Lecture 2

Keywords

Alternating Current motors – Двигатель переменного тока

Squirrel cage motors – Двигатель с короткозамкнутым ротором

Wound rotor motors – Двигатель с фазным ротором

Slip – скольжение

electromotive force (e.m.f.) – ЭДС

rev/min - (no periods), revolutions per minute – об/мин

air-gap – воздушный зазор

Switched Reluctance Motor – коммутируемый реактивный электродвигатель, двигатель с регулируемым магнитным сопротивлением

p.u. (per unit) - относительные единицы

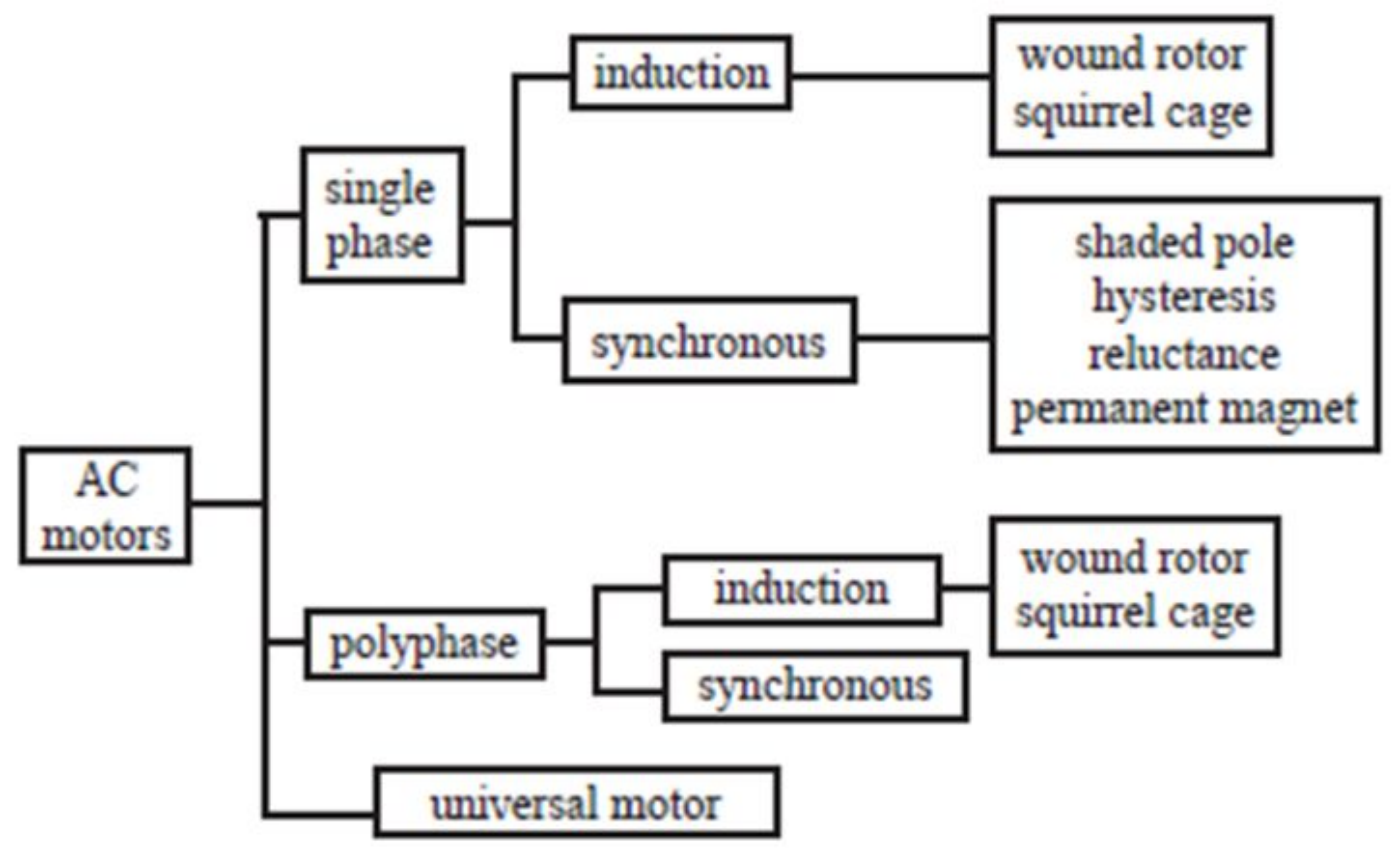
air-gap flux density - воздушный зазор плотности потока

maximum torque – критический момент

ABBREVIATIONS

BLAC - Brushless AC
BLDC - Brushless DC
BLDM - Brushless DC motor
EC - Electronic commutator
PM - Permanent magnet
IPMSM - Interior permanent magnet synchronous motor
PMSM - Permanent magnet synchronous motor
SPMSM - Surface permanent magnet synchronous motor
SCIM - Squirrel-cage induction motor
SRM - Switched reluctance motor
SyRM - Synchronous reluctance motor
VFD - Variable-frequency drive
WRIM - Wound-rotor induction motor
WRSM - Wound-rotor synchronous motor

Classification AC motor



AC motors

single phase

induction

wound rotor
squirrel cage

synchronous

shaded pole
hysteresis
reluctance
permanent magnet

polyphase

induction

wound rotor
squirrel cage

synchronous

universal motor

Electric drive with AC motors

Slip

A little thought will show that the behaviour of the rotor depends very much on its relative velocity with respect to the rotating Weld. If the rotor is stationary, for example, the rotating Weld will cut the rotor conductors at synchronous speed, thereby inducing a high electromotive force (e.m.f.) in them. On the other hand, if the rotor was running at the synchronous speed, its relative velocity with respect to the Weld would be zero, and no e.m.f.’s would be induced in the rotor conductors.

The relative velocity between the rotor and the field is known as the slip. If the speed of the rotor is N, the slip speed is $N_s - N$, where N_s is the synchronous speed of the Weld, usually expressed in rev/min (revolutions per minute). The slip (as distinct from slip speed) is the normalised quantity defined by

$$s = \frac{N_s - N}{N_s}$$

and is usually expressed either as a ratio as in equation, or as a percentage.

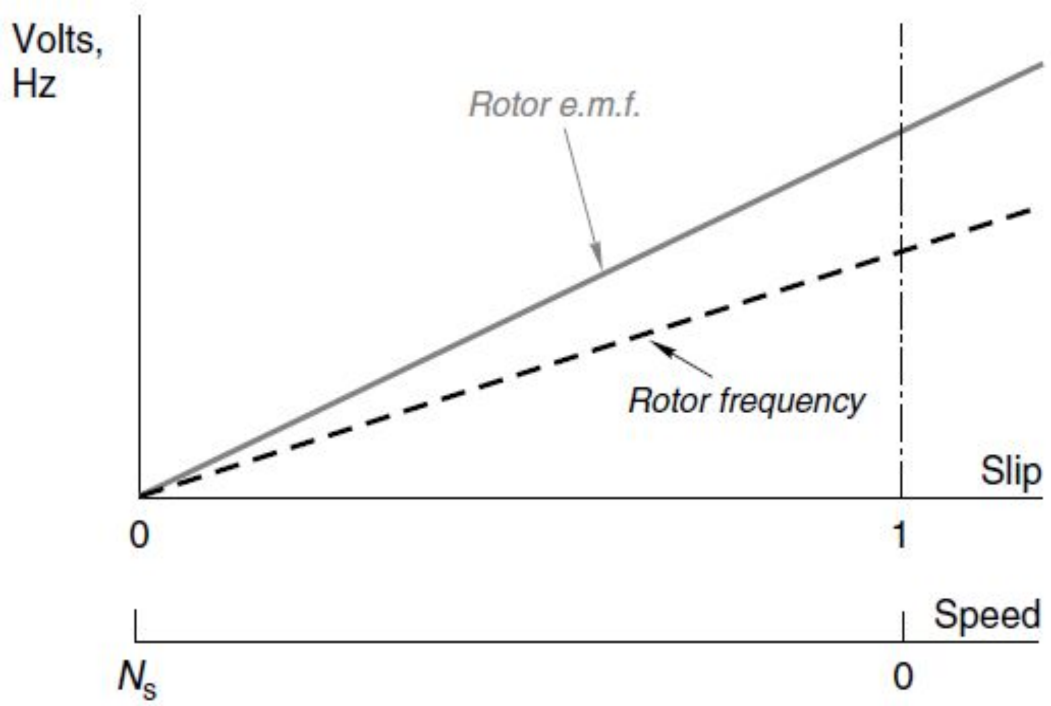
A slip of 0 therefore indicates that the rotor speed is equal to the synchronous speed, while a slip of 1 corresponds to zero speed. (When tests are performed on induction motors with their rotor deliberately held stationary so that the slip is 1, the test is said to be under ‘locked-rotor’ conditions. The same expression is often used loosely to mean zero speed, even when the rotor is free to move, e.g. when it is started from rest.)

Rotor induced e.m.f., current and torque

The rate at which the rotor conductors are cut by the flux – and hence their induced e.m.f. – is directly proportional to the slip, with no induced e.m.f. at synchronous speed ($s = 0$) and maximum induced e.m.f. when the rotor is stationary ($s = 1$).

The frequency of rotor e.m.f. is also directly proportional to slip, since the rotor effectively slides with respect to the flux wave, and the higher the relative speed, the more times in a second each rotor conductor is cut by a N and a s pole. At synchronous speed ($s_{lip} = 0$) the frequency is zero, while at standstill ($s_{lip} = 1$), the rotor frequency is equal to the supply frequency.

These relationships are shown in Figure



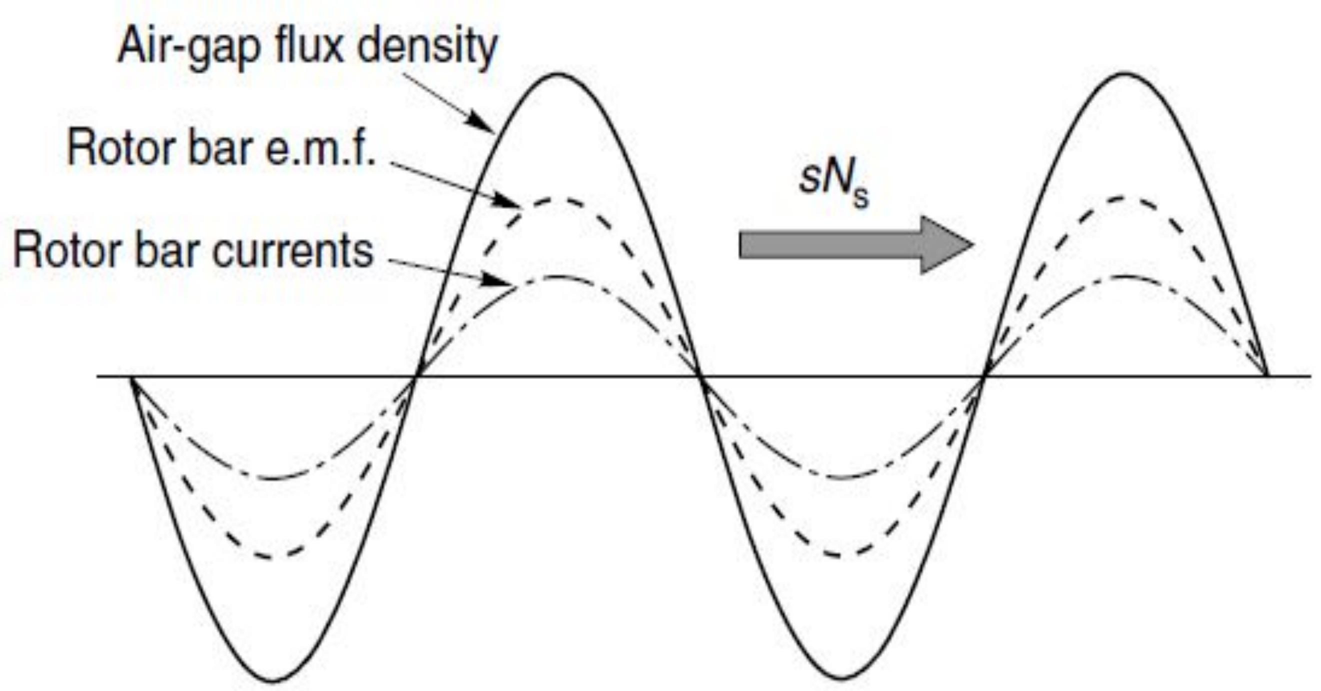
Variation of rotor induced e.m.f and frequency with speed and slip

Rotor currents and torque – small slip

When the slip is small (say between 0 and 10%), the frequency of induced e.m.f. is also very low (between 0 and 5 Hz if the supply frequency is 50 Hz). At these low frequencies the impedance of the rotor circuits is predominantly resistive, the inductive reactance being small because the rotor frequency is low.

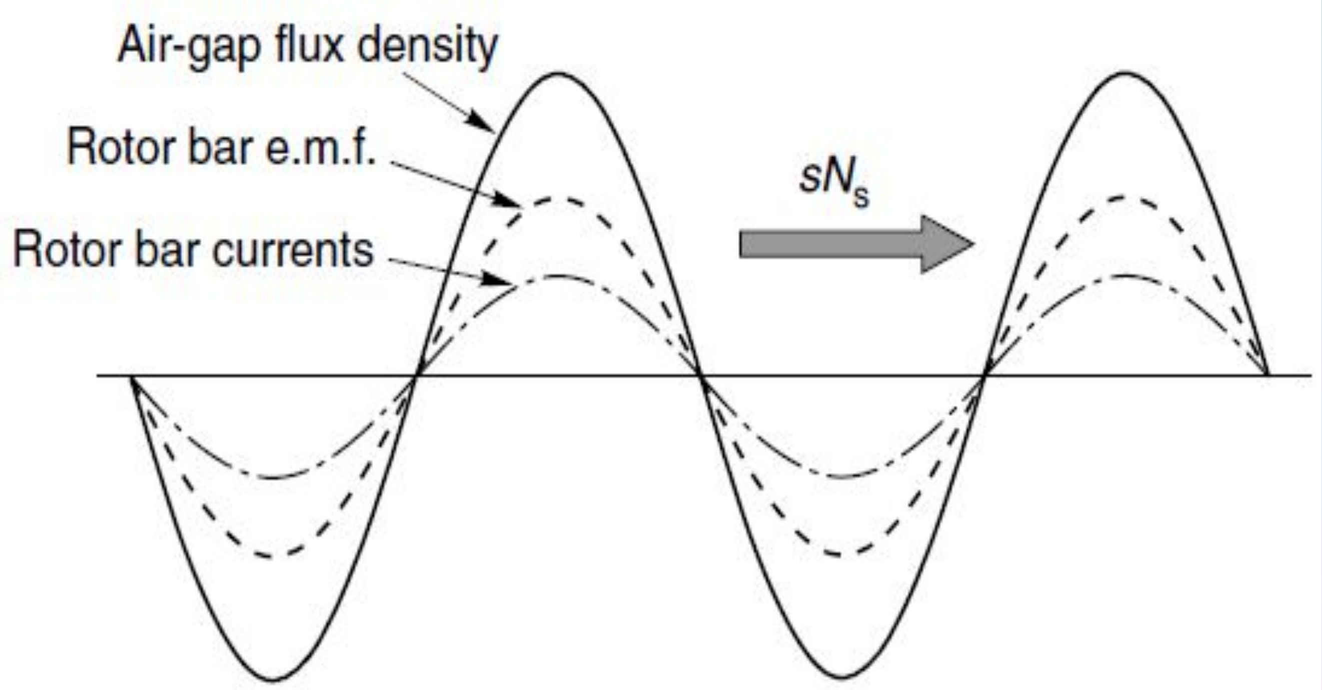
The current in each rotor conductor is therefore in time phase with the e.m.f. in that conductor, and the rotor current wave is therefore in space phase with the rotor e.m.f. wave, which in turn is in space phase with the flux wave.

This situation was assumed in the previous discussion, and is represented by the space waveforms shown in Figure



Pattern of air-gap flux density, induced e.m.f. and current in cage rotor bars at low values of slip

To calculate the torque we W_{nst} need to evaluate the ‘BIlr’ product to obtain the tangential force on each rotor conductor. The torque is then given by the total force multiplied by the rotor radius. We can see from Figure that where the flux density has a positive peak, so does the rotor current, so that particular bar will contribute a high tangential force to the total torque. Similarly, where the flux has its maximum negative peak, the induced current is maximum and negative, so the tangential force is again positive.



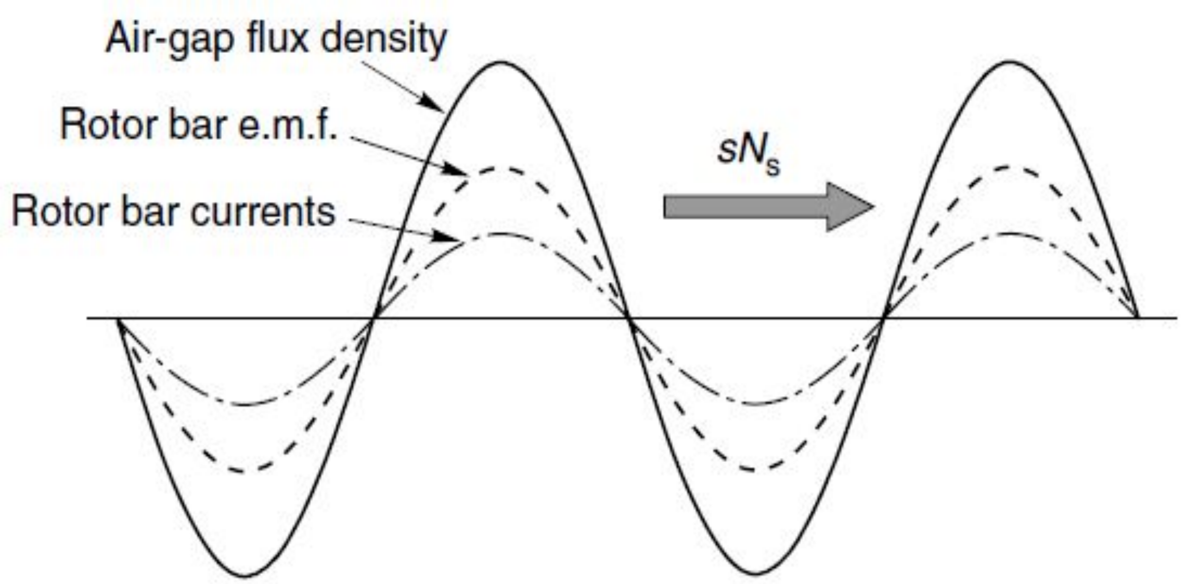
We don’t need to work out the torque in detail, but it should be clear that the resultant will be given by an equation of the form

$$T = k \cdot B \cdot I_r$$

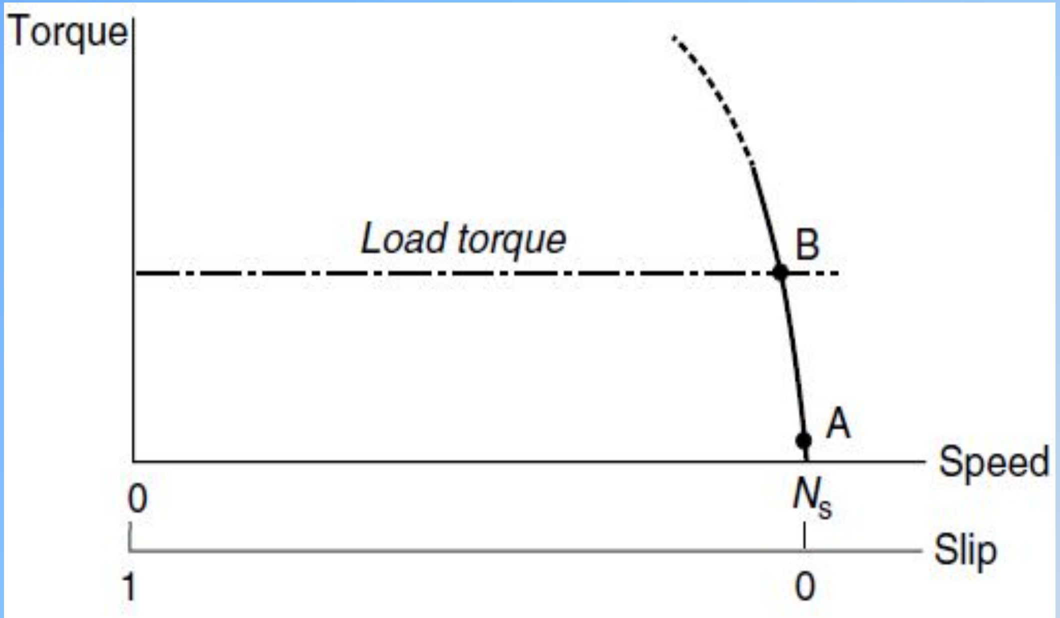
where B and I_r denote the amplitudes of the flux density wave and the rotor current wave, respectively.

Provided that there are a large number of rotor bars (which is a safe bet in practice), the waves shown in Figure will remain the same at all instants of time, so the torque remains constant as the rotor rotates.

If the supply voltage and frequency are constant, the flux will be constant. The rotor e.m.f. (and hence) is then proportional to slip, so we can see from equation that the torque is directly proportional to slip. We must remember that this discussion relates to low values of slip only, but since this is the normal running condition, it is extremely important.



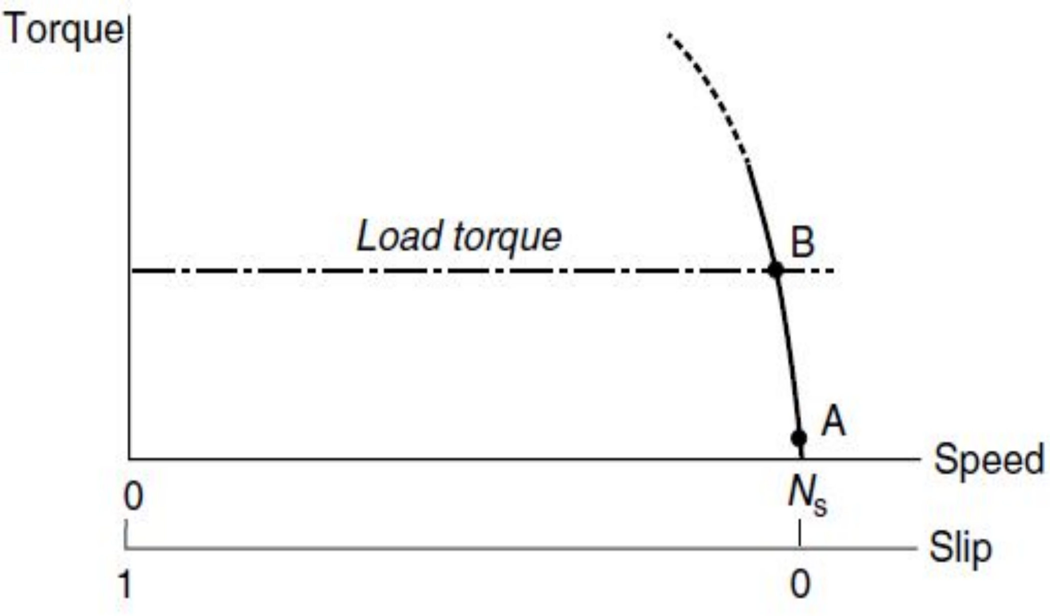
The torque–speed (and torque/slip) relationship for small slips is thus approximately a straight-line, as shown by the section of line AB in Figure



Torque–speed relationship for low values of slip

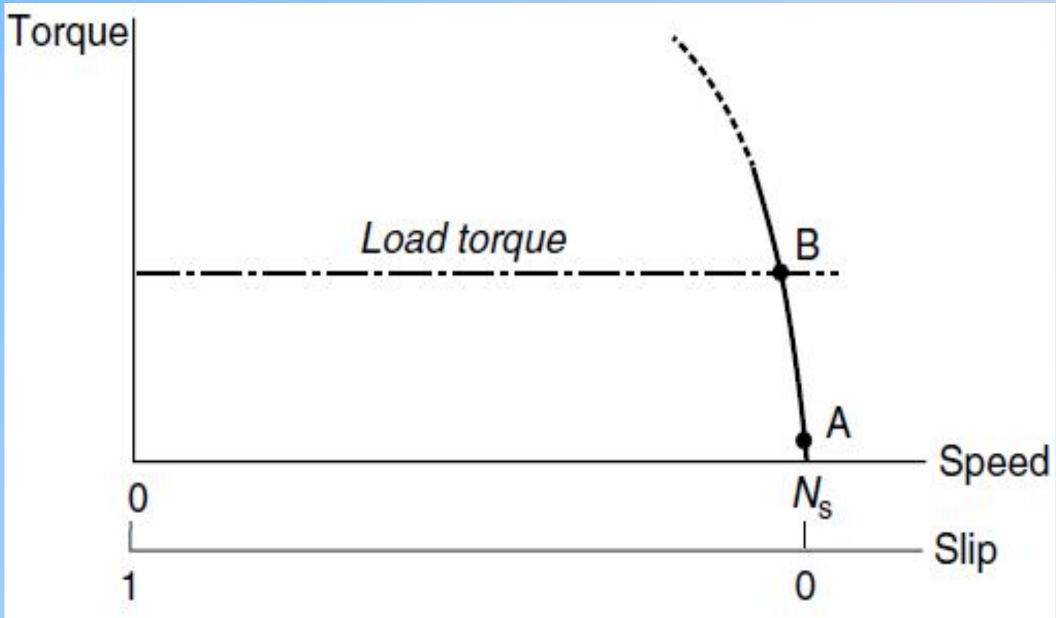
If the motor is unloaded, it will need very little torque to keep running – only enough to overcome friction in fact – so an unloaded motor will run with a very small slip at just below the synchronous speed, as shown at A in Figure.

When the load is increased, the rotor slows down, and the slip increases, thereby inducing more rotor e.m.f. and current, and thus more torque. The speed will settle when the slip has increased to the point where the developed torque equals the load torque – for example point B in Figure

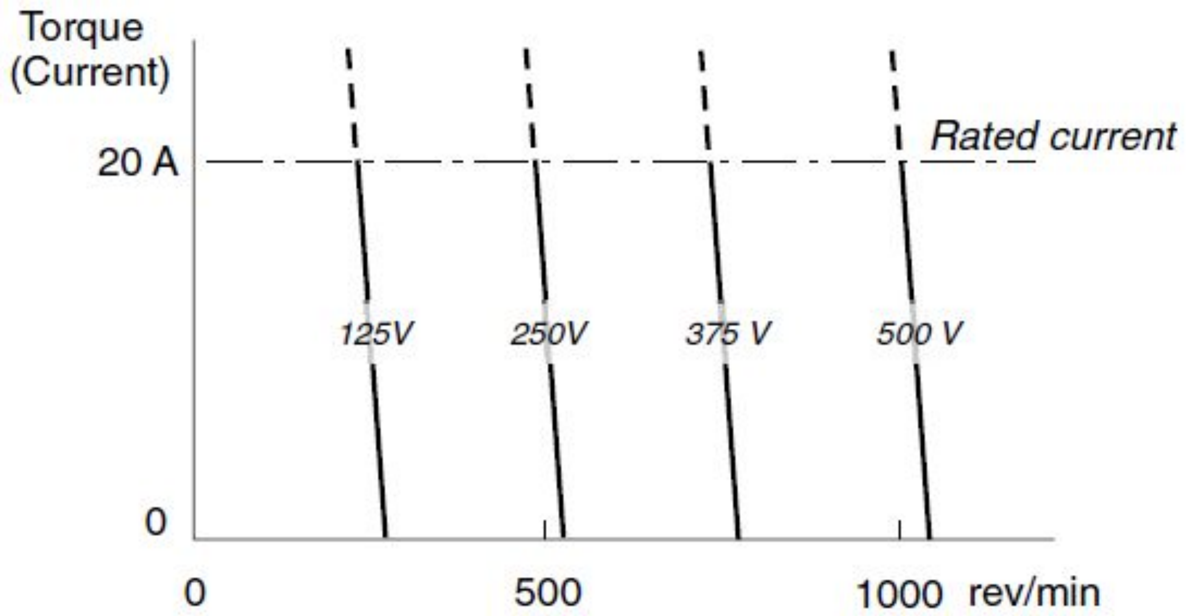


Induction motors are usually designed so that their full-load torque is developed for small values of slip. Small ones typically have a full-load slip of 8%, large ones around 1%. At the full-load slip, the rotor conductors will be carrying their safe maximum continuous current, and if the slip is any higher, the rotor will begin to overheat. This overload region is shown by the dotted line in Figure.

The torque–slip (or torque–speed) characteristic shown in Figure is a good one for most applications, because the speed only falls a little when the load is raised from zero to its full value.



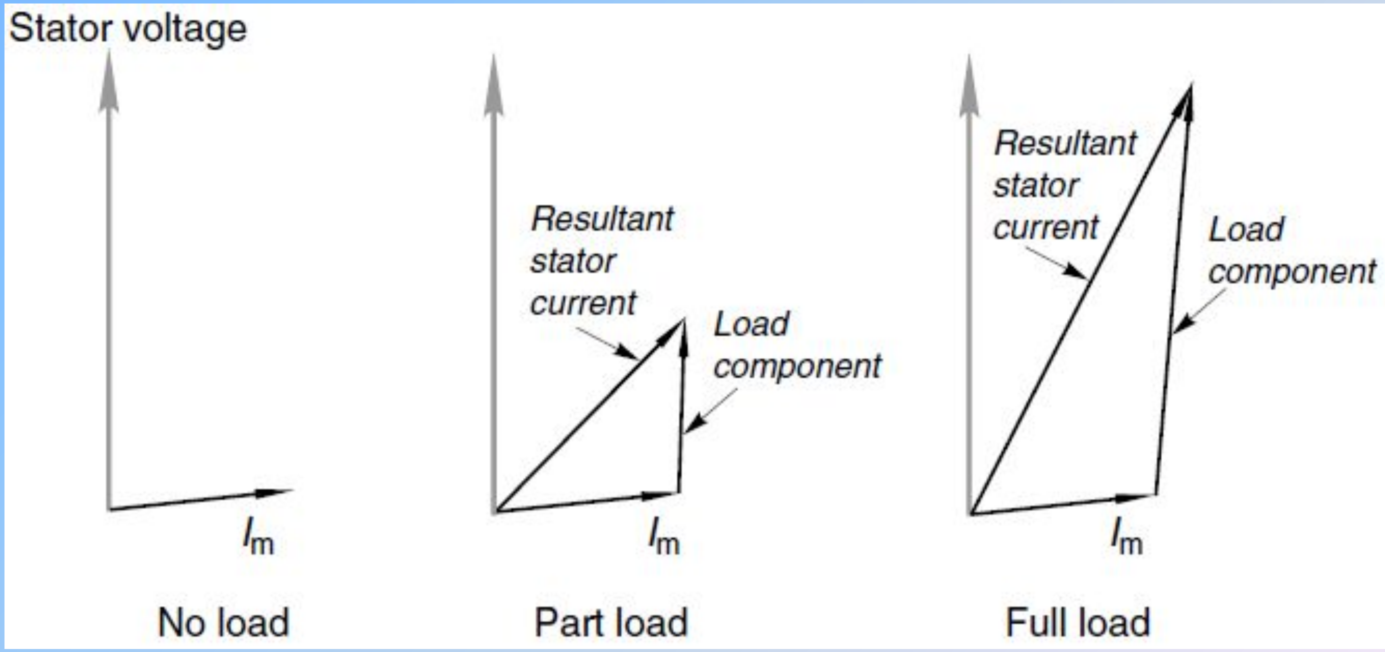
We note that, in this normal operating region, the torque–speed curve is very similar to that of a d.c. motor (Figure), which explains why both d.c. and induction motors are often in contention for constant-speed applications.



Family of steady-state torque–speed curves for a range of armature voltages

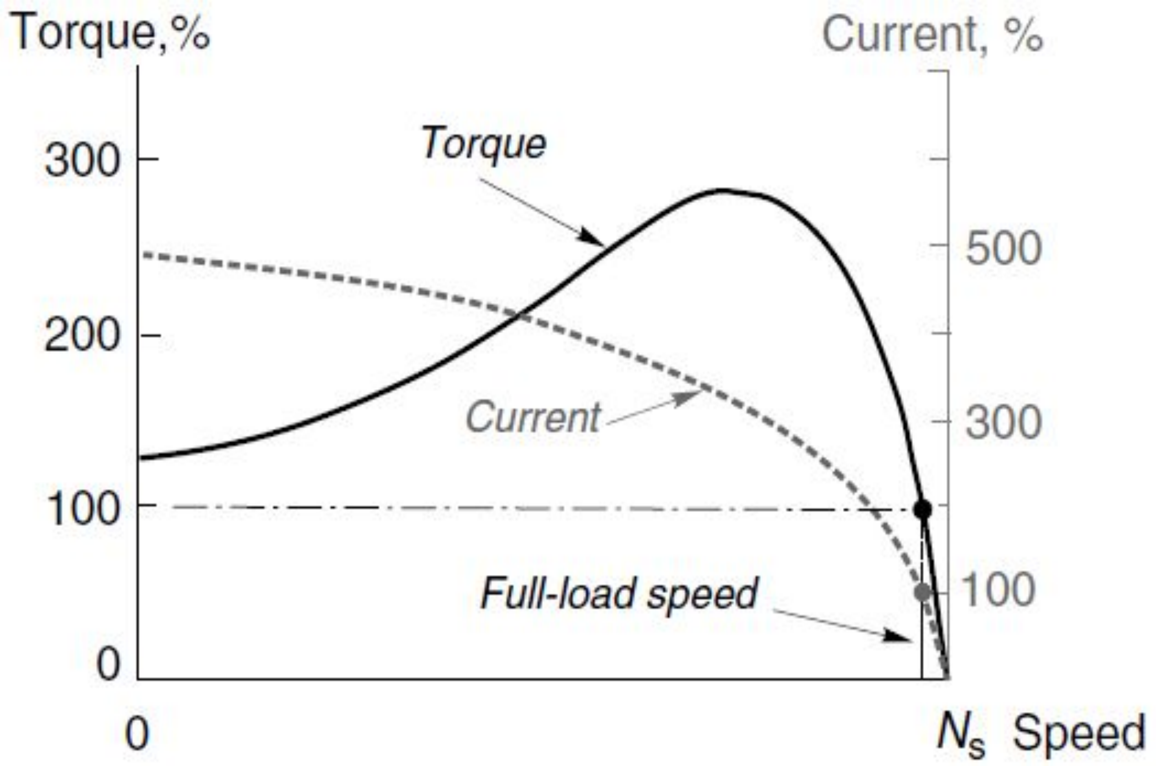
Stator current-speed characteristics

In the previous section, we argued that as the slip increased, and the rotor did more mechanical work, the stator current increased. Since the extra current is associated with the supply of real (i.e. mechanical output) power (as distinct from the original magnetising current which was seen to be reactive), this additional 'work' component of current is more or less in phase with the supply voltage, as shown in the phasor diagrams (Figure).



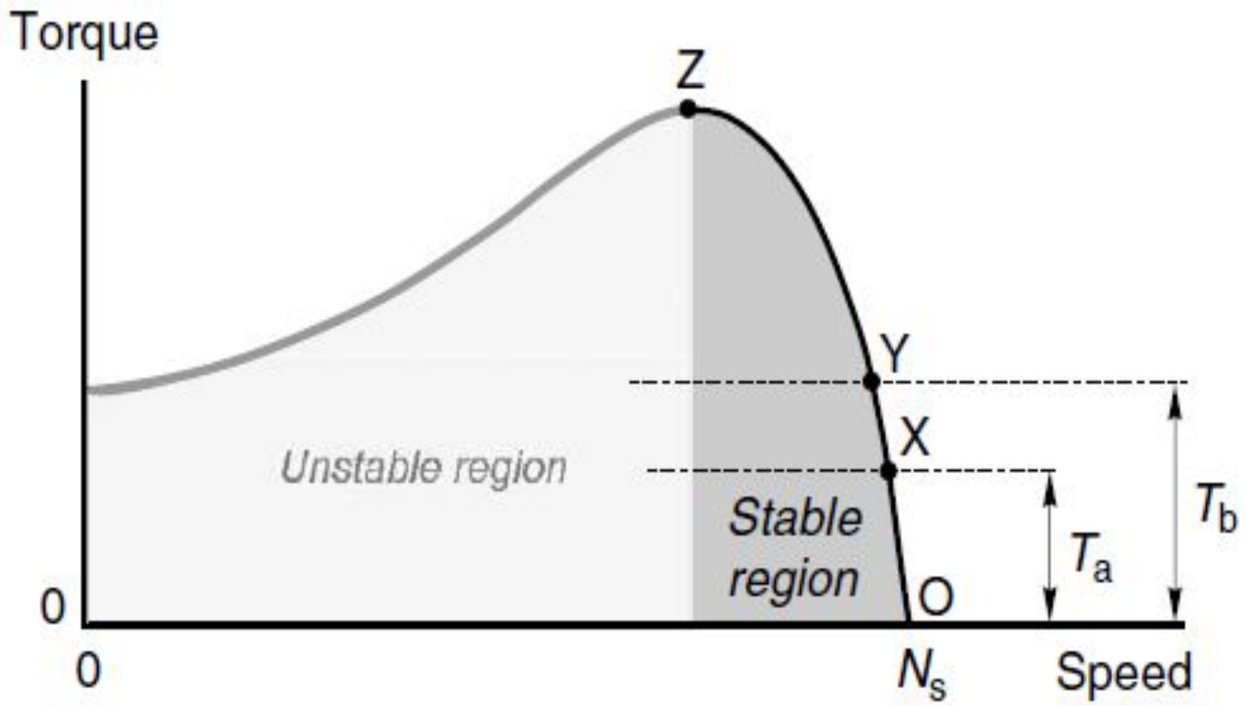
The resultant stator current is the sum of the magnetising current, which is present all the time, and the load component, which increases with the slip. We can see that as the load increases, the resultant stator current also increases, and moves more nearly into phase with the voltage. But because the magnetising current is appreciable, the difference in magnitude between no-load and full-load currents may not be all that great. (This is in sharp contrast to the d.c. motor, where the no-load current in the armature is very small in comparison with the fullload current. Note, however, that in the d.c. motor, the excitation (flux) is provided by a separate field circuit, whereas in the induction motor the stator winding furnishes both the excitation and the work currents. If we consider the behaviour of the work components of current only, both types of machine look very similar.)

Very high starting currents are one of the worst features of the cage induction motor. They not only cause unwelcome volt drops in the supply system, but also call for heavier switchgear than would be needed to cope with full-load conditions. Unfortunately, for reasons discussed earlier, the high starting currents are not accompanied by high starting torques, as we can see from Figure, which shows current and torque as functions of slip for a general-purpose cage motor.



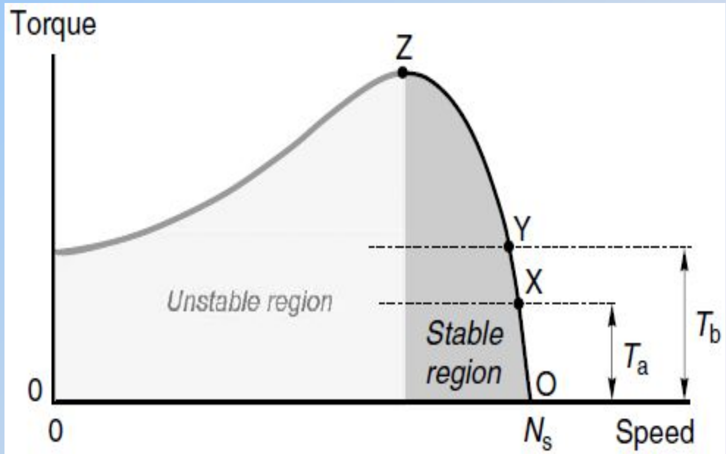
The torque and current axes are scaled so that 100% represents the continuously rated (full-load) value Steady-state stability – pullout torque and stalling.

We can check stability by asking what happens if the load torque suddenly changes for some reason. The load torque shown by the dotted line in Figure is stable at speed *X*, for example: if the load torque increased from T_a to T_b, the load torque would be greater than the motor torque, so the motor torque would decelerate.



As the speed dropped, the motor torque would rise, until a new equilibrium was reached, at the slightly lower speed (*Y*). The converse would happen if the load torque were reduced, leading to a higher stable running speed.

But what happens if the load torque is increased more and more? We can see that as the load torque increases, beginning at point *X*, we eventually reach point *Z*, at which the motor develops its maximum torque. Quite apart from the fact that the motor is now well into its overload region, and will be in danger of overheating, it has also reached the limit of stable operation. If the load torque is further increased, the speed falls (because the load torque is more than the motor torque), and as it does so the shortfall between motor torque and load torque becomes greater and greater.



The speed therefore falls faster and faster, and the motor is said to be ‘stalling’. With loads such as machine tools (a drilling machine, for example), as soon as the maximum or ‘pullout’ torque is exceeded, the motor rapidly comes to a halt, making an angry humming sound. With a hoist, however, the excess load would cause the rotor to be accelerated in the reverse direction, unless it was prevented from doing so by a mechanical brake.

Torque–speed curves – influence of rotor parameters

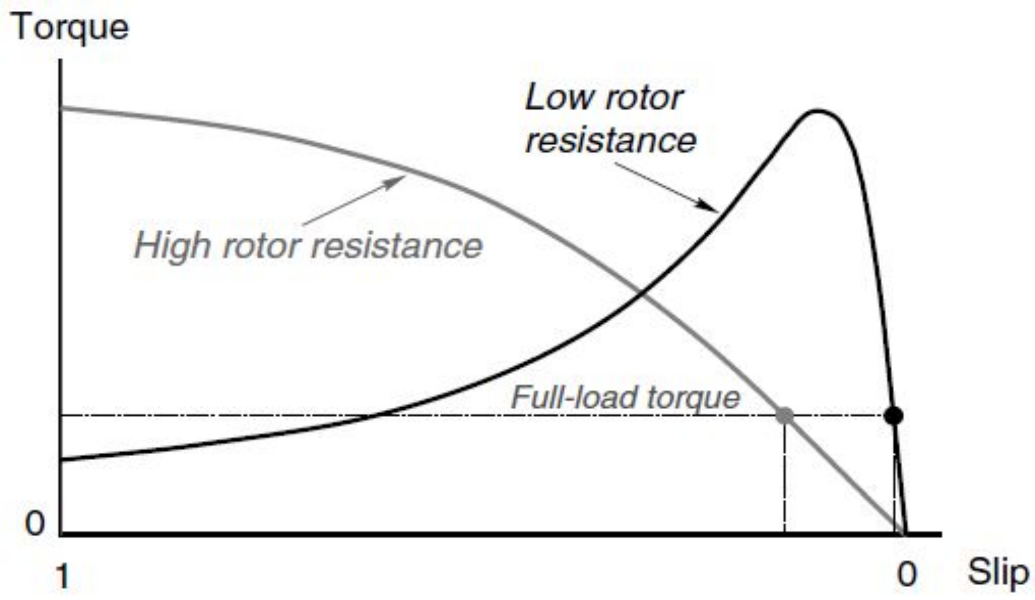
We saw earlier that the rotor resistance and reactance influenced the shape of the torque–speed curve. The designer can vary both of these parameters, and we will explore the pros and cons of the various alternatives. To limit the mathematics the discussion will be mainly qualitative, but it is worth mentioning that the whole matter can be dealt rigorously using the equivalent circuit approach.

We will deal with the cage rotor first because it is the most important, but the wound rotor allows a wider variation of resistance to be obtained, so it is discussed later.

Types of AC drives

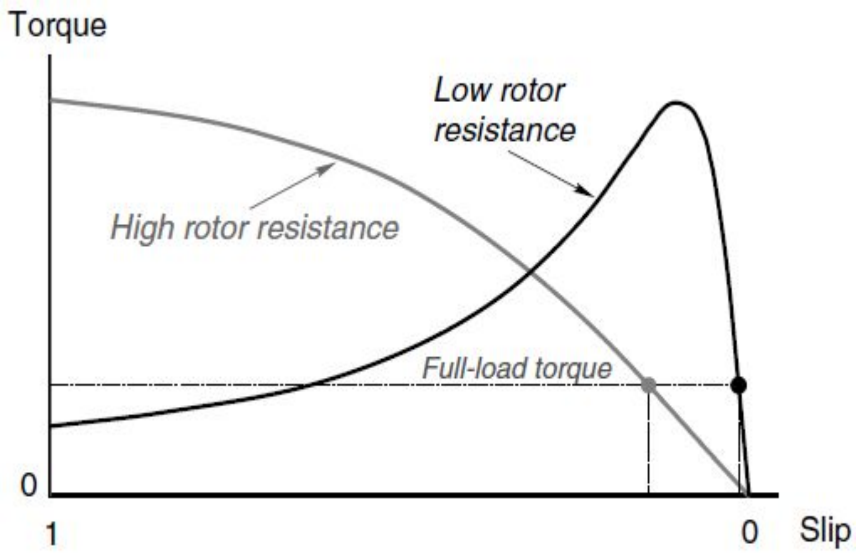
Cage rotor

For small values of slip, i.e. in the normal running region, the lower we make the rotor resistance the steeper the slope of the torque–speed curve becomes, as shown in Figure. We can see that at the rated torque (shown by the horizontal dotted line in Figure) the full-load slip of the low-resistance cage is much lower than that of the high-resistance cage. But we saw earlier that the rotor efficiency is equal to ( ), $1 - s$ where s is the slip.

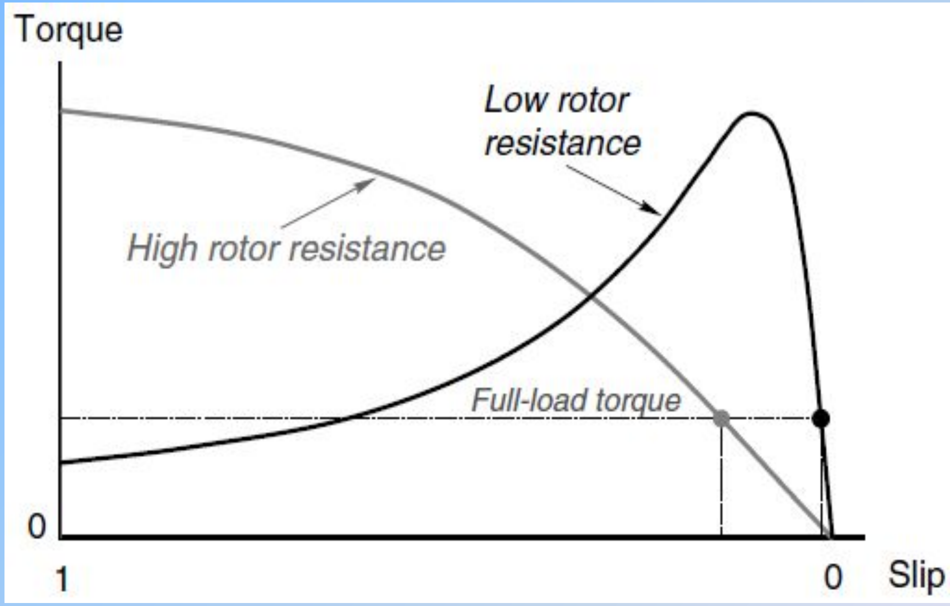


So, we conclude that the low-resistance rotor not only gives better speed holding, but is also much more efficient. There is of course a limit to how low we can make the resistance: copper allows us to achieve a lower resistance than aluminium, but we can't do anything better than fill the slots with solid copper bars.

As we might expect there are drawbacks with a low-resistance rotor. The starting torque is reduced (Figure), and worse still the starting current is increased. The lower starting torque may prove insufficient to accelerate the load, while increased starting current may lead to unacceptable volt drops in the supply.



Altering the rotor resistance has little or no effect on the value of the peak (pullout) torque, but the slip at which the peak torque occurs is directly proportional to the rotor resistance. By opting for a high enough resistance (by making the cage from bronze, brass or other relatively high resistivity material) we can if we wish to arrange for the peak torque to occur at or close to starting, as shown in Figure. The snag in doing this is that the full-load efficiency is inevitably low because the full-load slip will be high (Figure).

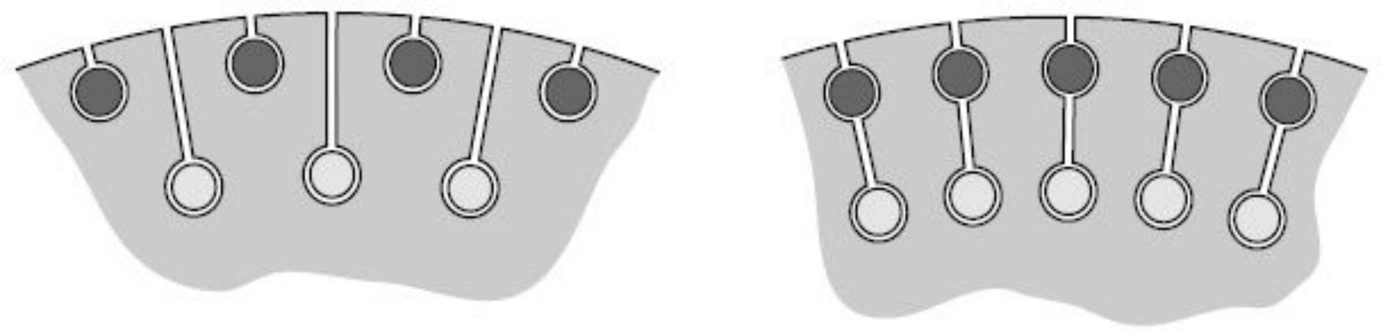


There are some applications for which high-resistance motors are well suited, an example being for metal punching presses, where the motor accelerates a flywheel, which is used to store energy. To release a significant amount of energy, the flywheel slows down appreciably during impact, and the motor then has to accelerate it back up to full speed. The motor needs a high torque over a comparatively wide speed range, and does most of its work during acceleration. Once up to speed the motor is effectively running light, so its low efficiency is of little consequence. High-resistance motors are also used for speed control of fan-type loads, where speed control is explored.

To sum up, a high-rotor resistance is desirable when starting and at low speeds, while a low resistance is preferred under normal running conditions. To get the best of both worlds, we need to be able to alter the resistance from a high value at starting to a lower value at full speed. Obviously we cannot change the actual resistance of the cage once it has been manufactured, but it is possible to achieve the desired effect with either a ‘double cage’ or a ‘deep bar’ rotor. Manufacturers normally offer a range of designs, which reflect these trade-offs, and the user then selects the one which best meets his particular requirements.

Double cage rotors

Double cage rotors have an outer cage made up of relatively high resistivity material such as bronze, and an inner cage of low resistivity, usually copper, as shown in Figure



Alternative arrangements of double cage rotors

The outer cage has a high resistance (e.g. bronze) while the inner cage has a low resistance (e.g. copper).

The inner cage is sunk deep into the rotor, so that it is almost completely surrounded by iron. This causes the inner bars to have a much higher leakage inductance than if they were near the rotor surface, so that under starting conditions (when the induced rotor frequency is high) their inductive reactance is very high and little current flows in them. In contrast, the bars of the outer cage are placed so that their leakage fluxes face a much higher reluctance path, leading to a low-leakage inductance. Hence, under starting conditions, rotor current is concentrated in the outer cage, which, because of its high resistance, produces a high starting torque.

At the normal running speed the roles are reversed. The rotor frequency is low, so both cages have low reactance and most of the current therefore flows in the low-resistance inner cage. The torque–speed curve is therefore steep, and the efficiency is high.

Considerable variation in detailed design is possible to shape the torque–speed curve to particular requirements. In comparison with a single-cage rotor, the double cage gives much higher starting torque, substantially less starting current, and marginally worse running performance.

Wound Rotor Motors

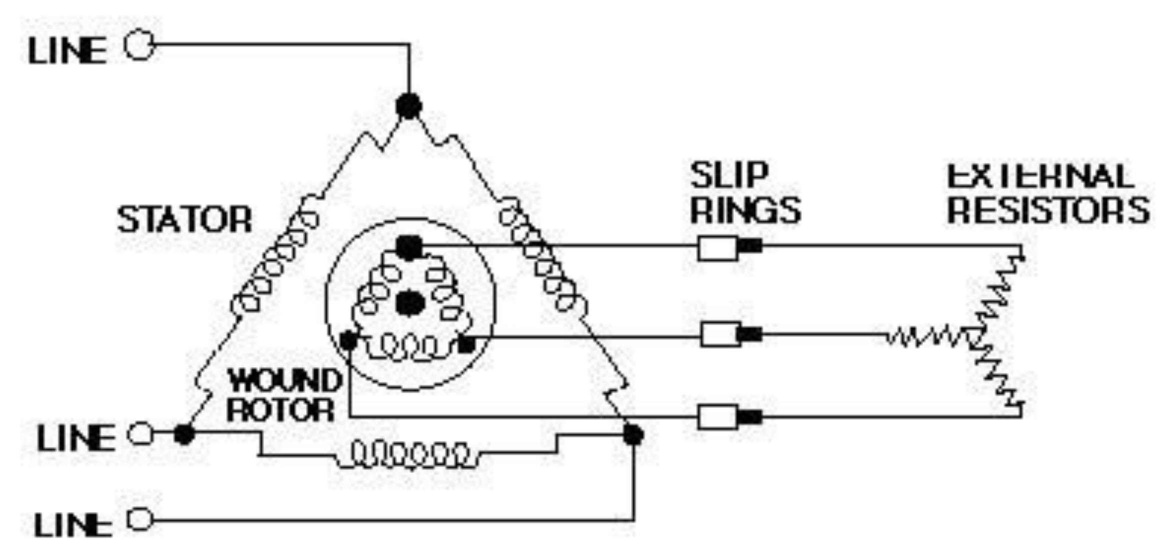
Older motor designed to operate at “variable speed”

- Advantages

– Speed Control, High Starting Torque, Low Starting Current

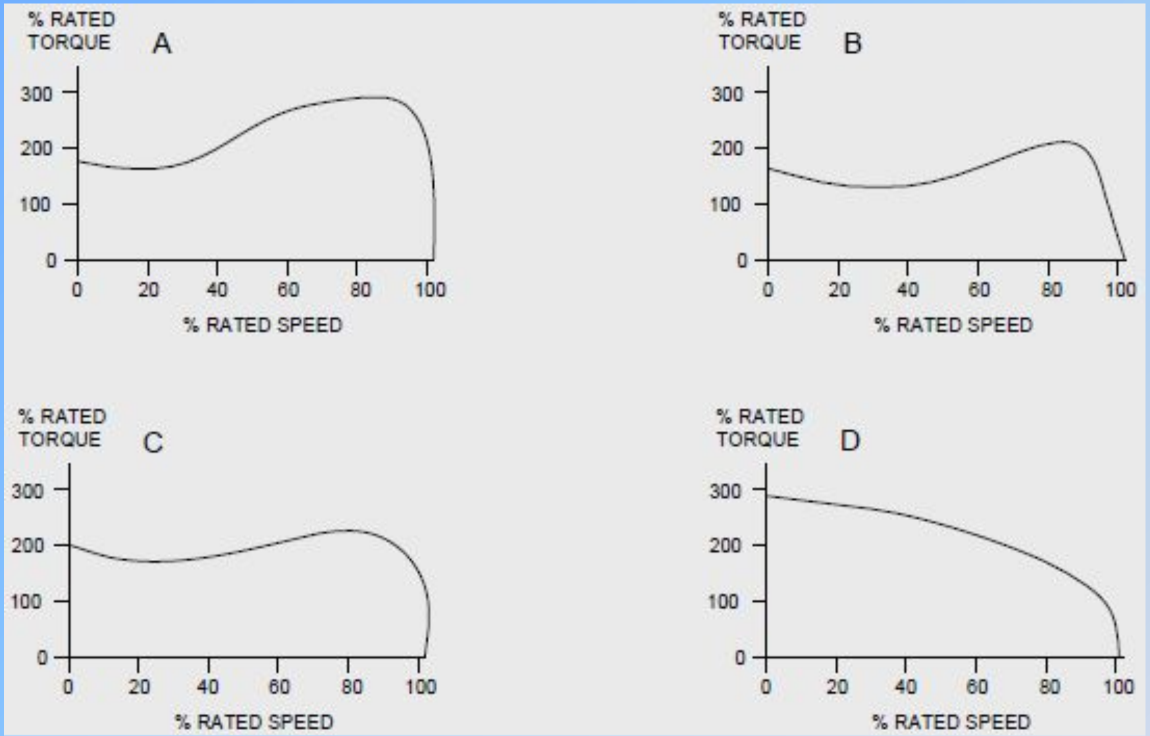
- Disadvantages

– Expensive, High Maintenance, Low Efficiency



Switched Reluctance Motor (SRM)

The advantage of a switched reluctance motor is high torque at low speed, plus a very high speed range (Figure).



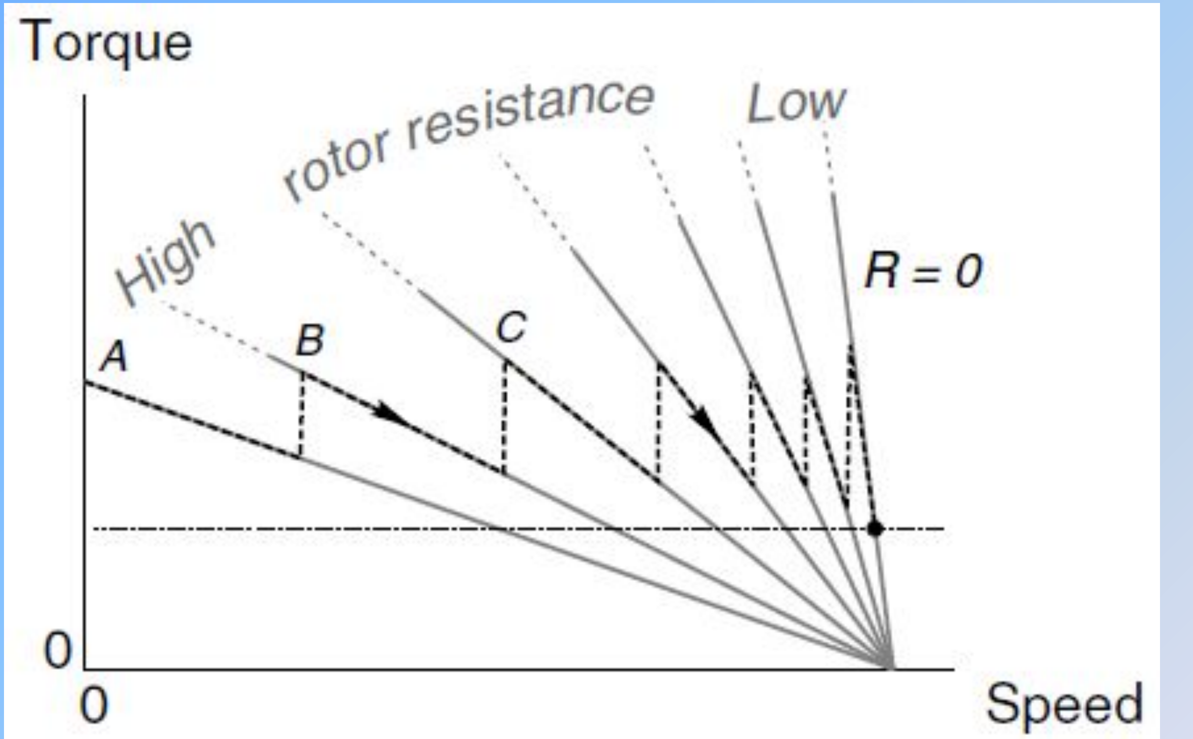
As with the ECM, electronics provide precisely timed voltages to the coils and use rotation position sensors for timing.

Switched Reluctance motors are used for several hundred thousand premium washing machines per year.

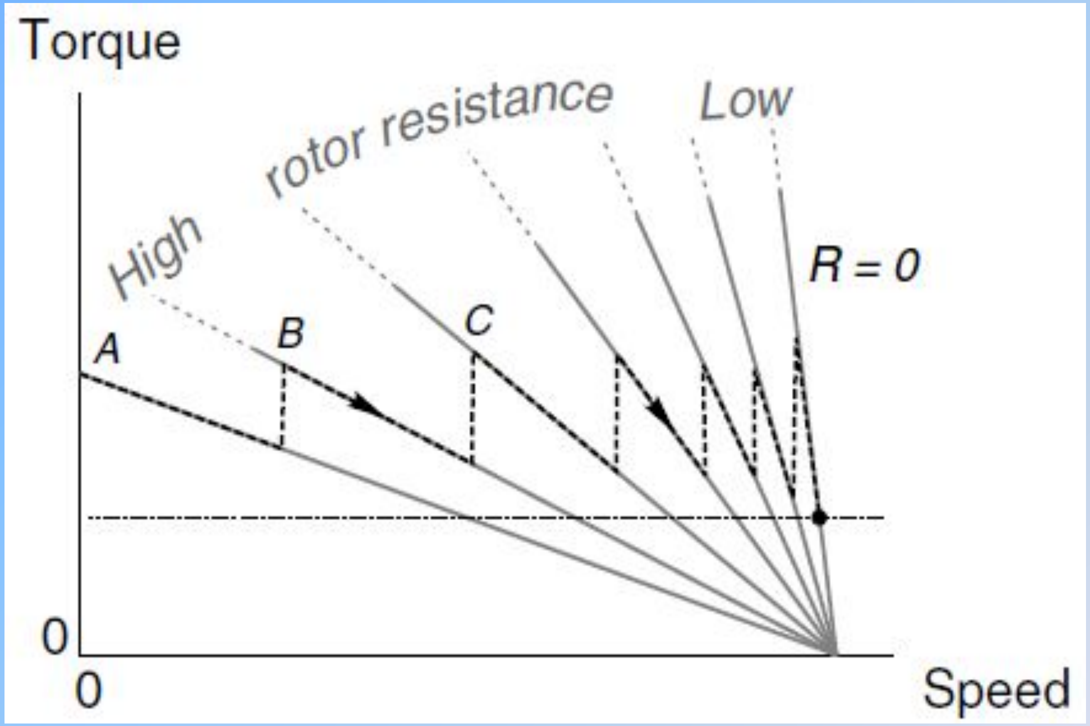
Starting and run-up of slipring motors

By adding external resistance in series with the rotor windings the starting current can be kept low but at the same time the starting torque is high. This is the major advantage of the wound-rotor or slipring motor, and makes it well suited for loads with heavy starting duties such as stone-crushers, cranes and conveyor drives.

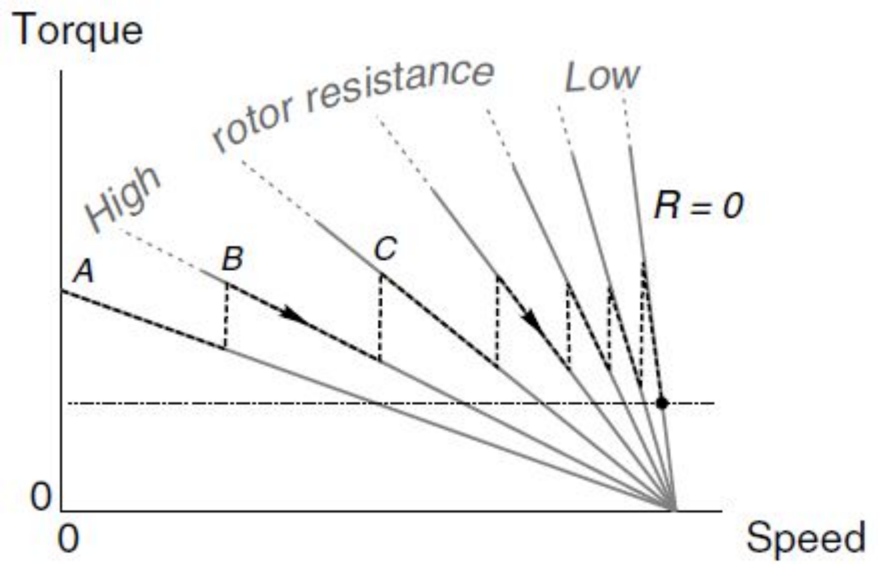
The influence of rotor resistance is shown by the set of torque–speed curves in Figure. The curve on the right corresponds to no added rotor resistance, with the other six curves showing the influence of progressively increasing the external resistance.



A high-rotor resistance is used when the motor is first switched on, and depending on the value chosen any torque up to the pullout value (perhaps twice full load) can be obtained. Typically, the resistance will be selected to give full-load torque at starting, together with rated current from the mains. The starting torque is then as indicated by point A in Figure



As the speed rises, the torque would fall more or less linearly if the resistance remained constant, so to keep close to full-load torque the resistance is gradually reduced, either in steps, in which case the trajectory ABC etc. is followed (Figure), or continuously so that maximum torque is obtained throughout. timately the external resistance is made zero by shorting-out the sliprings, and thereafter the motor behaves like a low-resistance cage motor, with a high running efficiency.



As mentioned earlier, the total energy dissipated in the rotor circuit during run-up is equal to the final stored kinetic energy of the motor and load. In a cage motor this energy ends up in the rotor, and can cause overheating. In the slipring motor, however, most of the energy goes into the external resistance. This is a good thing from the motor point of view, but means that the external resistance has to absorb the thermal energy without overheating.

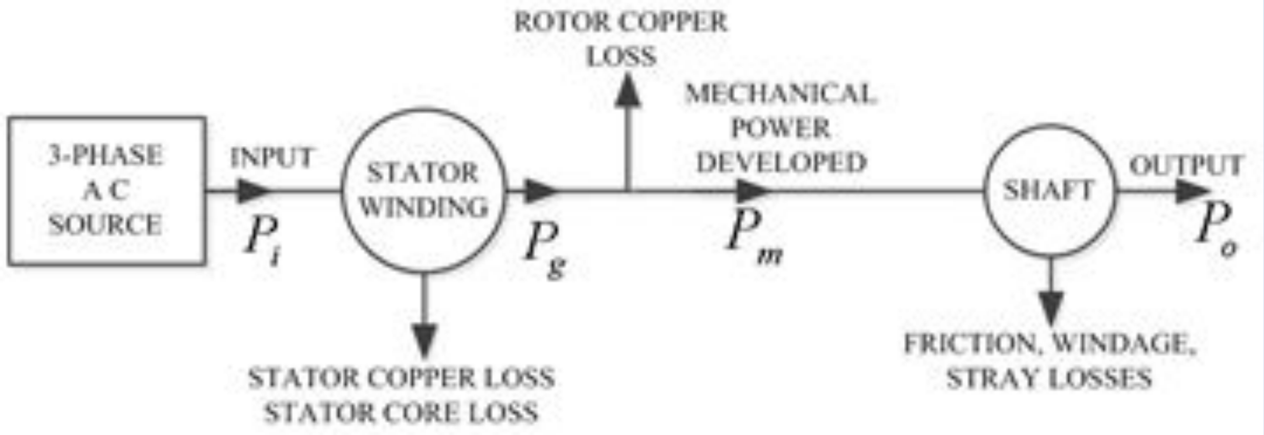
Fan-cooled grid resistors are often used, with tappings at various resistance values. These are progressively shorted-out during run-up, either by a manual or motor-driven drum-type controller, or with a series of timed contactors. Alternatively, where stepless variation of resistance is required, a liquid resistance controller is often employed. It consists of a tank of electrolyte (typically caustic soda) into which three electrodes can be raised or lowered.

The resistance between the electrodes depends on how far they are immersed in the liquid. The electrolyte acts as an excellent short-term reservoir for the heat released, and by arranging for convection to take place via a cooling radiator, the equipment can also be used continuously for speed control.

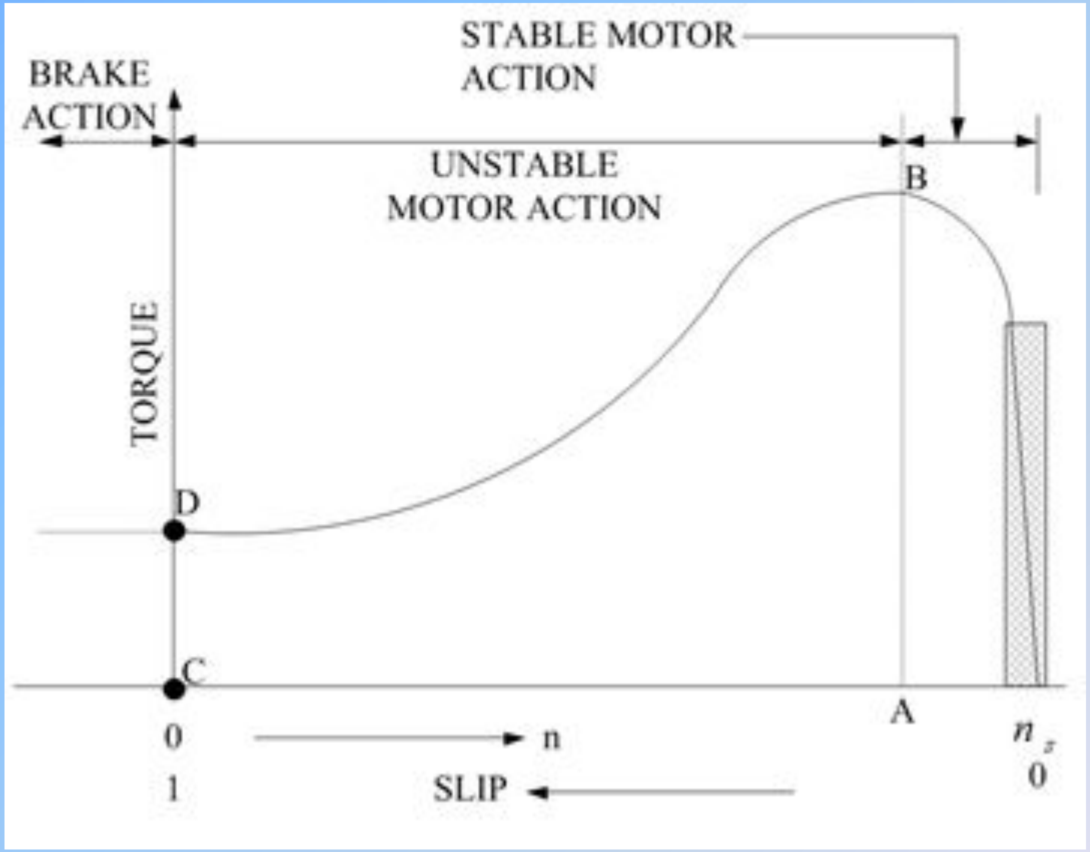
Attempts have been made to vary the effective rotor circuit resistance by means of a fixed external resistance and a set of series connected thyristors, but this approach has not gained wide acceptance.

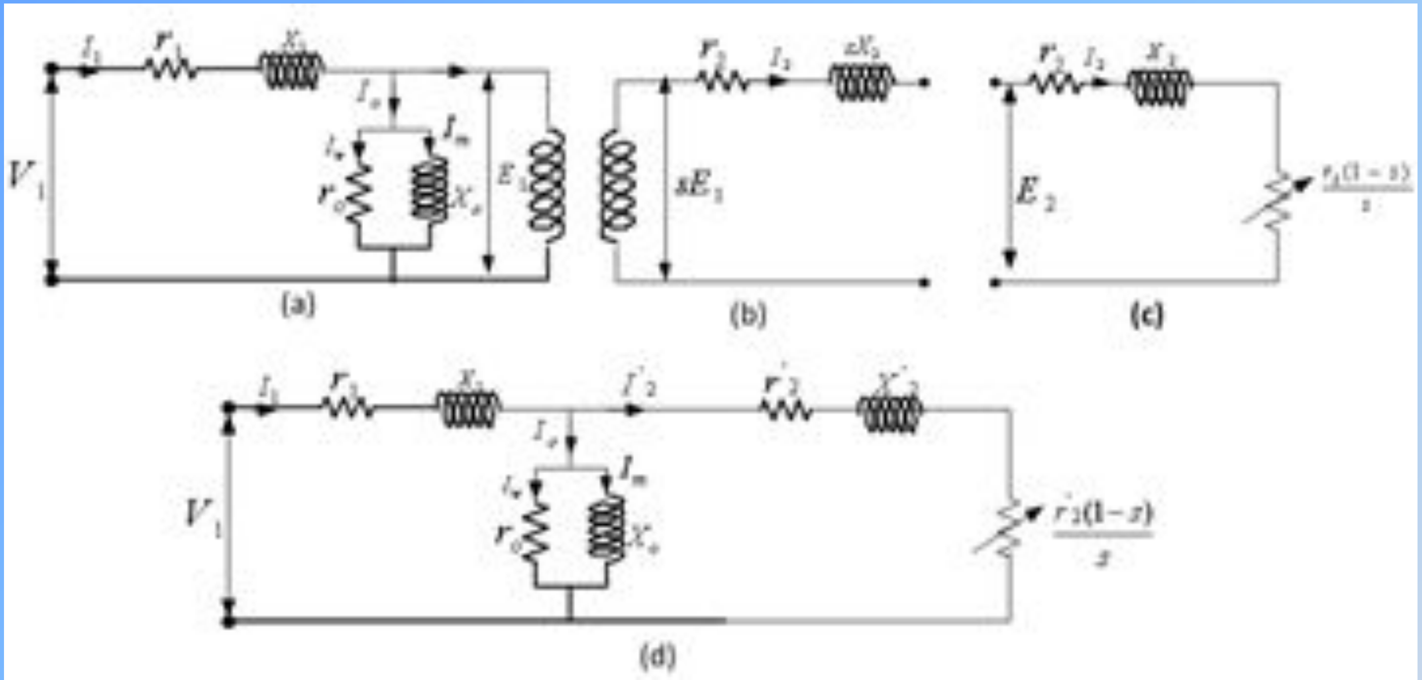
Different Methods of Speed Control of Three-Phase Asynchronous Motor

An induction or asynchronous motor is a type of AC motor where power is supplied to the rotor by means of electromagnetic induction, rather than a commutator or slip rings as in other types of motor. These motors are widely used in industrial drives, particularly poly-phase induction motors, because they are rugged and have no brushes. But they require much more complex methods of control, more expensive and higher rated power converters than DC and permanent magnet machines



Single-phase versions are used in small appliances. Their speed is determined by the frequency of the supply current, so they are most widely used in constant-speed applications, although variable speed versions, using variable frequency drives are becoming more common. The most common type is the squirrel cage motor, and this term is sometimes used for induction motors generally




I_1
r_1
X_1
I_o
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I_w
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(a)
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sE_1
(b)
r_2
I_2
X_2
E_2
$\frac{r_2(1-s)}{s}$
(c)
I_1
r_1
X_1
I'_2
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X_o
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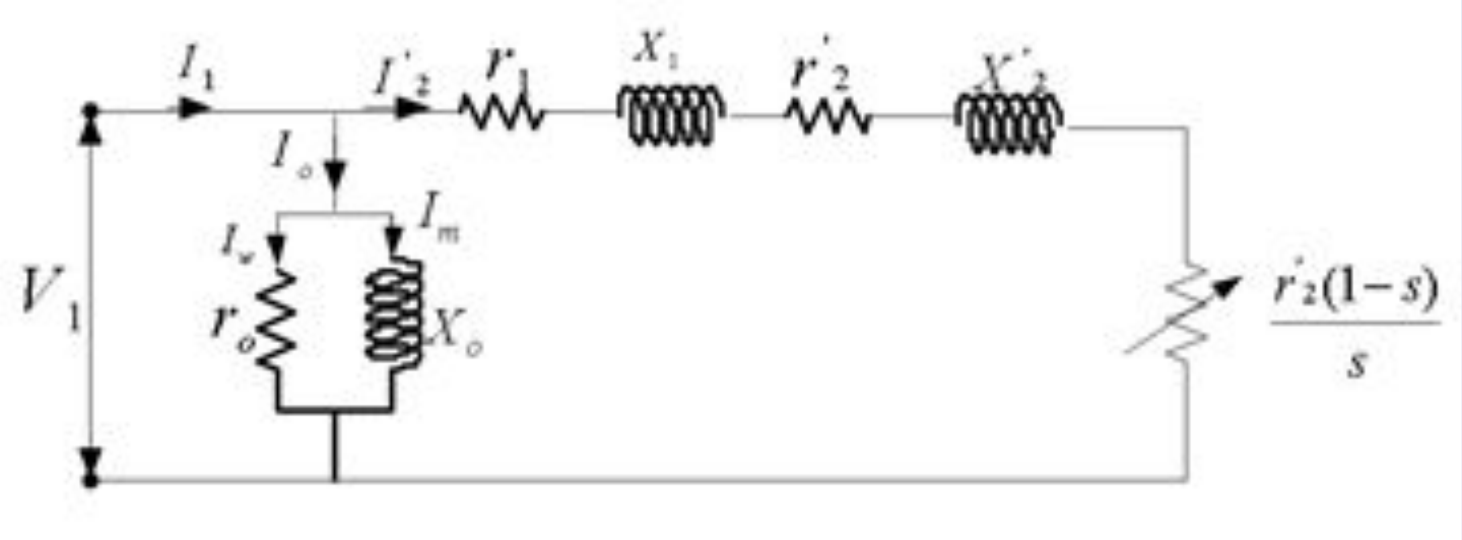
$\frac{r'_2(1-s)}{s}$
(d)


I_1
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I_m
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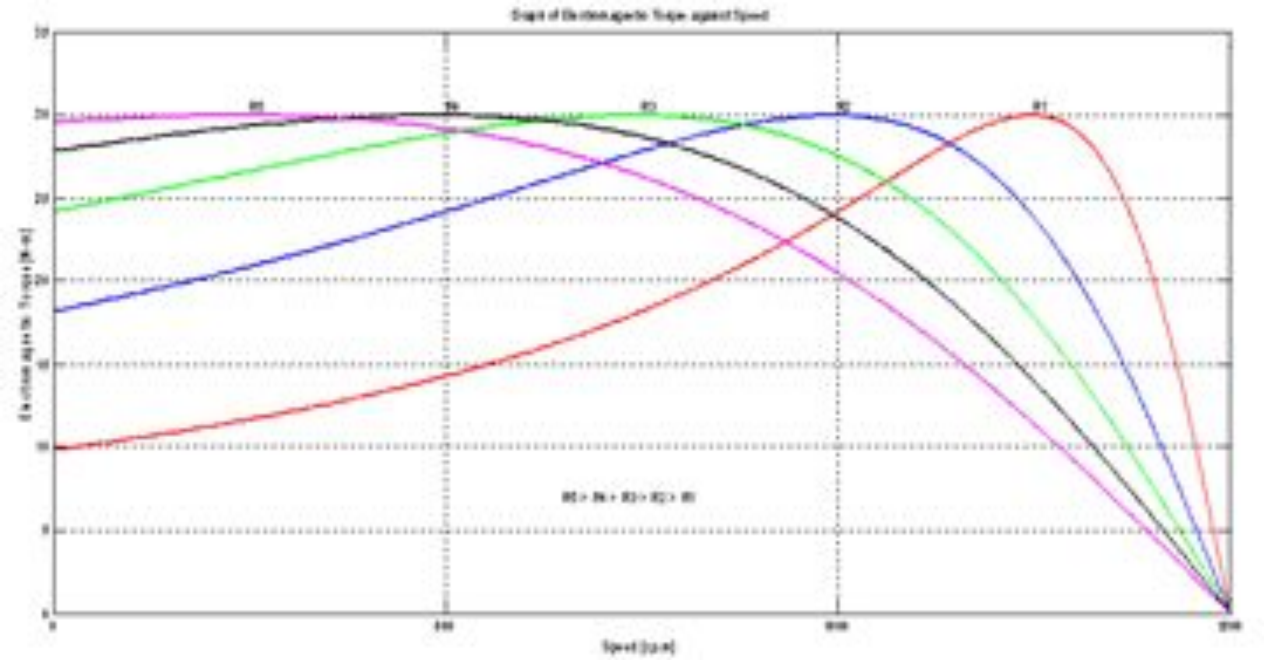
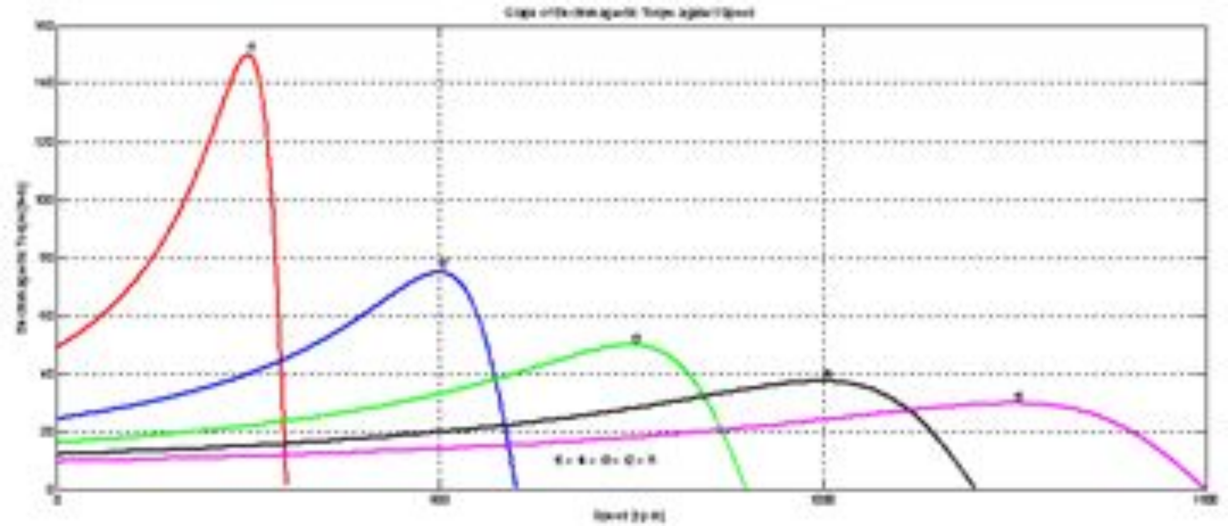
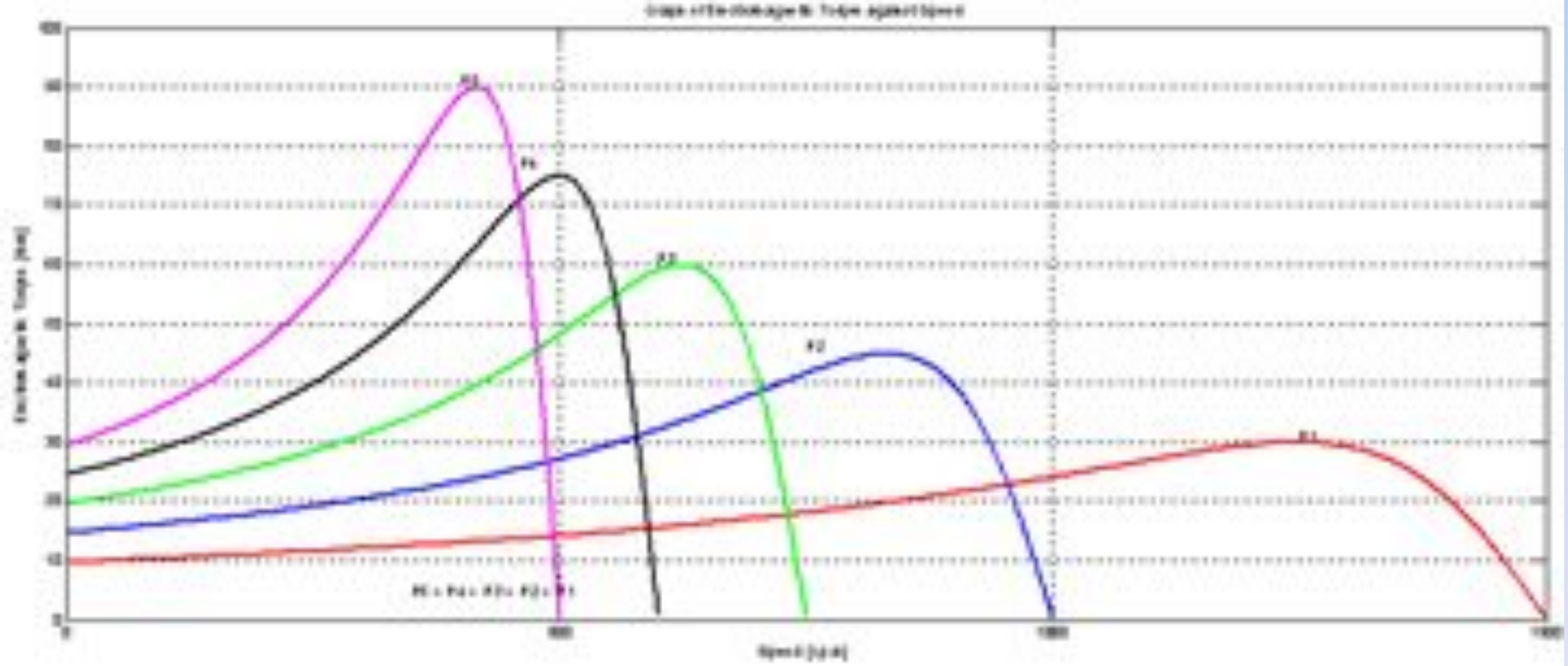
r_o
X_o
V_1
$\frac{r'_2(1-s)}{s}$


Graph of Electromagnetic Torque against Speed
Electromagnetic Torque [N-m]
Speed [rpm]
35
30
25
20
15
10
5
0
0
500
1000
1500
R5
R4
R3
R2
R1
R5 > R4 > R3 > R2 > R1

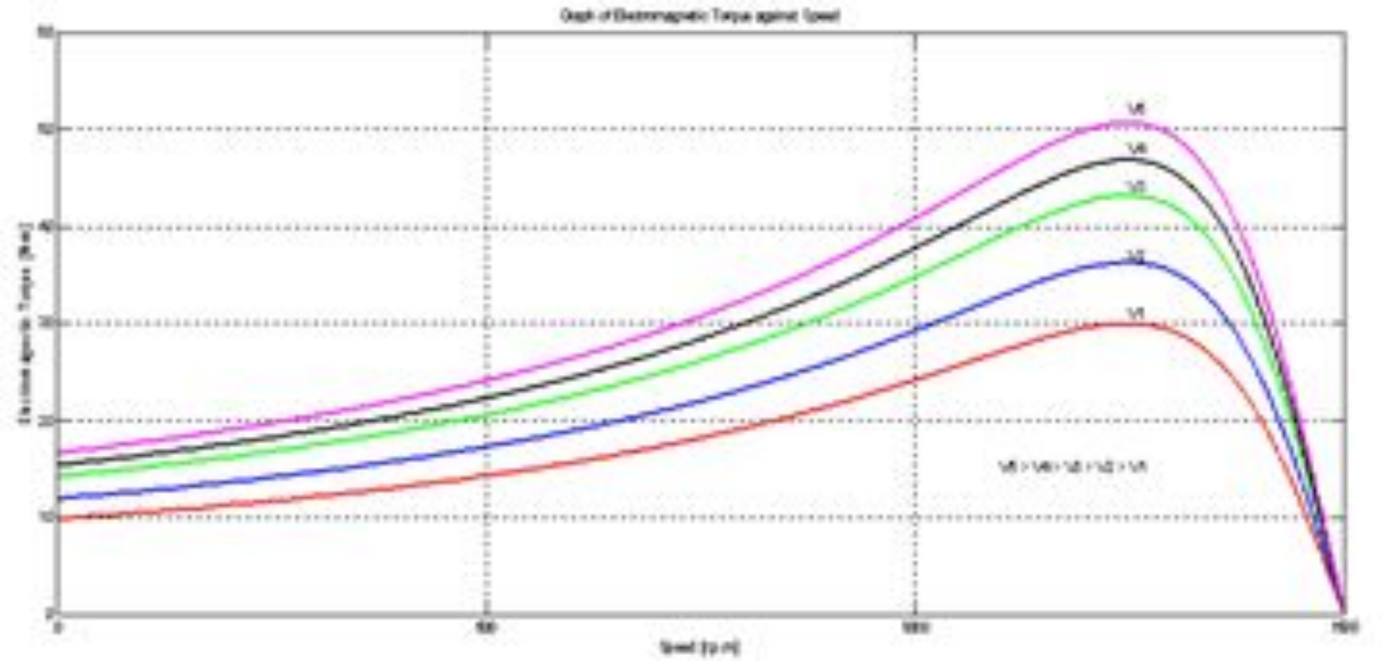
But it is desirable to replace the single phase induction motor drives by three phase induction motor drives in residential appliances, farming and low power industrial applications. Induction motors have performed the main part of many speed control systems and found usage in several industrial applications

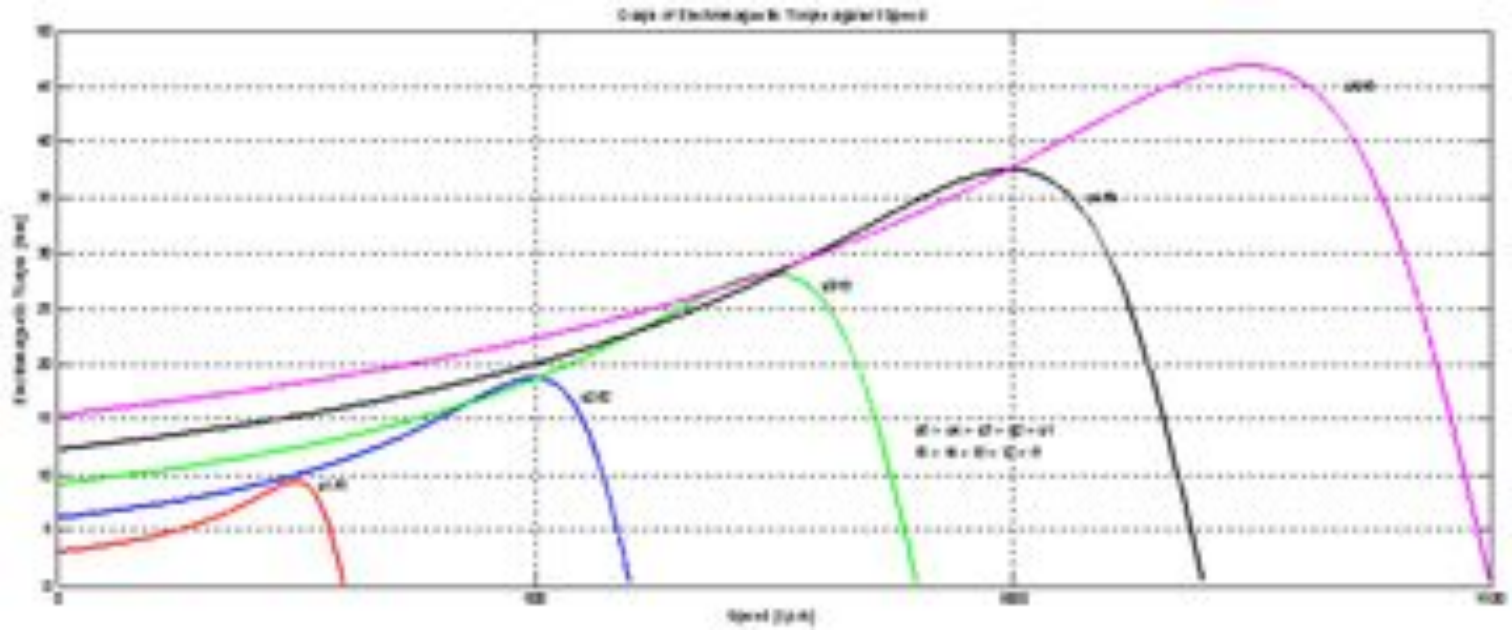


The benefit of improvement in the motor drive industry has touched varied applications, from heavy and large industrial equipment such as rolling mills in steel making plants, paper mills, etc. to “Mechatronics” equipment used in machine tools and semiconductor fabrication machines



Three phase induction machines are synchronous speed machines, operating below synchronous speed when motoring and above synchronous speed when generating





They are comparatively less expensive to equivalent size synchronous or dc machines and range in size from a few watts to 10,000hp. As motors, they are rugged and require very little maintenance. However, their speeds are not as easily as with dc motors. They draw large starting currents, typically, about six to eight times their full load values, and operate with a poor lagging power factor when lightly loaded.