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ELECTRICAL ELECTRONICS ENGINEERING
ELECTRICAL MACHINES (II) EEE326
TUTORIAL SOLUTION

QUESTION ONE

(a) **What is the limitation of single-Phase Induction Motor?**

- Auxiliaries are required to start a single-phase motor, in other words does not have a self-starting torque.
- The speed control of an induction motor is difficult to attain
- It has low efficiency
- It has low power output
- It can be noisy and have vibrations
- It has low power factor

(b) **Explain why a single-phase induction motor does no self-start. Discuss this based on the double revolving theory**

The double revolving field theory of a single phase induction motor states that a pulsating magnetic field is resolved into two rotating magnetic fields. They are equal in magnitude but opposite in directions. The induction motor responds to each of the magnetic fields separately. The net torque in the motor is equal to the sum of the torque due to each of the two magnetic fields. The equation for an alternating magnetic field is given as

$$b(\alpha)= \beta_{max} \sin \omega t \cos \alpha \text{.. Equation 1}$$

Where;β_{max} is the maximum value of the sinusoidally distributed air gap flux density produced by a properly distributed stator winding carrying an alternating current of the frequency ω and α is the space displacement angle measured from the axis of the stator.

Recall that:

$$\sin \alpha \cos \beta = \frac{1}{2}\sin(A-B) + \frac{1}{2}\sin(A+B)$$

So, the equation (1) can be written as

$$b(\alpha)= \frac{1}{2}\beta_{max} \sin(\omega t-\alpha)+ \frac{1}{2}\beta_{max} \sin(\omega t+\alpha)\text{………………..Equation 2}$$

The first term of the right-hand side of the equation (2) represents the revolving field moving in the positive α direction. It is known as a Forward Rotating field. Similarly, the second term shows the revolving field moving in the negative α direction and is known as the Backward Rotating field. The direction in which the single phase motor is started initially is known as the positive direction. Both the revolving field rotates at the synchronous speed. $\omega_s = 2\pi f$ in the opposite direction. Thus, the pulsating magnetic field is resolved into two rotating magnetic fields. Both are equal in magnitude and opposite in direction but at the same frequency.

At the standstill condition, the induced voltages are equal and opposite as a result; the two torques are also equal and opposite. Thus, the net torque is zero and, therefore, a single phase induction motor has no starting torque.

(c) **Explain the constructional features and principle of operation of a Single Phase induction motor.**

Constructional Features:

The main parts of a single -phase induction motor are the Stator, Rotor, Windings. The stator is the fixed part of the motor to which A.C. is supplied. The stator contains two types of windings. One is the main winding and the other is the Auxiliary winding. These windings are placed perpendicular to each other. A capacitor is attached to Auxiliary winding in parallel.

As A.C. supply is used for working of single -phase induction motor, certain losses should be looked out for such as- Eddy current loss, Hysteresis loss. To remove the eddy current loss the stator is provided with laminated stamping. To reduce the hysteresis losses, these stampings are usually built with silicon steel.

The rotor is the rotating part of the motor. Here the rotor is similar to the squirrel cage rotor. Besides being cylindrical the rotor has slots all over its surface. To get smooth, quite working of the motor, by preventing magnetic locking of the stator and rotor, slots are skewed rather than being parallel.

Rotor conductors are the aluminium or coppers bars, are placed in the slots of the rotor. End rings made up of either aluminium or copper electrically shorts the rotor conductors. In this single-phase induction motor slip rings and commutators are not used, so their construction becomes very simple and easy.

Principle of operation:

Single-phase induction motors main winding is supplied with a single -phase A.C. current. This produces fluctuating magnetic flux around the rotor. This means as the direction of the A.C. current changes, the direction of the generated magnetic field changes. This is not enough condition to cause rotation of the rotor. Here the principle of double revolving field theory is applied. According to the double revolving field theory, a single alternating filed is due to the combination of two fields of equal magnitude but revolving in the opposite direction. The magnitude of these two fields is equal to the half the magnitude of the alternating field. This means that when A.C. is applied, two half magnitude fields are produced with equal magnitudes but revolving in opposite directions. So, now there is a current flowing in the stator and magnetic field revolving on the rotor, thus Faraday's law of electromagnetic induction acts on the rotor. According to this law, the revolving magnetic fields produce electricity in the rotor which generates force 'F' that can rotate the rotor.

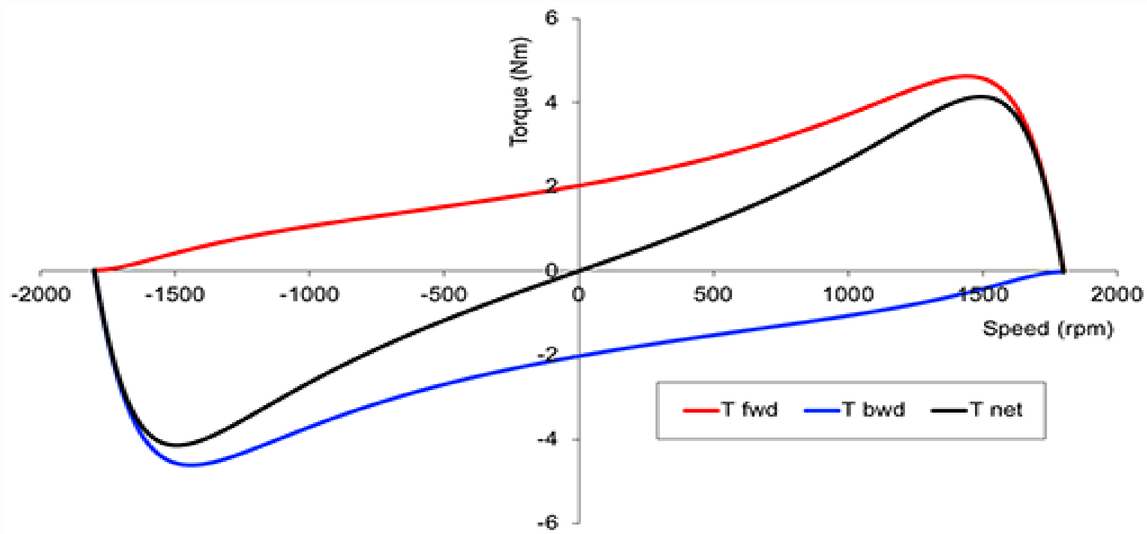
(d) **Using the double revolving field theory explain the torque –slip characteristics of a single-phase induction. Hence explain why a Single-phase induction motor are not self-starting.**

The Torque Slip Characteristic is represented by a rectangular hyperbola. For the immediate value of the slip, the graph changes from one form to the other. Thus, it passes through the point of maximum torque when $R_2 = sX_{20}$. The maximum torque developed in an induction motor is called the Pull Out Torque or the Breakdown Torque. This torque is a measure of the short time overloading capability of the motor. In Double revolving field theory, it is possible to think of a single phase induction machine as the sum of two smaller induction machines, each trying to rotate in opposite directions. The torque speed curve for a single phase induction machine can be sketched as the sum of two torque speed curves - one trying to drive the machine in the forward direction, one trying to drive the machine backwards. This idea is shown in Figure below. It can be seen that if there are two equal and opposing rotating fields, then the net torque at standstill will be zero. Considering the torque curves, if a single-phase induction motor can be made to start, a torque is created and the machine will operate as a motor.

Hence, why it is not self-starting is because;

According to Double Revolving Field theory, there are two magnetic fields with the same magnitude but revolving in the opposite direction. Thus, two force vectors are produced with equal magnitude but opposite in direction.

Thus, these force vectors, as they are of the same magnitude but opposite in direction, doesn't cause the rotor to rotate. So, single-phase induction motors are not self-starting.



TORQUE SPEED CHARACTERISTICS CURVE

(e) **List five types of Single-Phase Induction Motor and explain explicitly any two**

LIST:

1. Resistor-split phase motors
2. Permanent Capacitor motors
3. Capacitor start and run motors
4. Capacitor-star motors
5. shaded pole motor

EXPLANATION:

1) **RESISTOR SPLIT-PHASE MOTORS**

The stator of a split-phase induction motor is provided with an auxiliary or starting winding S in addition to the main or running winding M. The starting winding is located 90° electrical from the main winding and operates only during the brief period when the motor starts up. The two windings are so designed that the starting winding S has a high resistance and relatively small reactance while the main winding M has relatively low resistance and large reactance as shown in a schematic connections.

Mode of operation:

When the two stator windings are energized from a single-phase supply, the main winding carries current Im while the starting winding carries current Is (ii) Since main winding is made highly inductive while the starting winding highly resistive, the currents Im and Is have a reasonable phase angle a (25° to 30°) between them as shown in figure below. Consequently, a weak revolving field approximating to that of a 2-phase machine is produced which starts the motor. The starting torque is given by; $T_s = k\, I_m I_s \sin\phi$

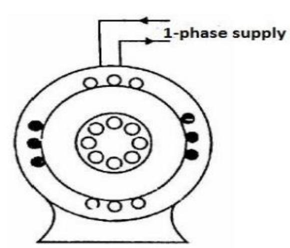
***Characteristics*:**

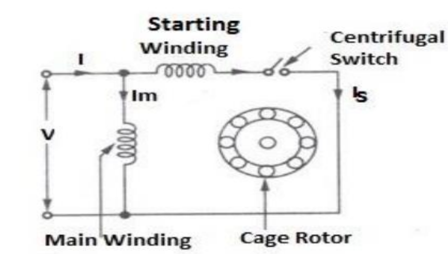
(i) The starting torque is 15 to 2 times the full-loud torque mid (starting current is 6 to 8 times the full-load current.

(ii) Power factor ranges from 0.55 to 0.65. The efficiency from 60 to 65%

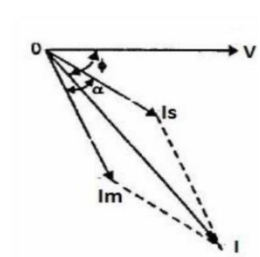
(iii) Since the starting ranges winding is made of fine wire, the current density is high and the winding heats up quickly. If the starting period exceeds 5 seconds, the winding may burn out unless the motor is protected by built-in-thermal relay. This motor is, therefore, suitable where starting periods are not frequent. An important characteristic of these motors is that they are essentially constant-speed motors. The speed variation is 2-5% from no-load to full-load

Diagrams representing a split phase induction motor





Schematic Diagram of Resistor-split phase motor



Applications:

These motors are suitable where a moderate starting torque is required and where starting periods are infrequent e.g., to drive:

a. Fans

b. washing machines

c. oil burners

d. Small machine tools etc.

2) Capacitor start motors:

The capacitor start motor is identical to a resistor split-phase motor except that the starting winding has as many turns as the main winding. Moreover, a capacitor C is connected in series with the starting winding as shown in figure below. The value of capacitor is so chosen that Is leads Im by about 80° (i.e., ϕ ~ 80°) which is considerably greater than 25° found in resistor split-phase motor . Consequently, starting torque ($T_s = k\ I_m\ I_s \sin\phi$) is much more than that of a split-phase motor Again, the starting winding is opened by the centrifugal switch when the motor attains about 75% of synchronous speed. The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed.

Characteristics

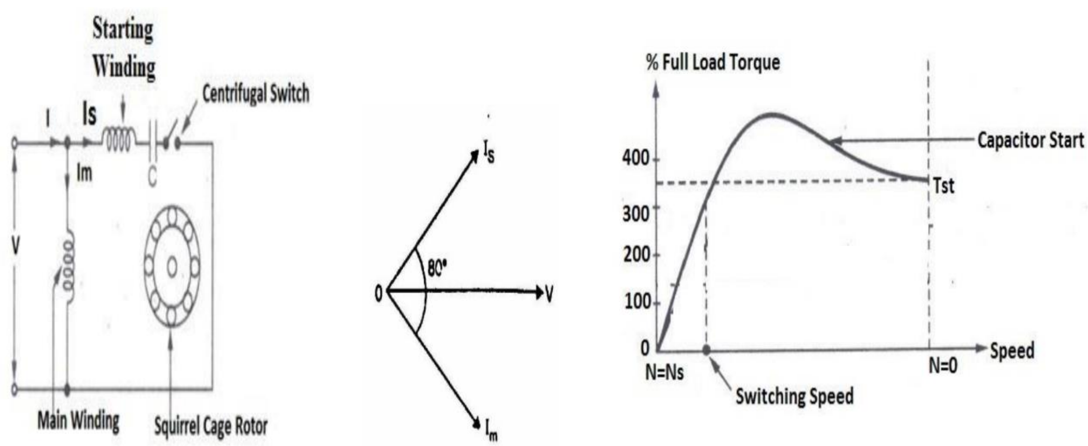
(i) Although starting characteristics of a capacitor-start motor are better than those of a resistor split-phase motor, both machines possess the same running characteristics because the main windings are identical.

(ii) The phase angle between the two currents is about 80° compared to about 25° in a resistor split-phase motor. Consequently, for the same starting torque, the current in the starting winding is only about half that in a resistor split-phase motor. Therefore, the starting winding of a capacitor start motor heats up less quickly and is well suited to applications involving either frequent or prolonged starting periods. The starting winding is disconnected by centrifugal switch.

(iii) The starting torque is 3 to 4 times its full load torque. It has improved power factor than the resistor-split phase motor.

(iv) It has lesser line current as compared to the resistor-split phase motor.

Diagrams representing a capacitor start induction motor



Applications:

Since the motors possess high-starting torque, these motors are used for

a. Refrigerators

b. Air-conditioners

c. Compressors

d. Reciprocating pumps e. Other loads requiring high-starting torques.

(f) **Describe the operation of Single-Phase Induction Motor using the Double-Field Revolving Theory.**

Double revolving field theory is based on the fact that any pulsating quantity such as magnetic or electric quantity can be resolved into two parallel components that are opposite in directions. A magnetic flux having magnitude of Φ_m can be broken into two components each having magnitude of $\Phi_m/2$ acting in opposite direction and each rotating at synchronous speed. The resultant flux which is alternating in nature acts perpendicularly to the two component fluxes. This principle is based on the starting of single-phase induction motor of which the alternating current supplies to the main winding of motor stator produces pulsating field that is divided into a forward and reverse or backward rotating field. These two fields or fluxes are equal in magnitude but opposite in directions. Each of the rotating fluxes or fields induces a voltage in the rotor that drives the current and produces torque which is equal in magnitude and opposite in direction so that each torque tries to turn the rotor in its own direction. Torque/rotor speed is used instead of the usual torque/synchronous speed characteristics on both forward and backward rotating magnetic field flux for better illustration of the two opposite pulsating quantities. The resultant torque is zero at starting and that is why a single phase induction motor is not self-starting. Since single phase induction motor requires the generation of the rotating magnetic field similar to that of three phase motor, this is achieved by converting the single phase supply into two phase supply through the use of additional winding known as starting winding to the main winding. The single phase induction motor can produce a rotating magnetic field by generating two currents which are out of phase using a capacitor. Resistance, capacitance or inductance when connected in series with the starting winding produces a phase shift which generates the starting torque, although capacitor is most frequently used in generating the starting torque . A centrifugal switch is connected in series with the capacitor in series of starting winding which disconnects as the rotor speed reaches 75 percent or more to the operating speed of the motor.

QUESTION TWO

a) What is a Universal Motor? List five (5) areas of application of this type of motor

A universal motor is a series-wound electric motor that can operate on both AC and DC power, designed from the connection of the armature and field windings connected in series. It is developed to provide improved starting torque, good power factor and better speed control.

Areas of application:

There are various applications where universal motors are used, such as

- power drills
- wash machines
- blowers
- kitchen appliances
- table fans
- grinders.

b) Describe the Construction of a Universal Motor.

Universal motor construction is extremely related to the DC machine’s construction. The components of this motor mainly include stator, rotor, exciters (brushes), and covers. It includes a stator where field poles are arranged. But the complete magnetic lane is coated to reduce the eddy currents. These will provoke while working on AC. The rotary armature in the motor is wound type which has skewed or straight slots, and commutator including brushes inactive on it. The commutation over an alternating current is poorer compared with direct current due to the induced current within the armature coils. Because of this reason, brushes in this motor have high resistance.

c) Distinguish Universal motor from the DC series motor with respect to the additional constructional features. Describe these additional constructional features.

Universal motor	Dc series motor
1) It is modified in several ways to run properly on AC supply operation	It runs very poorly when connected to an AC supply.
2) It is made up of a compensating winding typically added, along with laminated pole pieces	It is made up of the solid pole pieces but does not have compensating windings.
3) Its armature typically has far more coils and plates than the dc series motor.	Hence, it has fewer windings per coil than the universal motor.
4) It has good and adjustable speed regulation	It has poor speed regulation

Additional features:

1) For proper operation with AC supply, a universal motor incorporates a compensation winding, in series with the armature and field winding. Compensating winding is also known as pole face winding. This winding is embedded in the slots in pole faces. It is connected in series with the armature winding so that their mmfs are proportional to the same current. To compensate the effect of armature reaction, the direction of current in compensating winding must be opposite to that in the armature winding just below the pole face.
2) AC supply also induces more significant eddy currents than are produced when the motor operates on DC supply. To curtail eddy current losses, universal motors use laminated cores (rather than solid iron), which increases their resistance and reduces eddy currents.
3) In fact, if a DC series motor is running as a universal motor with no load (zero torque) it could lead to a runaway condition, where the speed increases until the motor begins to break apart.

   In other words, the converse of this phenomenon is that universal motors produce very good starting torque (high torque at low speeds) because they’re mechanically commutated

QUESTION THREE

(a) Describe the principle of operation of a three phase Induction Motor.

The three-phase induction motor is an alternating current motor which is driven by the electromagnetic torque generated by the interaction between the rotating magnetic field formed by the stator winding and the magnetic field of the induced current in the rotor winding.

When the 3 phase stator winding is energized from a 3 phase supply, a rotating magnetic field is produced which rotates around the stator at synchronous speed. The rotating magnetic field cuts the rotor conductors, which as yet, are stationary. Due to this flux cutting, emfs are induced in the rotor conductors. As rotor circuit is short circuited, therefore, currents start flowing in it. Now, as per Lenz's law , "the direction of induced current will be such that it opposes the very cause that produced it " . Here, the cause of emf induction is the relative motion between the rotating field and the stationary rotor conductors. Hence, to reduce this relative motion, the rotor starts rotating in the same direction as that of the stator field and tries to catch it but, can never catch it due to friction and windage and therefore emf induction continues and motor keeps rotating.

Thus, principle of 3 phase induction motor also explains why rotor rotates in same direction as the rotating field and why induction motor is self-starting.

(b) State the advantages and disadvantages of Three Phase Induction Motor.

Advantage

- It has low cost and requires minimum maintenance
- They have simple and rugged construction
- They have good power factor (0.89)
- They have high efficiency
- They have good speed regulation
- They are self-starting, hence they do not require an auxiliary winding
- They have reduced power losses

Disadvantage

- The speed control of an induction motor is not possible without sacrificing its efficiency level.
- Also, the speed of the motor decreases with increasing mechanical load.
- Its starting torque is a little bit lower than that of a DC shunt motor.
- Always operate under lagging power factor and during light load conditions it operates at very worst power factor (0.2 to 0.4 lagging).

(c) A 400V, three phases, star connected induction motor has a stator impedance of (0.06+j0.2) ohm and an equivalent rotor impedance of (0.06+j0.22) ohm. Determine the maximum gross power output and the slip at which it occurs.
Hint: take k as unity, solve using the approximate equivalent circuit referred to the Stator (Version 2)

Solution:

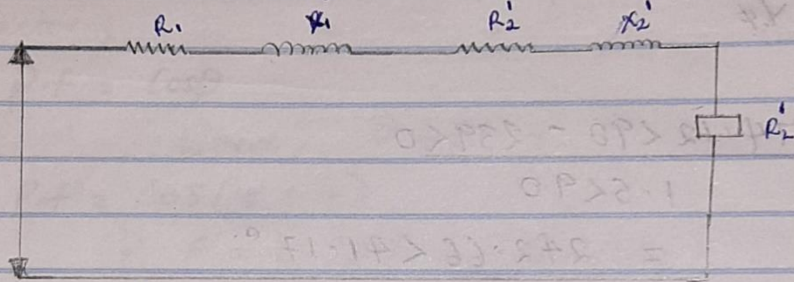
3c.

Given the following Parameters;

Line Voltage = 400V
Stator Impeadance ; $Z_s = (0.06 + j0.2)\Omega$.
Rotor impeadance ; $Z_r = (0.06 + j0.22)\Omega$.
K = unity

using approximate equivalent circuit refereed to the stator (version 2).

Diagramatic representation (Version 2)



Reffered to Primary (stator).

$\because \frac{R_2}{K_2^2} = R_2'$, $\frac{X_2}{X_2^2} = X_2'$

Where;

$R_1 = 0.06\Omega$, $R_2 = 0.06\Omega$, $X_1 = j0.2\Omega$, $X_2 = j0.22\Omega$.

$\therefore R_2' = \frac{0.06}{1^2} = 0.06\Omega$ $X_2' = \frac{0.22}{1^2} = 0.22$

; Equivalent motor resistance reffered to Primary (Stator) R_{01}

$R_{01} = R_1 + R_2'$
$= 0.06 + 0.06$
$= 0.12\Omega$.

; Equivalent motor reactance reffered to Primary (Stator) X_{01}

$X_{01} = X_1 + X_2'$
$= 0.2 + 0.22$
$= 0.42$.

Equivalent motor impeadance reffered to primary (stator) Z_{01}

$\therefore Z_{01} = \sqrt{(R_{01})^2 + (X_{01})^2}$

$Z_{01} = \sqrt{(0.12)^2 + (0.42)^2}$

$Z_{01} = 0.437\Omega.$

$\therefore$ Maximum gross power output;

$$P_{out} = \frac{3 * V^2}{2(R_{01} + Z_{01})}$$

Where; In star connection,

$$V_{phase} = \frac{V_{Line}}{\sqrt{3}}$$

$V_{phase} = 400/\sqrt{3}.$

$$\therefore P_{out} = \frac{3 * (400/\sqrt{3})^2}{2(0.12 + 0.437)}$$

$\Rightarrow 143,626W$

$\Rightarrow 143.63KW.$

$\therefore$ Slip at which it occurs;

$$S = \frac{R_2'}{R_2' + Z_{01}}$$

$$S = \frac{0.06}{0.06 + 0.437}$$

$S = 0.12.$

$S = 12\%.$

(d) Draw and explain the Torque Vs Slip relationship of three-phase Induction Motor.

The difference between the synchronous speed Ns and the actual speed N of the rotor is known as slip. Though it may be expressed in so many revolutions/second, yet it is usual to express it as a percentage of the synchronous speed. Actually, the term ‘slip’ is descriptive of the way in which the rotor ‘slips back’ from synchronism.

slip = (Ns-Nr)/Ns

Percentage slip=(Ns-Nr)/Ns x100

Where, Ns = 120f/P - Synchronous speed, Nr- The actual speed of the motor

Sometimes, Ns − N is called the slip speed. Obviously, rotor (or motor) speed is N = Ns (1 − s). It may be kept in mind that revolving flux is rotating synchronously, relative to the stator (i.e. stationary space) but at slip speed relative to the rotor.

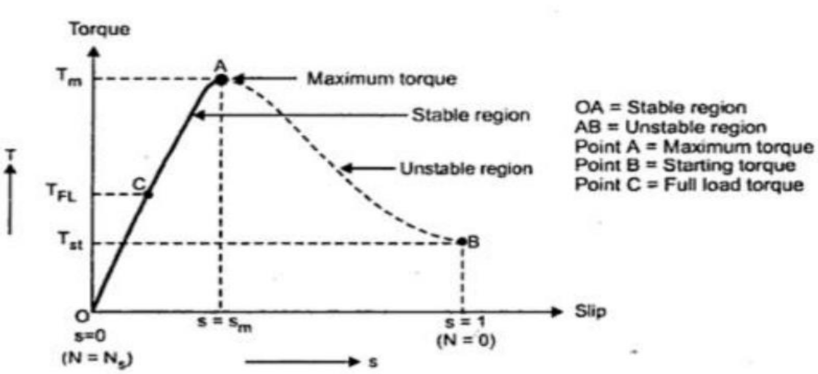
As the induction motor is located from no load to full load, its speed decreases hence slip increases. Due to the increased load, motor has to produce more torque to satisfy load demand. The torque ultimately depends on slip as explained earlier. The behavior of motor can be easily judged by sketching a curve obtained by plotting torque produced against slip of induction motor. The curve obtained by plotting torque against slip from s = 1 (at start) to s = 0 (at synchronous speed) is called torque-slip characteristics of the induction motor. It is very interesting to study the nature of torque-slip characteristics. We have seen that for a constant supply voltage, E2 is also constant. So, we can write torque equations as,

$$T = KsE_2^2 \frac{R_2}{R_2^2 + (sX_2)^2}$$

So, torque - slip characteristics has two parts,

1. Straight line called stable region of operation
2. Rectangular hyperbola called unstable region of operation.

In low slip region, as load increases, slip increases and torque also increases linearly. Every motor has its own limit to produce a torque. The maximum torque, the motor can produce as load increases is Tm which occurs at s = sm. So linear behavior continues till s = sm. If load is increased beyond this limit, motor slip acts dominantly pushing motor into high slip region. Due to unstable conditions, motor comes to standstill condition at such a load. Hence i.e. maximum torque which motor can produce is also called breakdown torque or pull out torque. So, range s = 0 to s = sm is called low slip region, known as stable region of operation. Motor always operates at a point in this region. And range s = s_m to s = 1 is called high slip region which is rectangular hyperbola, called unstable region of operation. Motor cannot continue to rotate at any point in this region. At s = 1, N = 0 i.e. start, motor produces a torque called starting torque denoted as T_{st}. The entire torque - slip characteristics is shown in the below figure:



(e) A 3-phase induction motor runs at 20rps on no-load, and 15 rps at full load when supplied with power from a 60Hz ,3-phase source. Calculate the following;

i. The number of poles of the motor

ii. The percentage slip at full load

iii. The frequency of the rotor's voltage

iv. The rotor's slip speed

v. The rotor's frequency at a slip of 10 percent

Solution:

3e.

Preamble.

Speed at No load, Ns = 20rps.

Speed at full load, N = 15 rps.

frequency = 60Hz

Solution;

Where; rps = rpm / 60.

∴ rpm = rps × 60

∴ Ns = 20rps

Ns = 20×60 rpm

Ns = 1200rpm.

N = 15rps

N = 15×60 rpm

N = 900.

(i) The Number of Poles.

using the formula for synchronous speed;

$N_s = \frac{120 * f}{P}$; $P = 120 * f / N_s$

$P = (120 * 60) / 1200$

P = 6 pole; No of poles = 6.

(ii) The percentage slip at full load;

using the formula for slip;

$S = \frac{N_s - N}{N_s} = \frac{1200 - 900}{1200} = 0.25$

∴ Percentage slip = 25%

3. The frequency of rotor's Voltage:
using the formula;

$f' = s * f$

$f' = 0.25 \times 60$

$f' = 15Hz$.

4. Rotors Slip speed
using the formula;

$n_{slip} = N_s - N$

$= 1200 - 900$

$= 300$.

5. rotor frequency at 10% of Slip
: 10% of slip

$= \frac{10}{100} \times 0.25$

$= 0.025$

$\therefore f' = 0.025 \times 60$

$= 1.5Hz$

QUESTION FOUR

(a) Highlight five methods of controlling the speed of Induction Motors

- By changing the applied voltage
- By changing the applied frequency
- Constant V/F control of induction motor
- Changing the number of stator poles
- By injecting EMF in rotor circuit

(b) List four methods of Starting the three phase Induction Motors

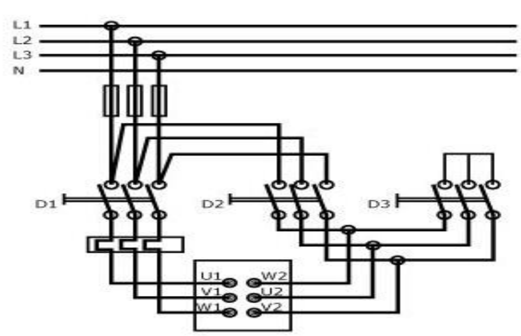
- Rotor Resistance Starter
- Auto Transformer Motor Starting
- Star-Delta Starter
- Direct on-Line Starter

(c) Explain any two methods in Q4(b) using appropriate circuit diagram

- **Star-Delta Starter**

A three-phase motor will give three times the power output when the stator windings are connected in delta than if connected in star, but will take 1/3 of the current from the supply when connected in star than when connected in delta. The starting torque developed in star is ½ that when starting in delta.

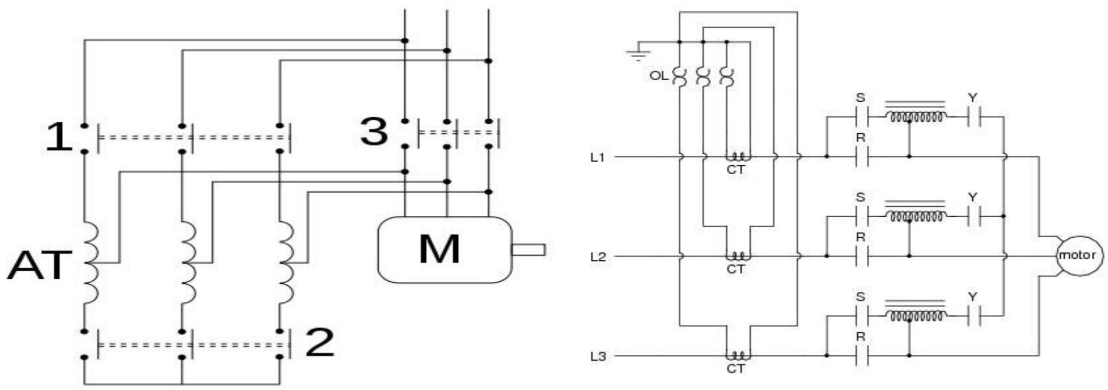
1. A two-position switch (manual or automatic) is provided through a timing relay.
2. Starting in star reduces the starting current.
3. When the motor has accelerated up to speed and the current is reduced to its normal value, the starter is moved to run position with the windings now connected in delta.
4. More complicated than the DOL starter, a motor with a star-delta starter may not produce sufficient torque to start against full load, so output is reduced in the start position. The motors are thus normally started under a light load condition.
5. Switching causes a transient current which may have peak values in excess of those with DOL.



Star-Delta Starter

- **Auto Transformer Motor Starting**

It is operated by a two-position switch i.e. manually / automatically using a timer to change over from start to run position. In starting position supply is connected to stator windings through an auto-transformer which reduces applied voltage to 50, 60, and 70% of normal value depending on tapping used. Reduced voltage reduces current in motor windings with 50% tapping used motor current is halved and supply current will be half of the motor current. Thus, starting current taken from supply will only be 25% of the taken by DOL starter. For an induction motor, torque T is developed by V2, thus on 50% tapping, torque at starting is only $(0.5V)^2$ of the obtained by DOL starting. Hence 25% torque is produced. Starters used in lager industries, it is larger in size and expensive. Switching from start to run positions causing transient current, which can be greater in value than those obtained by DOL starting.



Auto Transformer Motor Starting

QUESTION FIVE

(a) What is the importance of testing on three –phase Induction Motors

- To ensure that its performance is in accordance with its specifications.
- To determine the machine parameters necessary for modeling and vector controlling the machine.
- To improve its reliability and lifetime.
- To reduce the failure to determine how much performance margin it has.
- To limit interruption that could be caused by various factors.
- To ensure that the rotor speed is consistent with no noise/vibration.
- To avoid abnormal rise in temperature.
- To ensure that the power factor is in check, either it is consistent or improving.

(b) State two similarity and differences between the short-circuit test of transformers and the Blocked –Rotor test in Induction Motor.

Differences:

- Blocked rotor test is done at low voltage because if the voltage applies was at normal voltage it would cause overheating at the windings. Meanwhile, the short circuit test is done at high voltages.

- The short circuit test, Iron losses or magnetization losses arises. Meanwhile in the blocked rotor test, stator copper losses and rotor copper losses arise. In other words, their losses vary.

Similarities:

- They are both used to test for leakage impedance and leakage reactance.

- They both short circuit a part of the machine when being conducted i.e. blocked rotor test short circuits the rotor while short circuit test short circuits the primary side.

(c) State two similarity and differences between the Open circuit test in transformer and the No-load test in Induction Motor.

Differences:

- In No load test in induction motor, the secondary terminals are not open circuited (as seen from rotor) but in equivalent circuit model the secondary is assumed to be open. Meanwhile, in an open circuit test of a transformer, it is observed that the secondary is open circuited

- In the open circuit test in transformers the current is negligible (about 1% of rated full load current). Meanwhile, in the no load test in induction motor the current is a comparable value (10%-20% of rated full load current). this is because of the reluctance offered by the air gap in the induction motor which draws high magnetizing current.

Similarities:

- The open circuit and short circuit tests are performed for determining the parameter of the transformer like their efficiency, voltage regulation, circuit constant as well as determining the efficiency and the circuit parameters of the equivalent circuit of the three-phase induction motors respectively.

- The both tests are performed without the actual loading and because of this reason the very less power is required for the test.

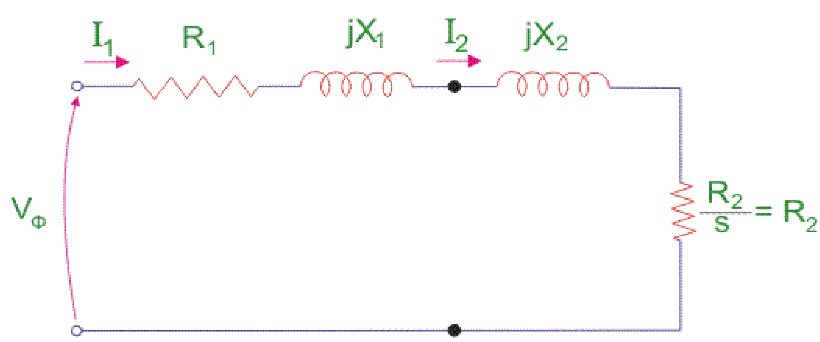
(d) List four types of testing carried out on three-phase Induction Motors and explain any one (1)

- Stator Resistance Test of Three-phase Induction Motor
- Load Test of Three-phase Induction Motor
- Blocked Rotor Test of Three-phase Induction Motor
- No load Test of Three-phase Induction Motor

Explain:

Blocked Rotor Test of Three-phase Induction Motor

A blocked rotor test is normally performed on an induction motor to find out the leakage impedance. Apart from it, other parameters such as torque, motor, short-circuit current at normal voltage, and many more could be found from this test. Blocked rotor test is analogous to the short circuit test of transformer. Here shaft of the motor is clamped i.e. blocked so it cannot move and rotor winding is short circuited. In slip ring motor rotor winding is short circuited through slip rings and in cage motors, rotors bars are permanently short circuited. In the blocked rotor test, it should be kept in mind that the applied voltage on the stator terminals should be low otherwise normal voltage could damage the winding of the stator. In block rotor test, the low voltage is applied so that the rotor does not rotate and its speed becomes zero and full load current passes through the stator winding. The slip is unity related to zero speed of rotor hence the load resistance becomes zero. Now, slowly increase the voltage in the stator winding so that current reaches to its rated value. At this point, note down the readings of the voltmeter, wattmeter and ammeter to know the values of voltage, power and current. The test can be repeated at different stator voltages for the accurate value.



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Circuit diagram of Blocked rotor test of an induction motor

(e) A 400-volts, three phase STAR connected Induction Motor gave the following results on no-load and short-circuit test

No Load Test	**400V**	**3.0A**	**645 Watts**
Blocked Rotor Test	**200V**	**12.0A**	**1660 Watts**

Given that the windage losses amount to 183 Watts, and the stator resistance as 5Ω; Determine the following;

- i. **The Energy component of the No-load current**
- ii. **The magnetizing component of the No-load current**
- iii. **The power factor on No-load**
- iv. **No-load resistance, R_0**
- v. **No-load reactance, X0**
- vi. **Equivalent resistance per phase as referred to the primary**
- vii. **Equivalent reactance per phase as referred to the primary**
- viii. **Power factor on Short Circuit**
- ix. **Short Circuit current with normal voltage applied of 400V across the stator**

Solution:

5e

Preamble;

V_{Line} = 400volt

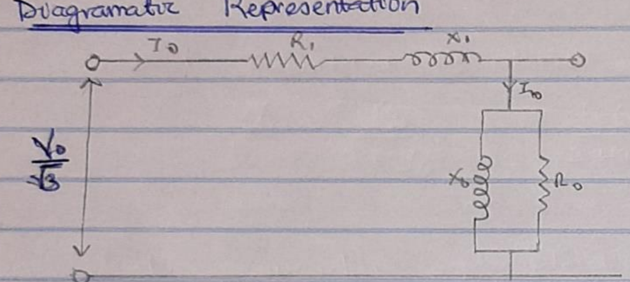
Windage losses = 183 watt

stator resistance = 5Ω.

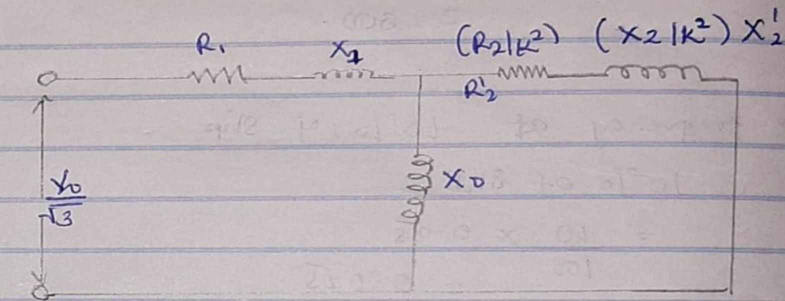
Result on Test.

No Load Test	400 V	3·0A	645watt
Blocked rotor Test	200V	12·A	1660watt

Diagramatic Representation



Equivalent circuit of a No load Test on an IM



Equivalent circuit of a blocked rotor Test on a IM

5e

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Windage losses = 183 watt

Stator resistance = 5Ω.

Result on Test.

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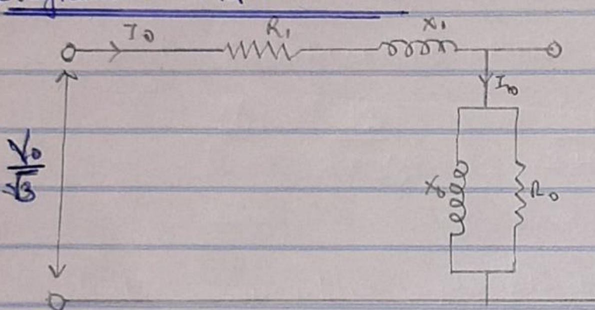
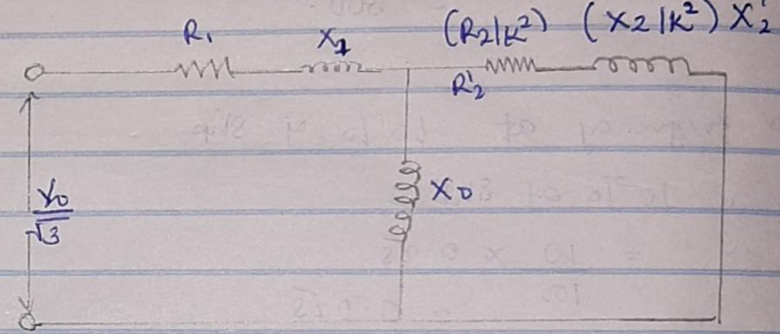
Diagramatic Representation



Equivalent circuit of a No load Test on an IM



Equivalent circuit of a blocked rotor Test on a IM

Recall in a Star Connection;

$V_{phase} = \frac{V_{Line}}{\sqrt{3}} \Rightarrow 400/\sqrt{3} \Rightarrow 230.94$.

Values from table above.

No load line Current $I_{Line} = I_{phase}$

$\therefore I_{Line} = 3A$.

$\therefore$ No load phase Current $I_{phase} = 3A$.

Input on no-load, $P_0 = 645$ watt.

$\therefore$ Stator copper loss $P_{cu} = 3I_0^2 * R_1$ where, $R_0 = 5$ $I = 3$.

$P_{cu} = 3 * 3^2 * 5$

$= 135$ watt.

$\therefore$ Windage and Frictional loss, $P_{wf} = 183$ watt.

$\therefore$ Total stator Core loss $P_i = P_0 - P_{cu} - P_{wf}$

$\Rightarrow 645 - 135 - 183$

$\Rightarrow 327$ watt.

3) No-load Power factor $\cos\phi_0 = \frac{P_0}{3 * V * I_0} = \frac{327}{3 * 230.94 * 3}$

$= 0.157$

1) Energy component of No load line Current I_{Lwe}

$I_{Lwe} = I_{L0} \cos\theta$

$= 3 \times 0.157$

$= 0.472$

$\simeq 0.5 A$

2) Magnetising Component of no load line Current

$I_{Lm} = \sqrt{(I_{L0})^2 - (I_{Le})^2}$

$= \sqrt{(3)^2 - (0.5)^2}$

$= 2.958 A$

4) No-load Resistance, $R_0 = \frac{V}{I_e}$

where $I_e \Rightarrow$ Energy Component of no load phase Current

$I_e = I_0 \cos\phi$

$= 3 \times 0.157$

$= 0.471 A$

$\therefore R_0 = \frac{230.94}{0.471} = 490.32 \Omega$

5) No Load Reactance, $X_0 = \frac{V}{I_m}$

$I_m = 2.958 / 3$

$I_m = \frac{2.958}{3} = 0.986 A$

$\therefore X_0 = \frac{230.94}{0.986} = 234.22 \Omega$

$\therefore$ On blocked rotor test voltage applied per phase

$V_{ph} = V_{Line}/\sqrt{3}$

$= 200/\sqrt{3}$

$= 115.47$ volt

On blocked rotor test   Line Current = 12A.

∴ I Line = I phase

on blocked rotor test phase Current = 12A.

∴ Input on short circuit $P_b = 1660$ watt.

6) ∴ Power factor on ~~block~~ rotor circuit ; $\cos\phi = \frac{P_b}{3 * V * I_b} = \frac{1660}{3 * 115.47 * 12}$

$= 0.399$

$\simeq 0.4$

7) Equivalent Resistance per phase when referred to Primary ;

$R_{01} = \frac{P_b}{3 * I_b^2} = \frac{1660}{3 * (12)^2} = 3.843\ \Omega/\text{phase}$.

Equivalent Impedance per phase ;

$Z_{01} = \frac{V_b}{I_b} = \frac{115.47}{12} = 9.623\ \Omega/\text{phase}$

8) Equivalent Reactance , X_{01}

$X_{01} = \sqrt{(Z_{01})^2 - (R_{01})^2}$

$= \sqrt{(9.623)^2 - (3.843)^2}$

$= 8.822\ \Omega/\text{phase}$

9) ∴ Short Circuit with Normal Voltage Applied Across the Stator

$I_{sc} = I_p * \frac{V}{V_b}$

$\Rightarrow 12 * \frac{400}{200}$

$\Rightarrow 24$ A.

QUESTION SIX

(a) **Explain the operation of synchronous generator**

Synchronous Generator, that is, an alternator (AC generator) with the same rotor speed as the rotating magnetic field of the stator. According to the structure, it can be divided into two types: rotating armature and rotating magnetic field. The operation of a synchronous generator is very simple. It also depends upon Faraday's law of electromagnetic induction which says the current is induced in the conductor inside a magnetic field when there is a relative motion between that conductor and the magnetic field. The DC supply is given to the rotor winding through the slip rings and brushes arrangement. Having understood the very basic principle of synchronous generator, the basic operational principal of a practical synchronous generator is as follows. During discussion of basic working of synchronous generator, we have considered that the magnetic field is stationary and conductors (armature) are rotating. But generally, in practical construction of synchronous generator, armature conductors are stationary and field magnets rotate between them. The rotor of a synchronous generator is mechanically coupled to the shaft or the turbine blades, which on being made to rotate at synchronous speed Ns under some mechanical force results in magnetic flux cutting of the stationary armature conductors housed on the stator. As a direct consequence of this flux cutting an induced emf and current starts to flow through the armature conductors which first flow in one direction for the first half cycle and then in the other direction for the second half cycle for each winding with a definite time lag of 120° due to the space displaced arrangement of 120° between them as shown in the figure 3.17. This particular phenomenon result in 3φ power flow out of the synchronous generator which is then transmitted to the distribution stations for domestic and industrial uses.

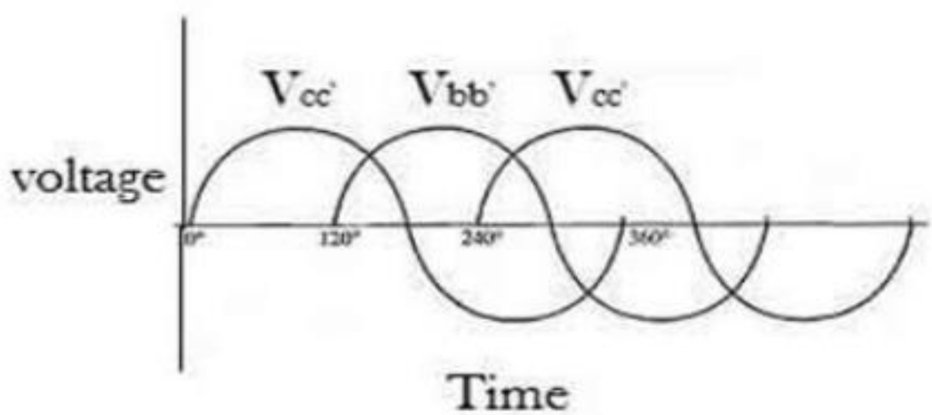


Fig. 3.17 Three phase generated voltage

(b) **A Y connected, two pole,50 Hz,11kV,10MVA synchronous generator with Xs=150Ω is operating at full load and 0.8 power factor lagging. Calculate the following**

- **The induced emf and load angle,Ef < δ**
- **The maximum power ,Pmax**
- **The maximum Torque**

6B

Preamble;

No of Poles = 2

frequency = 50 Hz.

Line Voltage = 11 kV.

rated power = 10MVA

Stator Reactance · Xs = 150Ω.

Power factor = 0.8 lagging

Solution

(1) Calculate the induced emf and Load angle Ef < δ

Recall in star connection;

$$V_{phase} = \frac{V_{Line}}{\sqrt{3}}$$

V_{phase} = 6350.85 Volt.

$$I_a = \frac{S_{rated}}{V_L * \sqrt{3}} \Rightarrow \frac{10\times10^6}{11\times10^3\times\sqrt{3}}$$

⇒ 524.86 A.

Power factor = 0.8

∴ cosθ = 0.8

θ = cos⁻¹ (0.8)

θ = -36.9°

∴ Emf;

$E_a = V_\phi + j * I_a * X_s$

⇒ 6350.85 < 0° + (150 < 90° * 524.86 < -36.9°)

⇒ 82698.27 < 49.579

∴ E_A = 82698.3 < 49.58° Volts.

To obtain Load Angle:

using The real power formula;

$$P_{out} = \frac{3 * V_\phi * E_a * \sin \delta}{X_s}$$

$$P_{out} = \frac{3 * 6350.85 * 82698.3 * \sin(49.58)}{150}$$

$P_{out} = 7996890.003 \simeq 7996890$ watt

∴ Ratio of Rated power to Real Power;

⇒ $(10 \times 10^6) / 7996890$

⇒ 1.25

∴ $E_{a_2} = 1.25 E_{a_1}$

$E_{a_2} = 103413.08$

Recalling the Formula for Induced torque to calculate Torque Angle (δ) / Load Angle

$$\therefore \frac{3 * V_\phi * E_{a_1} \sin \delta_1}{X_s} = \frac{3 * V_\phi * E_{a_2} * \sin \delta_2}{X_s}$$

$E_{a_1} \sin \delta_1 = E_{a_2} \sin \delta_2$

∴ $82698 * \sin 49.58 = 103413.08 \sin \delta_2$

∴ $\delta_2 = \sin^{-1}(0.6088)$

$\delta_2 = 37.50°$

∴ Load Angle $= 37.50° < 36.9° (\theta)$.

∴ 3). P_{max}; Maximum Power;

$$P_{max} \Rightarrow \frac{3 * V_\phi * E_a}{X_s} \quad \delta = 90°$$

$$P_{max} = \frac{3 * 6350.85 * 82698.3}{150}$$

$= 10504089$

$= 10.5$ M watt

(4) T_{max}, Maximum torque

$$\Rightarrow \tau_{max} = \frac{3 * V_\phi * E_A * \sin(90)}{2\pi f * X_s}$$

$$\tau = \frac{P_{max}}{2\pi f}$$

$$= \frac{10504089}{2 * \pi * 50}$$

~~= ...~~

$= 33435.55$ Nm

(c) **Explain the concept of parrallel connection of generators and give four (4) advantages of connecting generators in parallel.**

When a large number of or synchronous generators are connected in parallel to an infinite bus bar system having a constant terminal voltage, constant bus bar frequency and very small synchronous impedance, then this kind of connection is known as parallel operation of synchronous generators.

When the prime mover of a generator is set to deliver a certain power on the shaft, and the voltage is set to deliver that power to an electrical load, a certain operating point is reached [speed, Voltage, Power]. If the load increases, the generator speed (governor) will decrease (not enough power to move the shaft). Hence, we can see the typical prime mover/governor characteristic. The characteristic starts at the "no load speed", and drops.

ADVANTAGES

- Reliability: By using parallel generator we could get more reliability than a single generator unit. we could get the desired load by using the parallel generator so we could get the required load by this and in a certain case, if one unit fails the load can be distributed to the other unit of the system in case of parallel generators but it is not possible in a single unit generator
- Scalable: By using the parallel system one has the ability to expand to his needs. The required load could be received by this without overrunning the budget we can add generators according to the available space and generators can be detached according to our need
- Easily serviceable: If one of the generators needs to be serviced it can be dismantled from the unit and serviced thus it won't interrupt the function of the other loads.
- Flexibility: We can use small generators for parallel system and thus we could get the required load and the generator system will fit in the desired space and by using small size generator we could use it in places were space is restricted