EE6351 ELECTRICAL DRIVES AND CONTROL
UNIT 5
CONVENTIONAL AND SOLID STATE SPEED CONTROL OF A.C. DRIVES
PART A

1. What are the different types of slip power control system?

   Kramer system, Scherbius system.

2. What is meant by slip power?

   The portion of air gap power, which is not converted into mechanical power, is called slip power. Slip power is nothing but multiplication of slip *(s)* and air gap power (P ag)

   Slip power = s (P ag)

3. What are the advantages of slip power recovery system?

   The slip power can be recovered and fed back to the supply. The overall efficiency also improved.

4. What are the different types of slip power recovery system?(Nov 2015)

   These are classified two types.

   Kramer system

   *Conventional Kramer system *Static Kramer system

   Scherbius system

   *Conventional Scherbius system *Static Scherbius system

   * DC link static Scherbius system *Cycloconverter 0Scherbius system

5. What is meant by Kramer system?

   The Kramer system is only applicable for sub-synchronous speed operation because the slip power is fed back to the supply.

6. What are advantages of conventional Kramer method?

   - The main advantage of this method is that any speed, within the working range, can be obtainedinstead of only two or three, as with other methods of speed control.

   - If the rotor converter is over excited, it will take a leading current which compensates for the lagging current drawn by SRIM & hence improves the power factor of the system.

7. What is the function of static Kramer system?

   The slip power is converted into dc by diode bridge rectifier and the DC voltage is converted into AC by line commutated inverter and fed back to supply. As the slip power can flow only in one direction, static Kramer drive offers speed control below synchronous speed only.

8. Define slip power control. What is meant by slip power recovery system?

In slip ring induction motor the rotor power (slip power can be recover and fed back to supply or can be used to supply and additional motor which is mechanically coupled to the main motor. This type of drive is known as slip power recovery system and improves overall efficiency of the system.

9. What is the function of conventional Kramer System?

In conventional Kramer system, the slip power is converted into dc by rotary converter. The dc voltage is fed to dc motor. The dc motor is coupled with slip ring induction motor. The speed of the SRIM can be controlled by varying the field regulator of the de motor.

10. Where static Kramer drive is used?

In large power pump and fan type drives, where speed control within narrow range and below synchronous speed.

11. What are the advantages of static Kramer system?

i. The drive system is very efficient and the converter power rating is low, because it has to handle only the slip power.

ii. The drive system has dc machine-like characteristics and the control is very simple.

12. What are applications of static Scherbius drive system?

Multi-MW, variable speed pumps/generators. 2. Flywheel energy storage system.

13. What are the advantages and disadvantages of static Scherbius drive?

Advantages:

a) In this method, the problem of commutation near synchronous speed disappears.

b) The cyclo-converter can easily operates as a phase-controlled rectifier, supplying dc current in the rotor and permitting true synchronous machine operation.

c) The near-sinusoidal current waves in the rotor, which reduce harmonic loss, and a machine over excitation capacity that permits leading power factor operation on the stator side. So the line's power factor is unity.

d) The cyclo-converter is to be controlled so that its output frequency tracks precisely with the slip frequency.

Disadvantages:

a) The cyclo-converter cost is increases, b) The control of the Scherbius drive is somewhat complex.

14. Compare conventional method of Kramer and Scherbius system(May 2015)

Kramer Method	Scherbius Method
This system consists of SRIM, Rotary converter and dc motor and Induction generator rotary converter, dc motor	This system consists of SRIM, Rotary converter and dc motor
Here, the return power is Mechanical	Here, the return power is mechanical
Less cost.	More cost

15. What are advantages of stator voltage control?

1. The control is very simple
2. More compact and less weight
3. Its response time is quick
4. This is an economical method

16. What are the variable frequency AC drive applications?(May 2013)

VFDs are used in applications ranging from small appliances to the largest of mine mill drives and compressors.

17. What is slip?

The difference between the synchronous speed Ns and the actual speed N of the rotor is known as slip.

18. What are the various methods available for speed control of three phase induction motor?
(Dec 2011) (Nov 2015)

Induction motors are of two types - Squirrel-cage motor and Wound-rotor motor. There are various types of speed control methods of induction motor. These are – (i) Pole Changing, (ii) Stator Voltage Control, (iii) Supply Frequency Control,(iv) Rotor Resistance Control, (v) Slip Power Recovery.

19. What are applications of three phase AC voltage controllers?(Dec 2011) (Dec 2014)

- Lighting / Illumination control in ac power circuits.
- Induction heating.
- Industrial heating & Domestic heating.
- Transformer tap changing (on load transformer tap changing).
- Speed control of induction motors (single phase and poly phase ac induction motor control).
- AC magnet controls.

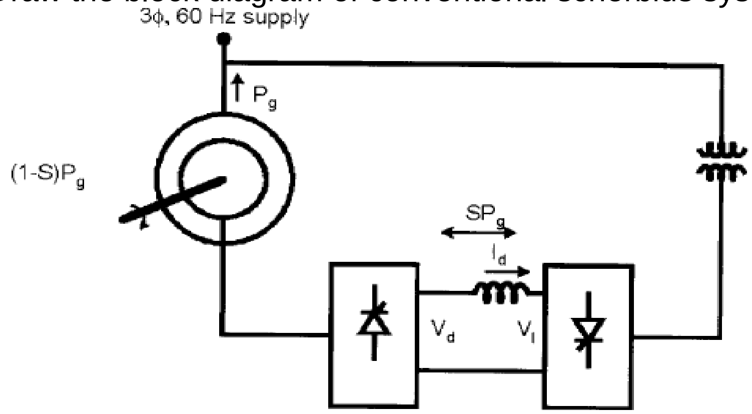
20. How can the direction of rotation of three phase induction motor be reversed. (Dec 2011)

The direction of rotation of three phase induction motor can be reversed by interchanging the input phase sequence from RYB to RBY.

21. State the applications where stator voltage control is employed for three phase induction motor. (Dec 2013)

Fans, Centrifugal pumps, Compressor and etc.

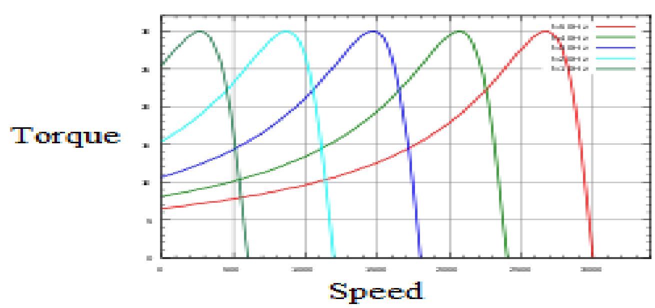
22. Draw the block diagram of conventional scherbius system. (May 2013)



23. What is meant by v/f control? (May 2014)

If the ratio of voltage to frequency is kept constant; the flux also remains constant. At low frequency, the air gap flux is reduced due to the drop in the stator impedance and the voltage has to be increased to maintain the torque level. This type of control is usually known as volts/hertz (v/f) control. The voltage at variable frequency can be obtained from three-phase inverter or cyclo-converter.

24. Draw a sketch of neat sketch of Speed- Torque Characteristics of Induction Motor with v/f control.(Dec 2014)



25. What are the conventional methods of control of three phase induction motor from the stator side? (May 2014)

Stator voltage control, primary resistance starter

26. What is the function of an inverter? (May 2015)

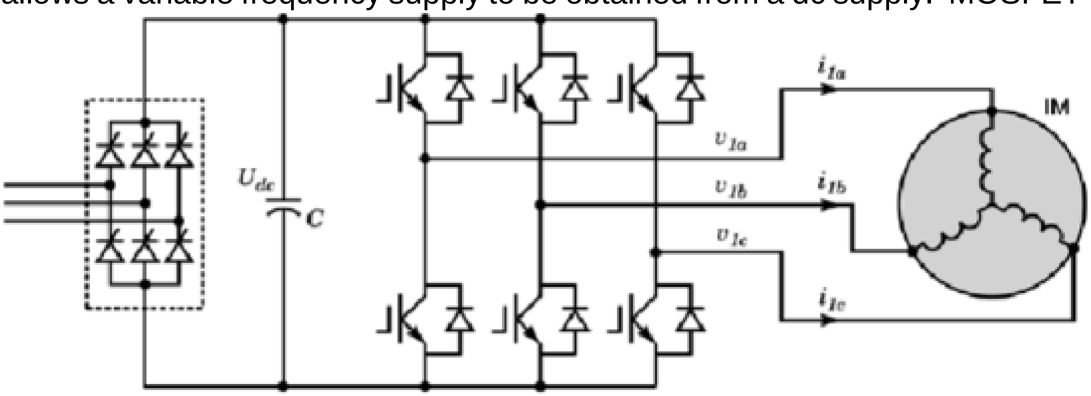
The inverters are basically d.c to a.c converters. The inverters are used to convert a d.c input voltage to a symmetrical a.c output voltage of desired magnitude and frequency.

PART-B

1. Draw the power circuit arrangement of three phase variable Frequency inverter for the speed control of three phase induction motor and explain its working.

An inverter is defined as converter that converts dc into ac. An inverter called voltage source inverter, if viewed from the load side, the ac terminals of the inverter function as a voltage source i.e, the input voltage should be constant. The VSI has low internal impedance. Because of this the terminal voltage of a VSI remains constant with variations in load. The VSI are capable of supplying variable frequency variable voltage for the speed control of induction motors.

VSI allows a variable frequency supply to be obtained from a dc supply. MOSFET is used



Voltage-source inverter (VSI) for induction motor (*IM*) drives.

in low voltage and power inverters. Power transistors and IGBTs are used to medium power level or inverters. For high power level of inverters thyristors, GTOs and IGCTs (Insulated Gate Commutated Thyristor) are used. Above fiure shows VSI employing IGBTs.

Voltage source inverter can be operated as a stepped wave inverter or a pulse width modulated (PWM) inverter. Inverter operated as a stepped wave inverter, IGBTs are switched in the sequence of their numbers with a time difference of T/6 and each IGBT is kept for the duration T/2, where T is the time period of the one cycle.

2.Explain the V/f control method of AC drive with neat sketches.

If we reduce the supply frequency at rated supply voltage, the air gap flux will tend to saturate and causes excessive stator current to flow in which results in distortion of the flux wave. Thus the region below the rated frequency should be proportional reduction of stator voltage so as to maintain the airgap flux constant.

- The below figure 2 is the Torque-Speed characteristic at volt/Hz = constant.In Lower frequency region the air gap flux is reduced by stator impedance drop ($V_m<V_s$).Therefore this region has to be compensated by an additional boost voltage so as to restore T_{em} value.
- If air gap flux is kept constant in constant torque region then the torque sensitivity in ampere of stator current is high by permitting fast transient of the drive.
- In the variable frequency ,variable voltage operation of the drive system, the machine usually has low slip characteristic(i.e low rotor resistance)giving high efficiency.
- In low starting torque for base frequency the machine can always be started at maximum torque indicated in the below figures. The absence of high inrush of starting current in a direct start drives reduces the stress and improves the life of the machine

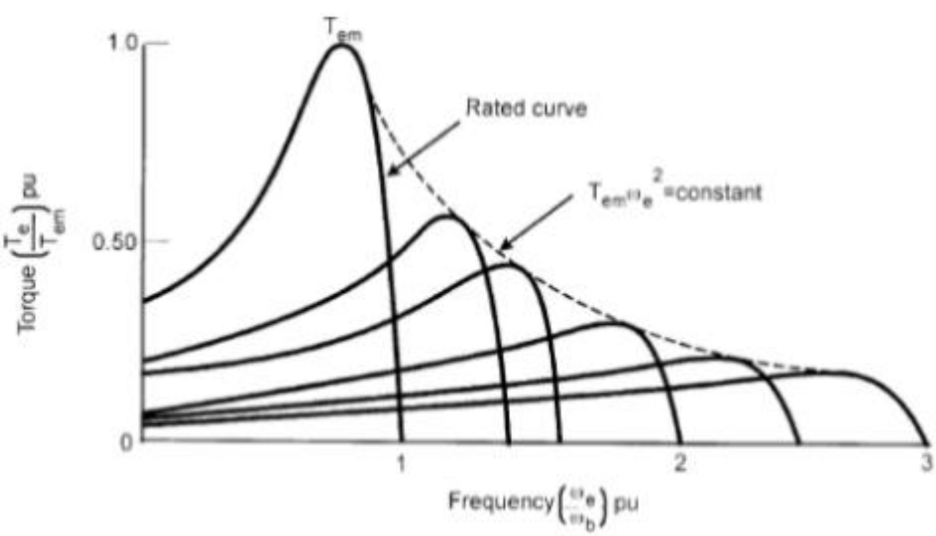


Figure 1 Torque-speed curves with variable stator voltage

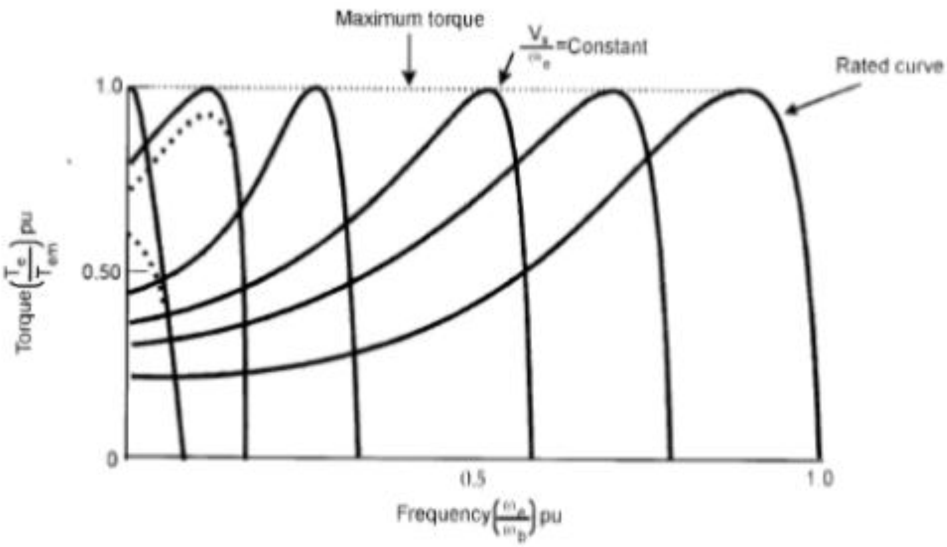


Figure 2 Torque-speed curves at constant volts/Hz

3. Discuss the speed control of AC motors by using three phase AC Voltage regulators.

The stator voltage is controlled in these speed control systems, by means of a power electronic controller. There are two methods of control as follows

On-off control

Phase control

In On-off control, the thyristors are employed as switches to connect the load circuit to the source for a few cycles of source voltage and then disconnect it for another few cycles. Here thyristors act as high speed switch (contactor). This method is known as integral cycle control.

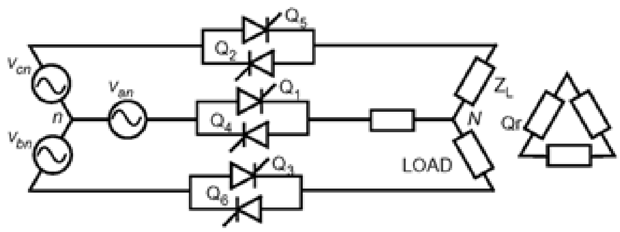
In phase control, the thyristors are employed as switches connect the load to the ac source for a portion of each cycle of input voltage. The power circuit configuration for on-off control and phase control do not differ in any manner. Normally, thyristors in phase control modes are used. The various schemes are i) single phase or 3 phase half wave ac votage controller ii) single phase or 3 phase full wave ac voltage controller.

Figure a and b shows the circuits of three phase half wave and full wave ac voltage controllers for star connected stators. In half wave ac voltage controller consists of 3

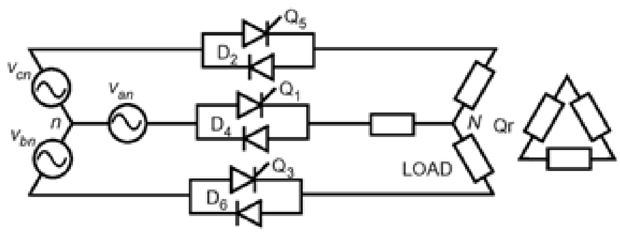
SCRs and 3 diodes. Here one SCR and one diode in antiparallel are connected between the line and motor in a phase.

The full wave ac voltage controller consists of 6 SCRs. Here 2 SCRs are in anti parallel are connected between the line and motor in a phase. The main advantage of half wave controller is saving the cost of semi conductor devices and does not give rise to dc components in any part of the system. The disadvantage is that, it introduces more harmonics into the line current. The effective load voltage in 3 phase ac circuit can be varied by varying thyristor firing angles.

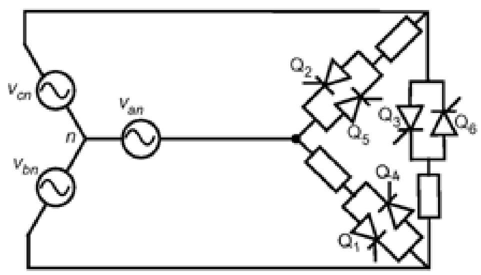
Figure c shows 3 phase full wave ac voltage controller for delta connected load. It may be used and has the advantage of reducing the current of the device. When the motor is delta connected, the third harmonic voltages produced by motor back emf causes circulating current through the windings which increases losses and thermal loading of the motor. For low power rating motors anti-parallel SCR pairs can be replaced by a triac.



(a)



(b)



(c)

a) Full wave ac voltage controller
b) Half wave ac voltage controller
c) Delta connected controller

4. Explain in detail about Slip power recovery scheme. (Dec 2011) (Dec 2014)(Nov 2015)(May 2015)

Squirrel cage induction motor is mostly preferred than wound rotor because wound rotor machine is heavier,more expensive ,have larger inertia,high speed limitations,maintainence and reliability problem due to brushes and slip rings. However wound rotors with mechanically varying rotor circuit rheostat is the simplest and oldest method for speed control, slip power is available from slip rings. For limited speed control appliances the slip power is only a fraction of the total power rating of the machine

Slip power recovery control is used in following appliances:

- Large capacity pumps and fan drives.

- Variable speed wind energy system.
- Shipboard VSCF(variable speed/constant frequency) systems.
- Variable speed hydro pumps or generators.
- Utility system fly wheel energy storage system.

The slip power recovery system can be classified into 2 types

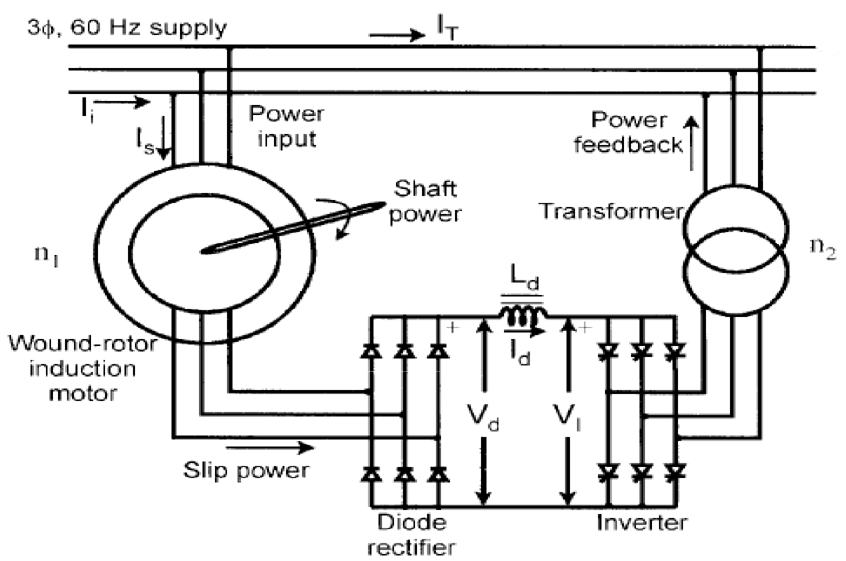
Kramer system

Scherbius system

Instead of wasting slip power in the rotor circuit resistance ,it can be converted to 60Hz AC and pumped back to the line.

The slip power control drive that permits only sub synchronous range of speed control through convertor cascade is known as static karmer drive system.

The static karmer drive system is used in large power pumps and fan type drives system where the range os speed is limited below synchronous speed. Its is very efficient and convertor power rating is low.



Static Kramer drive system

Speed Control of Kramer Drive:

Kramer drive has the characteristic of separately excited DC motor and therefore the control strategy is similar to the phase controlled recifier DC drive.

With essential Air gap flux the torque is proportional to DC link current I_d which is controlled by inner feedback loop.If the command speed W_r^0 is increased by step , the motor accelerates at constant developed torque corresponding to $I_d^{\,0}$ limit set by the speed control loop.

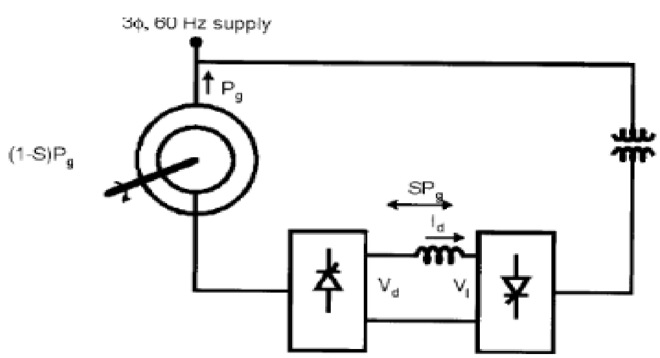
The inverter firing angle alpha initially decreases with high slope to establish I_d and gradually decreses as speed increases.

As the actual speed approached the command speed , the DC link current is reduced to balance the load torque at the certain angle in steady state I_d is restored so that the developed torque balances with the load torque , the air gap flux remains constant.

Scherbius System:

Karmer drive has only a forward motoring modes of operation.For regenerative mode of operation the rotor current should be reversed and corresponding phasorI_{rf}should be negative. This feature requires that the slip power in the rotor flow in reverse direction.If the diode rectifer on the machine side is controlled by a rectifier bridge then the slip power can be controlled to flow in either direction

With reverse power flow at subsynchronousspeed ,the power corresponding to shaft input mechanical power can be pumped out of the stator.

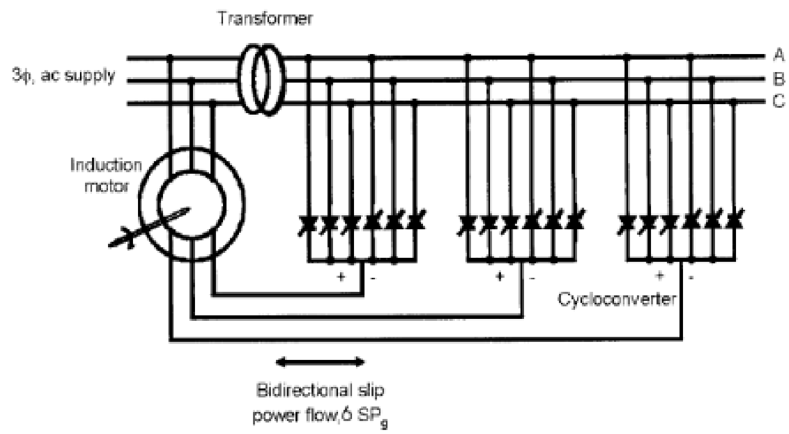


Static Scherbius drive system using dc-link thyristor converters

The system with bidrectional slip power flow can be controlled for motoring and regenerting in both the synchronous and subsynchronous speeds .This scheme is called as Scherbius drive system.The line commutation of the machine side convertor becomes difficult near synchronous speed when AC voltage is small.

The above figure can be replaced by a single phase controlled line commutated cycloconvertor as shown in below figure;

The use of cyclo convertor is complex and costly , but the resulting output is advantageous. Cyclo convertor can easily operate as phase controlled as phase

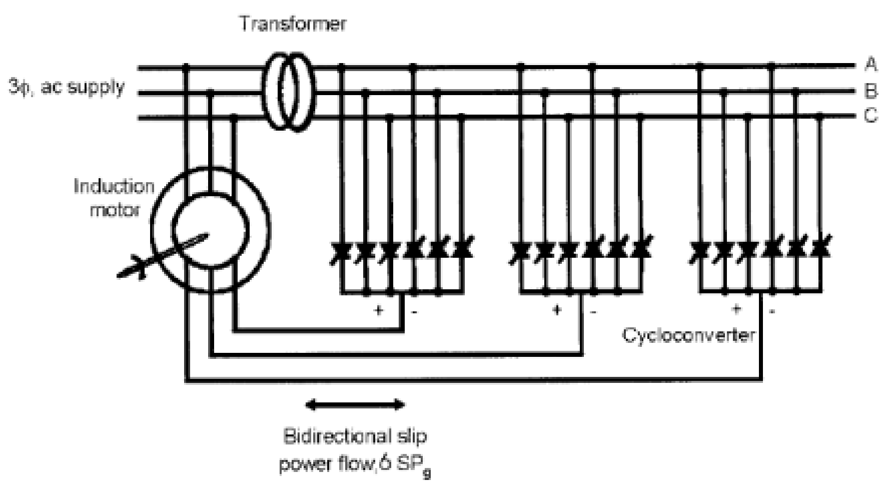


Static Scherbius drive using cycloconverter

controlled rectifier permitting DC current in the rotor .The additional advantage are , the current waves are sinusoidal ,reduces harmonic loss and the machines over excitation capability that permits leading power factor operation on the rotor side .The cycloconvertor lagging pf can be cancelled by machines leading pf so the line's pf is unity .The cycloconvertor should be controlled so that the output frequency and phase track precisely with those of rotor slip frequency voltages

This drive also requires resistive starter for starting .speed control is possible only in forward direction.

It is used in Multi MW variable speed pumps/Generators and in flywheels storage system



Static Scherbius drive using cycloconverter

the transformer used in above system is to reduce the convertor power rating.

5. Explain the different methods of speed control used in three phase induction motors.
i. Control from stator side ii. Control from the rotor side(May 2014)

Control from stator side

a) By changing applied voltage

b) By changing applied frequency

c) By changing the number of stator poles

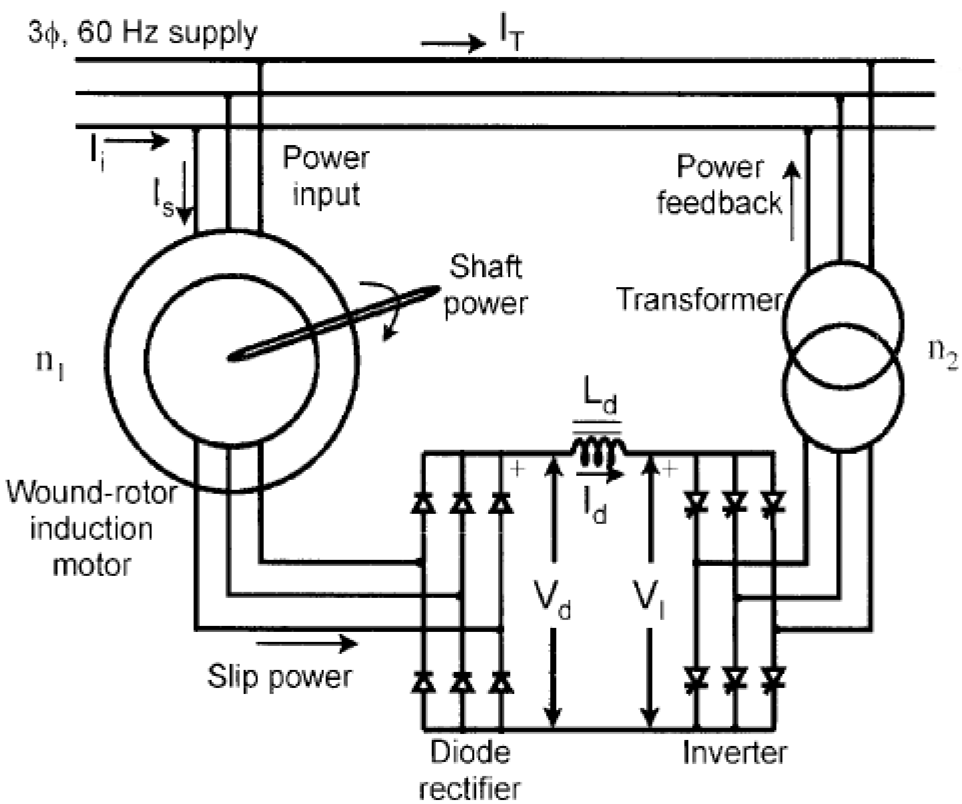
Control from the rotor side

a) Rotor rheostat control

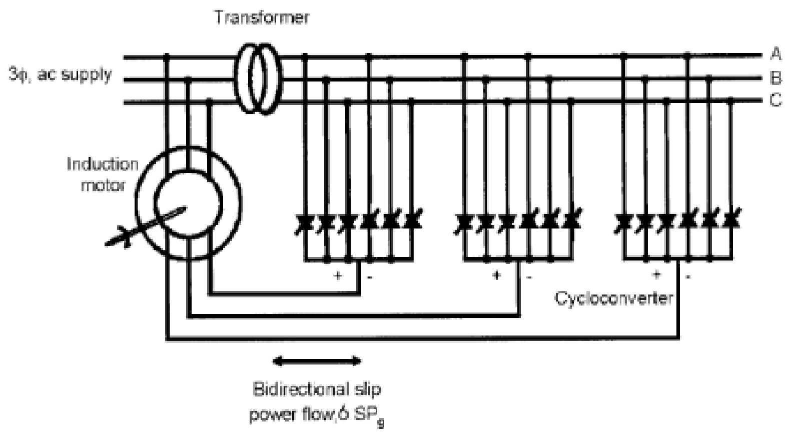
b) By operating two motors in concatenation

c) By injecting an emf. in the rotor circuit

6. Explain the working of following methods with neat circuit diagram.
i)Kramer system ii) Scherbius system (Dec 2013)(May 2013) (May 2014)



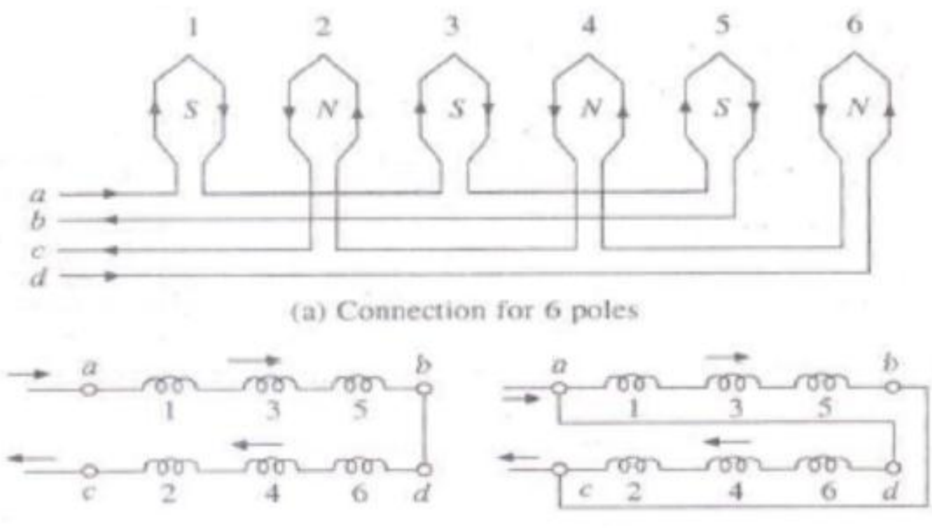
Static Kramer drive system



Static Scherbius drive using cycloconverter

7. (i) Explain the operation of Pole changing method of speed control.(May 2015)

- For a given frequency , the synchronous speed is inversly proportional to the number of poles .so that the speed of the motor can be changed by changing the number of poles.The pole changing motor or multi-speed motor helps in changing the number of poles so that the speed can be controlled.
- In squirel cage motor the number of poles are same as stator winding.so no need to change the poles for controlling the speed.But for wound rotor arrangement ,changing the poles in rotor is required.
- A simple but expensive arrangement for changing number of stator poles is to use two separate winding which are wound for two different pole numbers.An economical and common way to is to use single stator winding divided into few coil groups.By changing the connection of these coil groups changes the number of poles.Theoritically by dividing winding into number of coil groups and bringing out terminals of these group a number of arrangements of different pole number is obtained.



(a) Connection for 6 poles

(b) Series connection (c) Parallel connection

- Figure shows the phase winding with 6 coil divided into two groups a-b consisting of odd number of coils(1,3,5) connected in series and c-d consisting of even number of coils (2,4,6) connected in series.
- The coil can be made to carry currents in the given directions by connecting coil groups either in series or in parallel as shown in the figure (b) and ©
- If the current in the coil a-b is reversed , then all coils will produce north poles.Flux coming out of north poles will now find a paths through interpole spaces for going out by consequently producing south poles in the interpole spaces .The machine will now have 12 poles
- Here again the direction of the current through coils an be obtained by connecting two sections a-b and c-d either in series or parallel for both pole numbers 6 and 12.

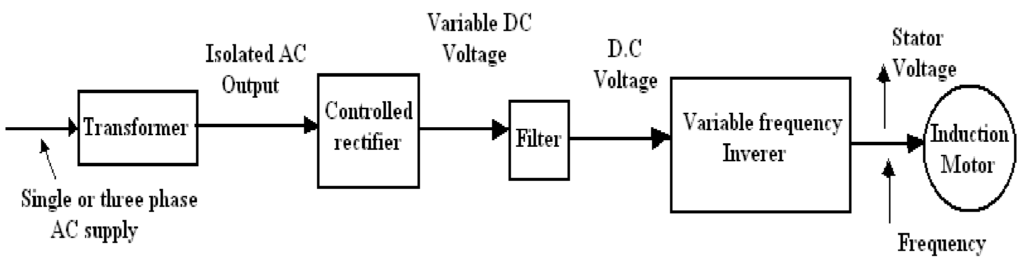
(ii) Explain the pole amplitude modulation method.

The basic principle of this method is the modulation of two sinusoidal varying mmf waves, with different number. This is called suppressed carrier modulation

If one of the two poles is suppressed then the rotating magnetic field with number of poles as P_1 and P_2 Now, if the three stator winding are placed such that the angle between phase axis is (2/3)r radians where r is an integer which is not divisible by 3 , then the phase axis angle for modulation is given by

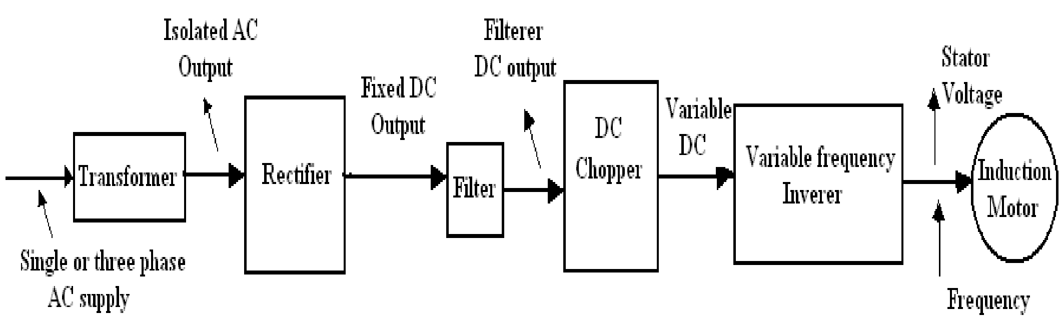
Now to suppress one of the two poles, then the angle between the phase axis should be the multiplier of 2

8. Explain in detail about the various methods of solid state speed Control techniques by using inverters.(Dec 2014)
Scheme 1



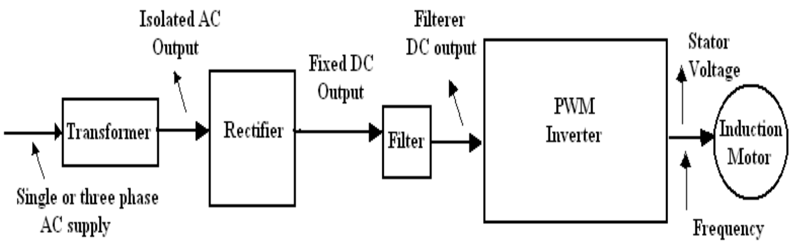
transformer is used to step-up or step down the supply voltage and also provides the isolation. Single phase or three Phase Bridge is used to provide a variable D.C. voltage. L.C filter is used to give smooth variable D.C. volt to inverter. The inverter provide, variable frequency voltage to the induction motor (I.M). This scheme is simple but gives low power factor at low speeds due to phase angle control. It is also an economical method.

Scheme -2



It uses single phase or 3ϕ bridge rectifier to provide unfiltered fixed D.C. output voltage. The filtered DC voltage is converted to a variable D.C. voltage by use of D.C. Chopper. The filtered, variable D.C. voltage is converted to variable frequency Ac voltage by voltage source inverter, the output of which varies the speed of induction motor. This method provides higher power factor at all speeds. This method is also more complicated and costlier. The abovefigure shows the block diagram of this method.

SCHEME 3



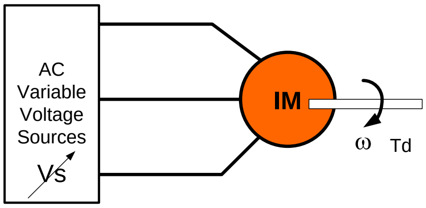
It uses a bridge rectifier, to L-C filter and provides a constant D.C. voltage to PWM Inverter. The pulse width modulation inverter various the output voltage and frequency both and provide an A.C voltage for the speed control of induction motor.This scheme is compact, reliable and costlier but provides higher power factor at all the speeds. The harmonic contents are reduces and the output voltage is also sinusoidal. Compare to other scheme, this is the best scheme.

It has the following merits:

1. Due to sinusoidal PWM, the O/P of the inverter is very close to sine wave. Low order harmonies are completely illuminated and higher order harmonics are filtered.
2. The pulsation is torque at low speed is avoided and at the same time the heating due to harmonics is reduced.
3. Filters are not necessary after the inverter
4. As bridge rectifier is used to a fixed dc voltage is given to PWM inverter, the power factor remains high at all the speeds.
5. Demerits in the PWM techniques is, as the number of pulses per half cycle are increased for PWM, the switching losses in transistor and Thyristor increases which may give low efficiency.

9. Explain the solid state stator voltage control technique for the Speed control of three phase induction motor.

Controlling Induction Motor Speed by Adjusting The Stator Voltage



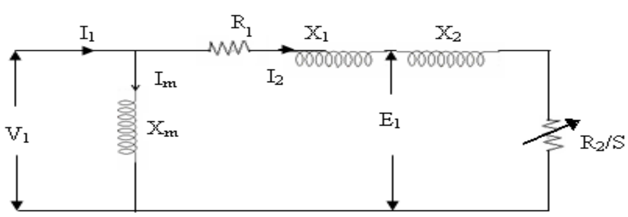
$$T_d = \frac{3R_r^{'}V_s^2}{S\,\omega_s\left[\left(R_s + \frac{R_r^{'}}{S}\right)^2 + \left(X_s + X_r^{'}\right)^2\right]}$$

Scalar control of an ac motor drive is only due to variation in the magnitude of the control variables. By contrast vector control involves the variation of both the magnitude and phase of the control variables.

Voltage can be used to control the air gap flux and frequency or slip can be used to control the torque. However, flux and torque are functions of frequency and voltage, respectively but this coupling is disregarded in scalar control.

Using the characteristics of the induction motor, we have understood that, the speed can be controlled by varying the stator voltage. This method of speed control is known as stator voltage control. Here the supply frequency is constant.

By using the simplified equivalent circuit of the induction motor shown in below figure, the stator voltage control is explained as follows.



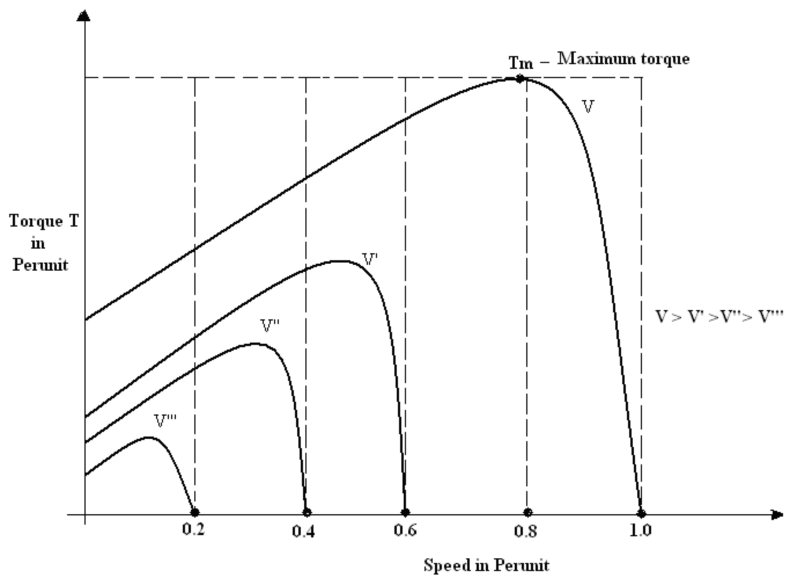
Starting torque $T_S = \frac{3p}{\omega_1}\left[\frac{V_1^{\,2}R_2}{(R_1+R_2)^2 + (X_1+X_2)^2}\right]$

Here $(R_1 + R_2) <<< (X_1 + X_2)$

Therefore the equation becomes

Starting torque $T_S \cong \frac{3P}{\omega_1}\left[\frac{V_1^{\,2}R_2}{(X_1+X_2)^2}\right]$

Thus, the starting torque is directly proportional to the square of stator voltage, rotor resistance and inversely proportional to the square of the leakage reactance. From that for the same slip and frequency, a small change in stator voltage results in a relatively large change in torque. For analyzing the control methods the speed torque characteristics of the induction motor is necessary. Figure below shows the speed torque characteristics of induction motor under stator voltage.



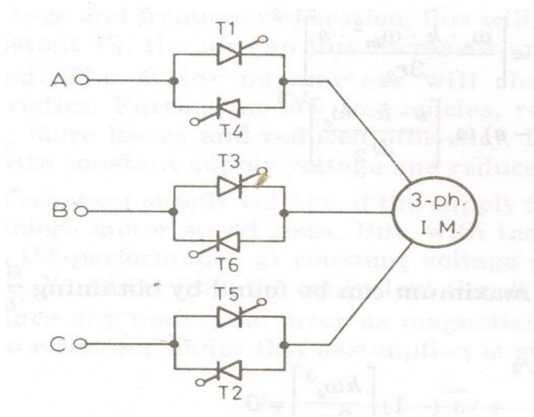
Speed Vs Torque of Induction motor under stator voltage

Here the slip at maximum torque remains unchanged

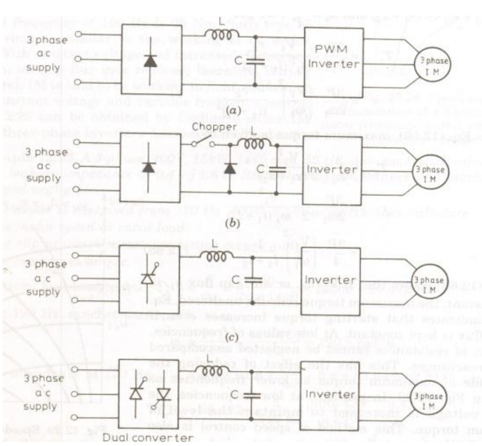
Because the slip at maximum torque

$$S_m = \pm \frac{R_2}{\left[R_1^{\,2} + (X_1 + X_2)^2\right]^{1/2}} \qquad S_m = \pm \frac{R_2}{\left[R_1^{\,2} + (X_1 + X_2)^2\right]^{1/2}}$$

Since it is not a function of voltage. For a low slip power, thus speed range is very narrow. So this method is not used for wide range of speed control and constant torque load. This is applicable for requiring low starting torque and a narrow speed range at relatively low slip.



10. Explain the constant torque mode and constant power mode of operation of voltage sourceinverter fed induction motor drive with necessary diagrams. (Dec 2013)



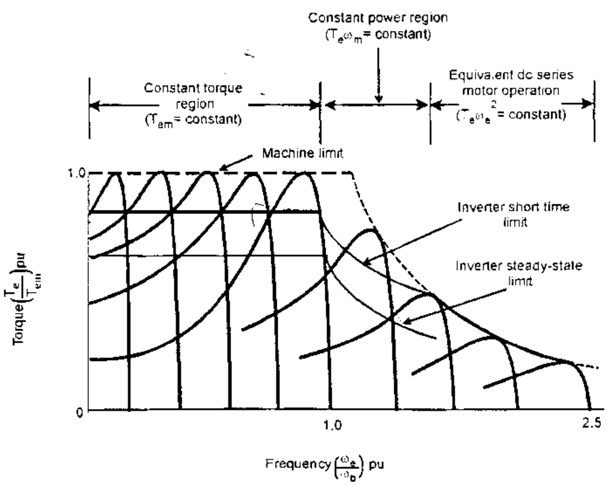
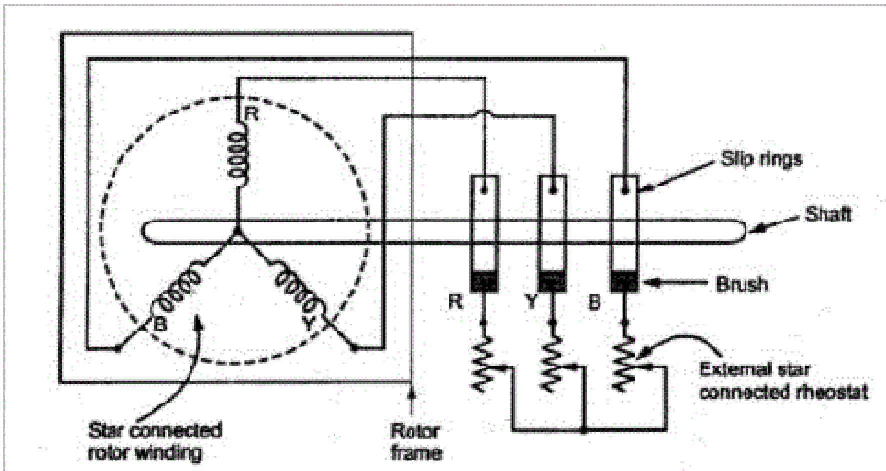


Figure 2.13 Torque-speed curves at variable voltage and variable frequency up to field-weakening region

constant torque and constant power mode of VSI should be explained.

11. Explain the rotor resistance control employed in 3Φ induction motor. (Nov 2015)



1. Adding external resistance on rotor side – In this method of speed control of three phase induction motor external resistance are added on rotor side. The equation of torque for three phase induction motor is

$$T \propto \frac{sE_2^2R_2}{R_2^2 + (sX_2)^2}$$

The three phase induction motor operates in low slip region .In low slip region term $(sX)^2$ becomes very very small as compared to R_2. So, it can be neglected .and also E_2 is constant. So the equation of torque after simplification becomes,

$$T \;\propto\; \frac{s}{R_2}$$

Now if we increase rotor resistance, R_2 torque decreases but to supply the same load torque must remains constant. So, we increase slip, which will further results in decrease in rotor speed. Thus by adding additional resistance in rotor circuit we can decrease the speed of three phase induction motor. The main advantage of this method is that with addition of external resistance starting torque increases but this method of speed control of three phase induction motor also suffers from some disadvantages :

   1. The speed above the normal value is not possible.
   2. Large speed change requires large value of resistance and if such large value of resistance is added in the circuit it will cause large copper loss and hence reduction in efficiency.
   3. Presence of resistance causes more losses.
   4. This method cannot be used for squirrel cage induction motor.

2. Cascade control method – In this method of speed control of three phase induction motor, the twothree phase induction motor are connected on common shaft and hence called cascaded motor. One motor is the called the main motor and another motor is called the auxiliary motor. The three phase supply is given to the stator of the main motor while the auxiliary motor is derived at a slip frequency from the slip ring of main motor.

   Let N_{S1} be the synchronous speed of main motor.
   N_{S2} be the synchronous speed of auxiliary motor.
   P_1 be the number of poles of the main motor.
   P_2 be the number of poles of the auxiliary motor.

F is the supply frequency.
F_1 is the frequency of rotor induced emf of main motor.
N is the speed of set and it remains same for both the main and auxiliary motor as both the motors are mounted on common shaft.
S_1 is the slip of main motor.

$$S_1 = \frac{N_{S1} - N}{N_{S1}}$$

$$F_1 = S_1 F$$

The auxiliary motor is supplied with same frequency as the main motor i.e

$$F_1 = F_2$$

$$N_{S2} = \frac{120F_2}{P_2} = \frac{120F_1}{P_2}$$

$$N_{S2} = \frac{120S_1F}{P_2}$$

Now put the value of

$$S_1 = \frac{N_{S1} - N}{N_{S1}}$$

$$We\ get,\ \ N_{S2} = \frac{120F(N_{S1} - N)}{P_2N_{S1}}$$

Now at no load , the speed of auxiliary rotor is almost same as its synchronous speed i.e $N = N_{S2}$

$$N = \frac{120F(N_{S1} - N)}{P_2N_{S1}}$$

Now rearrange the above equation and find out the value of N, we get,

$$N = \frac{120F}{P_1 - P_2}$$

This cascaded set of two motors will now run at new speed having number of poles ($P_1 + P_2$). In the above method the torque produced by the main and auxiliary motor will act in same direction, resulting in number of poles ($P_1 + P_2$). Such type of cascading is called cumulative cascading. There is one more type of cascading in which the torque produced by the main motor is in opposite direction to that of auxiliary motor. Such type of cascading is called differential cascading; resulting in speed corresponds to number of poles ($P_1 - P_2$). In this method of speed control of three phase induction motor, four different speeds can be obtained

1. When only main induction motor work, having speed corresponds to $N_{S1} = 120 F / P_1$.
2. When only auxiliary induction motor work, having speed corresponds to $N_{S2} = 120 F / P_2$.
3. When cumulative cascading is done, then the complete set runs at a speed of $N = 120F / (P_1 + P_2)$.
4. When differential cascading is done, then the complete set runs at a speed of $N = 120F / (P_1 - P_2)$.