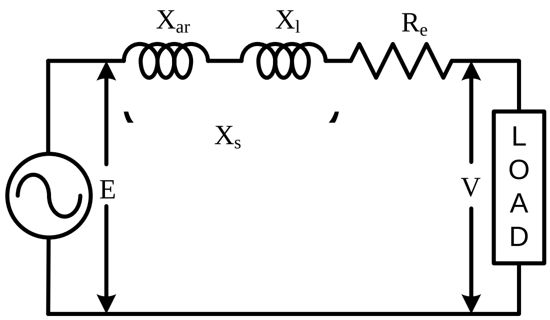


Fig.3.1. Equivalent circuit

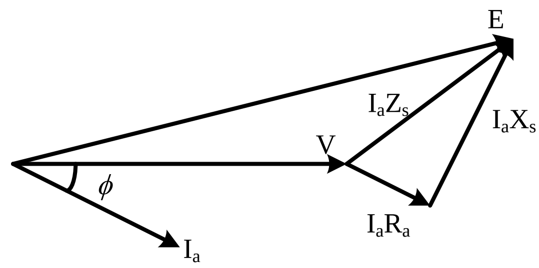


Fig.3.2 Phasor Diagram

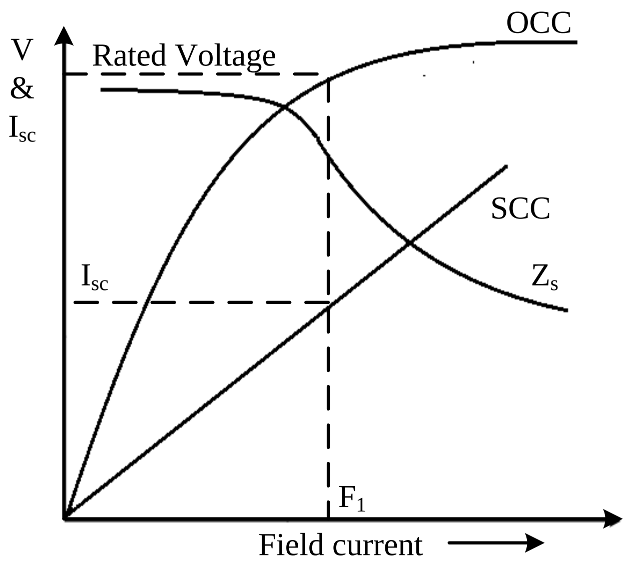


Fig.3.3. Regulation by Synchronous Impedance Method

varying with excitation, for proper application the value of $Z_s$ chosen should correspond to the degree of saturation at which the machine is operating. In practice $Z_s$ is chosen corresponding to the rated value of field current as shown in Fig.3.3. However for laboratory purposes $Z_s$ is chosen corresponding to the field current for the rated value of open circuit voltage.

**Equipment and Components**

a) One three-phase alternator coupled to d.c. motor.
b) One three-phase autotransformer.
c) Ammeters: One a.c. ammeter.
One d.c. ammeter.
d) One a.c. voltmeter.
e) One wattmeter.

f) Rheostat of suitable range for field control.
g) Tachometer.

**Procedure, Connection Diagram, Experimentation and Precautions**

***a) Open Circuit Test***

Make the connection as shown in fig.3.4. Start the d.c. motor and adjust it to synchronous speed. Keeping the speed constant, starting from zero increase the field current of the alternator in steps till saturation is achieved to a good extent. Note the simultaneous readings of the field current and the open circuit armature voltage of the alternator.

***b) Short Circuit Test***

Drive the alternator at the synchronous speed with the armature terminals short circuited. Gradually increase the alternator field current from its initial value of zero until full load armature current is achieved. Measured the corresponding values of armature current and plot the short circuit characteristic. During the test keep the speed constant at synchronous speed.

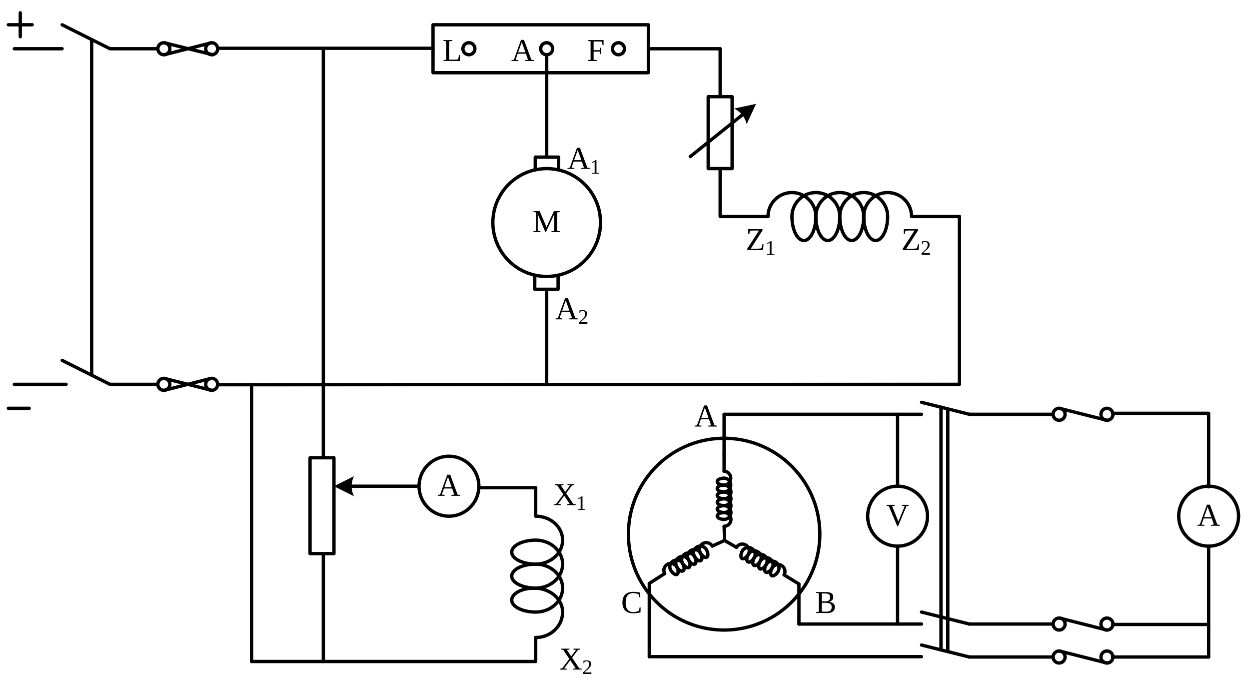


Fig.3.4. Open circuit and Short circuit Test

***c) Load Test***

Make the connection diagram as shown in fig.3.4 except that instead of short circuiting the three terminals (of the alternator) after the ammeter, connect these terminals to a 3-phase load. Start the d.c. motor and bring it to synchronous speed. Adjust the alternator field current to get the rated terminal voltage. Now change the load such that the current through the alternator varies from zero to full-load current. At every load condition, note the terminal voltage, current and the input power to the DC motor. This will allow you to compute the efficiency and voltage regulation at UPF condition. Calculate these theoretically from the equivalent circuit parameters and compare the two.

***c)*** Measure the armature resistance by using a low voltage d.c. supply. Take effective resistance as 1.5 $R_{dc}$.

**Data Sheet**

***Name plate details of d.c. motor alternator set***

Name of manufacturer:

BHP/kW: Class of insulation:

Voltage: RPM:

Frequency: Ampere:

Rating: Power Factor:

Excitation: Connections:

Table. 3.1. O.C.C. of the alternator

Rated Speed=

| S. No. | $I_f$ | $V_t$ per phase |
|---|---|---|
| | | |

Table. 3.2 S.C.C. of the alternator

Rated Speed=

| S. No. | $I_f$ | $I_{sc}$ per phase |
|---|---|---|
| | | |

Table. 3.3. Load characteristics

Rated armature current= A $I_f$ = A Speed = rpm Eg (open circuit voltage) = V

| S. No. | $I_a$ Amp | $V_t$ per phase | DC motor Input Power |
|---|---|---|---|
| | | | |

Table. 3.4. Measurement of armature resistance

| S. No. | V | I | $R_{dc}$ |
|---|---|---|---|

| | | | |
|---|---|---|---|
| | | | |

Approximate effective resistance $R_a = 1.5\ R_{dc}$

**Data Processing and Analysis**

Process all data on per unit basis.

***a) Synchronous Impedance Method***

Draw the open circuit and short circuit characteristics on the same graph sheet. Read the field current for rated armature current ($I_{sc}$) under short circuit from short circuit characteristic. Read the open circuit terminal voltage ($V_o$) corresponding to this field current from the open circuit characteristic. Calculate the synchronous reactance by using the formulae.

$$Z_S = \frac{O.C.Voltage\,(V_o)}{S.C.Current\,(I_{sc})}$$

$$X_S = \sqrt{Z_S^{\,2} - R_S^{\,2}}$$

Draw the phasor diagram and calculate the regulations at rated kVA at 0.8 lagging, unity and 0.8 leading power factors.

Compare the Efficiencies and regulations obtained at UPF by synchronous impedance method and load test. Discuss the results.

**Experimental Quiz**

a) What do you understand by saturated and unsaturated synchronous reactances? Which of the two values is higher?
b) What are the typical values of synchronous reactance in p.u.?
c) The synchronous impedance method gives a regulation that is higher than the actual value. Explain.
d) Explain why armature reaction is always compensated in d.c. machines but not in alternators.
e) Define short circuit ratio of an alternator and show its approximate relationship with the synchronous reactance.
f) Discuss the effect of short circuit ratio on the design and performance of alternator.

**Suggestions For Further Studies**

a) Study the constructional details of Water-Wheel and Turbo-alternators. Study the method of cooling of Turbo-alternators.
b) Compute the machine parameters from design data and calculate the regulation with the test results.
c) Conduct the direct load test on an alternator and find its regulation.

d) Draw and study the phasor diagram of salient pole alternator.

**References**


a) M.G. Say, *The Performance and Design of Alternating Current Machines*, ELBS and Pitman, London (1969).
b) A.E. Fitzgerald, C. Kingsley and A. Kusko, *Electric Machinery*, McGraw-Hill, Kogakusha Ltd (1966).
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# CYCLE-2: Experiment 4

## Synchronization of a synchronous machine with infinite bus and Steady-state performance of a 3-phase synchronous motor

By conducting suitable tests synchronize the given synchronous machine with utility and then obtain: “V” and inverted “V” curves.

**Motivation**

Normally in a power system majority of loads work at lagging power factors while for economic operation it is essential that the system power factor be made as close to unity as possible. The property of a synchronous motor that its power factor varies with the variation of its excitation can be used with advantage in improving the power factor of a system. Thus the study of variation of armature current and power factor of a synchronous motor with its excitation (which is known as V-curves) is very important.

**Theory**

For a synchronous motor the armature current phasor is given by;

$$I_a = \frac{V - E}{Z_a}$$

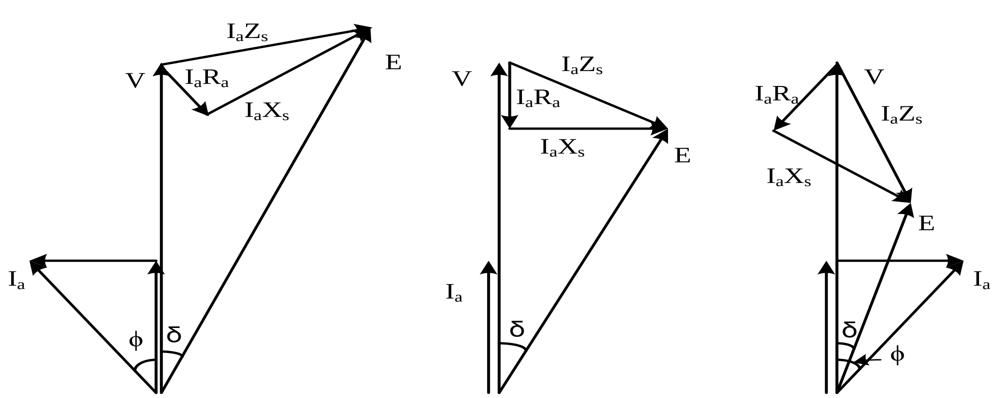
Where V is applied voltage phasor and is constant.

E is induced emf phasor, the magnitude of which depends on the d.c. excitation.

$Z_a$ is synchronous impedance

From the above relationship it is clear that the magnitude and angle of the phasor$I_a$ depends on the value of d.c. excitation. The phasor diagrams of Fig.4.1 shows that synchronous motor draws lagging current when it is under-excited and leading current when over-excited.

The approximate plots of armature current vs. field current have been sketched in Fig.4.2. Because of their shapes these plots are called V-curves and inverted V-curves respectively.



(a) Leading p.f. (b) Unity p.f. (c) Lagging p.f.

Fig.4.1.Synchronous motor with Constant Output and Variable Excitation.

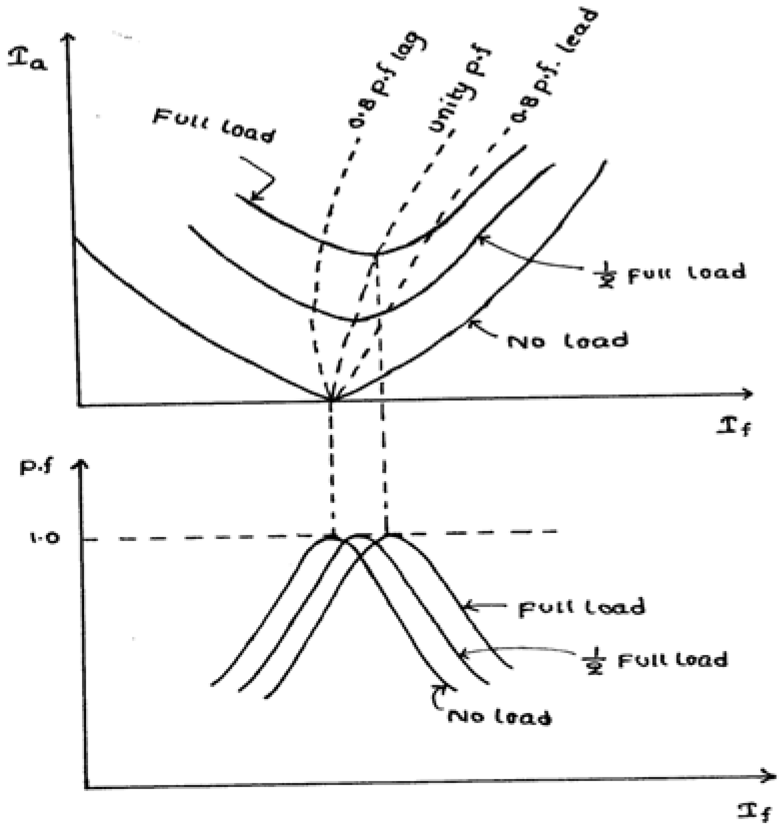



Fig.4.2.V-curve and Inverted V-curve.

## Equipment and Components

(a) Synchronous machine coupled to a d.c. machine.
(b) d.c. /a.c. ammeters and voltmeters.
(c) Two wattmeters with reversing switch.
(d) Rheostats of suitable range for field control synchronizing board.
(e) Tachometer.

## Procedure, Connection Diagrams, Experimentation and Precautions

Make the connections as per the circuit diagram shown in Fig 4.3. Start the d.c. machine as a motor and bring it to synchronous speed. Adjust the alternator field current to get the rated terminal voltage and synchronize the alternator to the mains. For synchronizing the machine with the mains, two bright lamp and one dark lamp method is used. Please read about this from the internet and come prepared for viva-voce. Disconnect the d.c. machine from the mains. Now the synchronous machine is working as a synchronous motor and d.c. machine as self-excited generator.

With no load on d.c. generator, adjust the alternator field current so that its armature current is minimum. This point corresponds to unity power factor. Note the field current, armature current and wattmeter readings. Now vary the field current in both the direction in steps and note the simultaneous readings of field current, armature current and wattmeters. These readings will give V-curves under no load conditions. While increasing the field current, beyond a particular point, one of the Wattmeters will kick back; at that point reverse the Wattmeter's voltage coil with the help of the reversing switch and note that reading as a negative value. Similarly, when the field current is decreased below the UPF condition, at some point, the other wattmeter will kick back; at that point reverse the Wattmeter's voltage coil with the help of the reversing switch and note that reading as a negative value. The two indicate leading and lagging power factor conditions respectively.

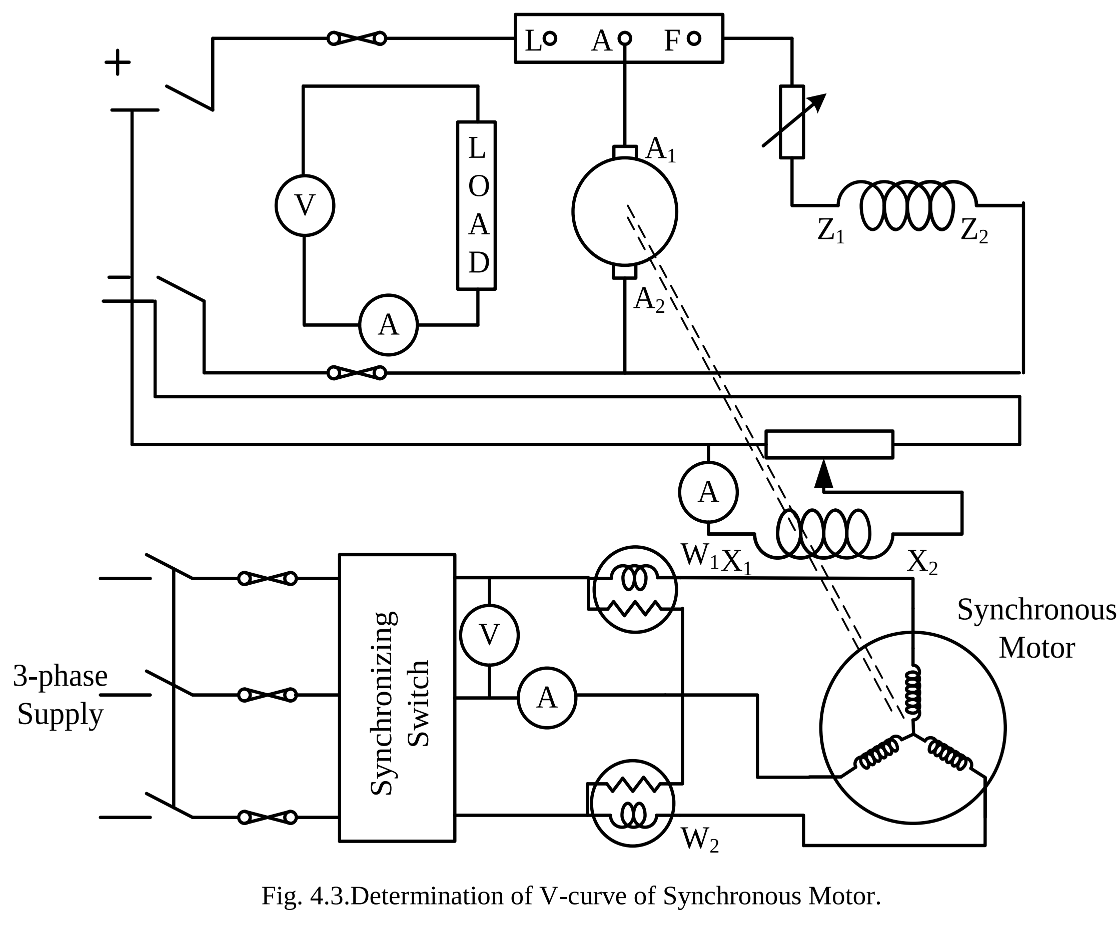



Fig. 4.3.Determination of V-curve of Synchronous Motor.

Now load the synchronous motor by connecting load to the d.c. generator and again repeat the experiment for constant output of 25%, 50% and 100% of full load.

## Data Sheet

***Name plate details of the synchronous machine and d.c. machine.***

Name of the manufacturer:

| | |
|---|---|
| Machine no.: | Class of insulation: |
| BHP/kW: | RPM: |
| Voltage: | Amperes: |
| Frequency: | Phases: |
| Rating: | Connections: |

Table.4.1 Readings with constant output (from the DC generator)
(constant output kW)

| S.No. | $I_f$ | $I_a$ | $W_1$ | $W_2$ | PF |
|---|---|---|---|---|---|
| | | | | | |

## Data Processing and Analysis

Calculate the power factor at each reading with the help of two wattmeter readings by the formula;

$$\tan\theta = \sqrt{3}\,\frac{(W_2 - W_1)}{(W_2 + W_1)}$$

Plot the armature current vs. field current for constant output conditions to get a family of V-curves. Plot the power factor vs. field current to obtain inverted V curves for constant output power conditions.

## Experimental Quiz

(a) Why is it impossible to start a synchronous motor with its d.c. field energized?
(b) Can a synchronous motor be started as an induction motor?
(c) At what power factor is the current a minimum when the synchronous motor is running on constant power output?
(d) Under conditions of normal excitation, describe the effects of increased load on a synchronous motor’s power factor and armature current.
(e) Can a synchronous motor fall out of synchronism even without overloading its shaft?
(f) Discuss the effect of fluctuations in supply voltage and frequency on synchronous motor's operation.
(g) Explain the phenomenon of hunting in a synchronous motor.
(h) Why are the synchronous motors normally provided with damper windings?
(i) What are the applications of synchronous motors in the field of electric drives?

(j) Explain the difference in the operation of a synchronous motor as a (i) motor, (ii) synchronous condenser.
(k) What are the various methods of braking of synchronous motors?
(l) What is meant by inertia constant of synchronous machine? What effect has it got on machine dynamics?
(m) Mention different types of synchronous motors- conventional and unconventional.

**References**

(a) A. Fitzgerald, C. Kingsley and A. Kusko, *Electric Machinery*, McGraw-Hill Kogakuha(1971).
(b) M.G. Say, The *Performance and design of Alternating Current Machines*, ELBS and Issac Pitman, London (1969).
(c) A.F. Puchstein, T.C. Lloyd and A.G. Conrad, *Alternating Current Machines*, Asia, Third ed.,(1968).
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# CYCLE-2: Experiment 5

## Steady-state performance of a 3-phase variable frequency driven squirrel-cage induction motor

By conducting suitable tests, run the given VFD at different frequencies and then observe variable speed operation. Conduct load test (at different frequencies) and then obtain (i) speed-vs.-output power, (ii) current-vs.-output power and (iii) efficiency-vs.-output power at any given input frequency.

**Motivation**

In many industrial applications, the speed control is required to be varied either in steps or smoothly. In certain special applications such as textile and mining industry a group of motorsare required to be run at different speeds with extremely good accuracy. In such applications DC shunt motor is being used because of its characteristics and easy speed control. However, the use of squirrel cage induction motor is desirable due to its well-known advantages over all other motors namely rugged construction, low maintenance and high efficiency. The problem however is that the speed of induction motor cannot be controlled easily. It requires additional expensive equipment. The knowledge of a system whereby speed is controlled by varying the frequency is important for applied engineers. The system is best suited for applications such as mining, chemical industries and textiles.

**Theory**

From Faraday's law, the air gap component of armature voltage in an AC machine is proportional to the peak flux density in the machine and electrical frequency. Thus, neglecting the voltage drop across the armature resistance and leakage reactance, the stator voltage can be written as;

$$V_a = \left(\frac{f_e}{f_{rated}}\right)\left(\frac{B_{peak}}{B_{rated}}\right)V_{rated} \qquad \text{Eq.5.1}$$

where $V_a$ is the amplitude of armature voltage,

$f_e$ is the operating frequency,

$B_{peak}$ is the peak flux density and

$f_{rated}$, $B_{rated}$, $V_{rated}$ are the corresponding rated values.

The speed of induction motor can be precisely controlled by frequency control and can be made independent of variation in supply voltage, field current and load. Therefore, keeping $V_a = V_{rated}$, Eq.5.1 can be rewritten as;

$$B_{peak} = \left(\frac{f_{rated}}{f_e}\right)B_{rated} \qquad \text{Eq.5.2}$$

This demonstrates the constant voltage, variable frequency operation. In this mode, a machine operating in saturation at rated voltage and frequency, any reduction in frequency will lead to further increase in flux density. Higher flux density will result in increased core loss and higher machine currents. Therefore, for frequencies less than or equal to rated frequency, the machine is operated at constant flux density, i.e. $B_{peak} = B_{rated}$. This makes the Eq.5.1 as;

$$V_a = \left(\frac{f_e}{f_{rated}}\right)V_{rated} \Rightarrow \frac{V_a}{f_e} = \frac{V_{rated}}{f_{rated}} \qquad \text{Eq.5.3}$$

This is constant voltage per hertz (V/f) operation. It is typically maintained from rated frequency to the low frequency at which armature resistance drop becomes significant component of the applied voltage. For frequencies higher than the rated *f*, with the voltage at its rated value, the air-gap flux density will drop below its rated value (referring Eq.5.1). Thus, to maintain the rated flux density the voltage has to be increased, which may result in insulation failure. Therefore, for frequencies above the rated frequency, the terminal voltage is kept at rated value. Assuming that machine cooling is not affected by rotor speed, the maximum permissible terminal current will remain constant at its rated value $I_{rated}$. Therefore for frequencies below rated frequency the machine power will be proportional to $f_e V_{rated} I_{rated}$. Fig.5.1 shows the typical characteristics with variable frequency drive.

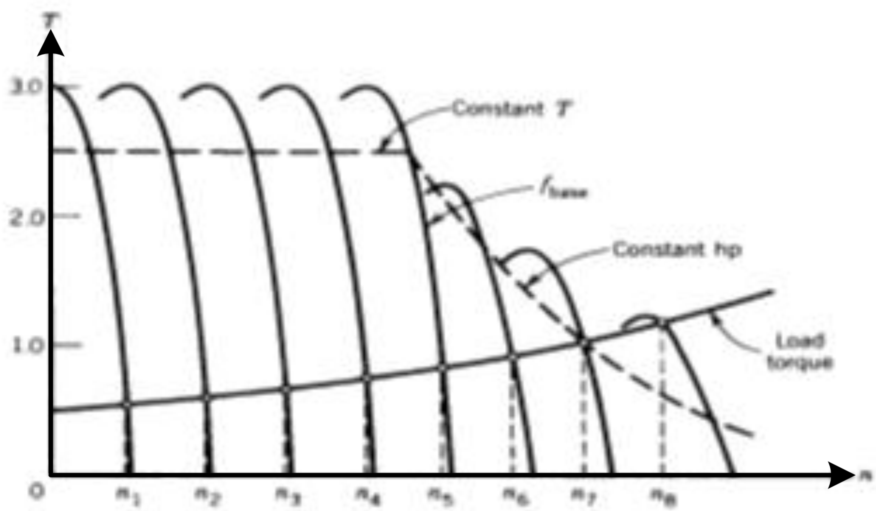


Fig.5.1. Torque-Speed curve.

**Equipment and Components**

(a) Three-phase induction motor coupled to separately excited DC motor.
(b) Variable voltage- variable frequency AC drive.
(c) Wattmeter, ammeter, and voltmeter

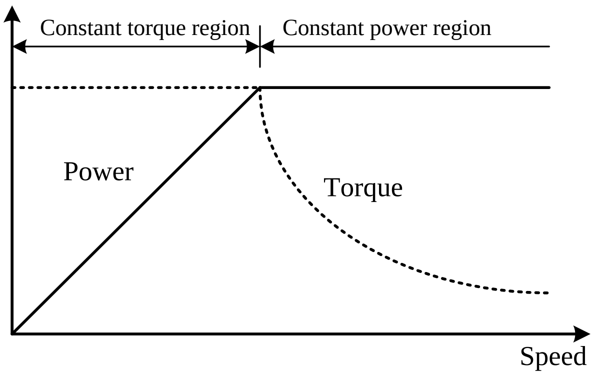


Fig.5.2. Operating regions with V/f operation.

**Procedure, Connection Diagrams, Experimentation and Precautions**

*No-load test:* Fig.5.3 shows the connection diagram for speed control of induction motor using variable frequency AC drive. Apply the rated voltage to AC drive using variac. As soon as the rated voltage reach rated AC voltage, the green indicator will start glowing. Push the start button and slowly increase the speed controller knob to observe the rise in induction motor speed. Record the results (speed, frequency, stator voltage, stator current and power factor) using Fluke 43B analyzer OR Wattmeter, Voltmeter and Ammeter at different speed and tabulate in Table.5.1 for no load speed.

*Load test:* Switch on the field DC supply of separate DC generator. Start the AC drive and increase the speed till motor frequency reaches 25 Hz. Now switch on the load on DC generator step-wise and record the result in Table.5.1.

Reduce the load on the generator to minimum and then increase the speed of motor till frequency reaches to 50 Hz. Now switch on the load at DC generator step wise and record the results in Table.5.2.

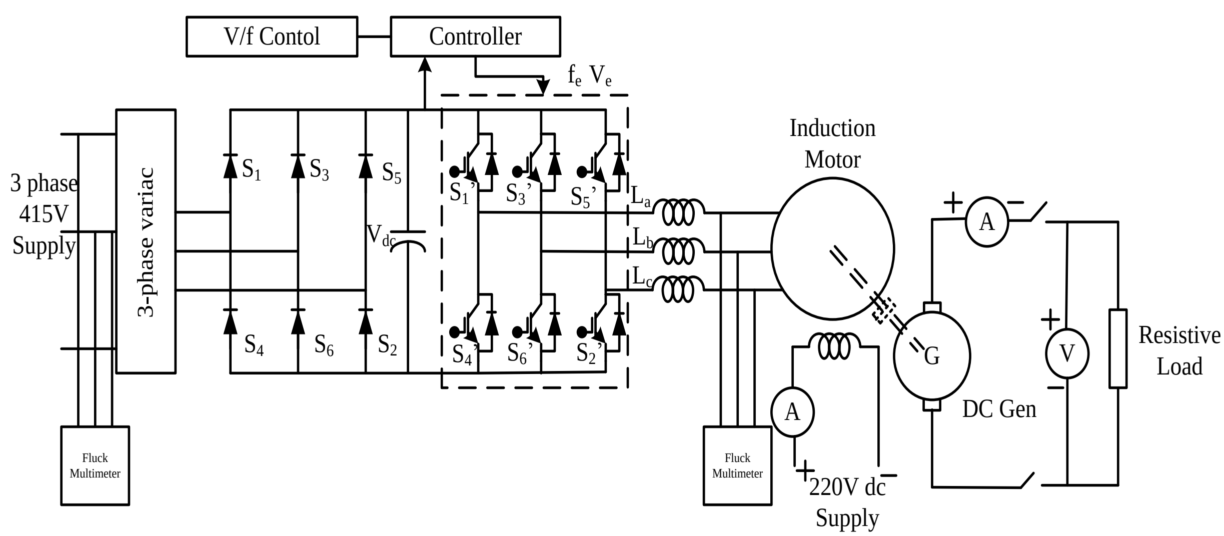


Fig.5.3. Connection diagram of variable frequency AC drive

**Data Sheet**

***Name plate details of the machine***

Name of the manufacturer: Rated output:

Rated voltage: Rated current:

Supply frequency: No. of phases:

Rated speed: No. of poles:

Table.5.1

| S.No. | Speed of I.M. | Input Line current $I_L$ | Power input | Frequency | Power factor |
|---|---|---|---|---|---|
| | | | | | |

Table.5.2

| S.No | Torque on I.M. | Speed of I.M. | Input current $I_L$ | Power Input | | Armature current $I_a$ | Armature voltage $V_a$ | Field Excitation $I_f$ |
|---|---|---|---|---|---|---|---|---|
| | | | | $W_1$ | $W_2$ | | | |
| | | | | | | | | |

**Data Processing and Analysis**

(a) Determine the equivalent circuit parameters of the Induction motor.

(b) Draw the following characteristics: (i) Speed vs. Output power, (ii) Current vs. Output power, (iii) Power factor vs. Output power and (iv) Efficiency vs. Output power at 25 Hz and 50 Hz.

(c) Compute the starting torque and the starting stator current for (i) constant V/f from 5 Hz to 50 Hz, (ii) constant flux from 5 Hz to 50 Hz.

(d) Draw the following characteristic: (i) torque-speed, (ii) stator current-speed at 10 Hz, 25 Hz and 50 Hz keeping constant V/f ratio.

**Experimental Quiz**

(a) What will be the change in torque speed characteristics of the induction motor if there is change in V/f ratio?

(b) Can higher starting torque be obtained at very low frequencies? Comment on the basis of the observations.

(c) Can constant torque speed characteristics be achieved at different frequencies?

(d) What are the advantages and disadvantages of this method of speed control?

(e) How are the equivalent circuit parameter affected by frequency?
(f) What is the effect of variation of frequency on maximum torque, starting torque, slip at maximum torque, if V/f is kept constant?
(g) At constant V/f, is the developed power at all frequency same at rated input current?

**References**

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