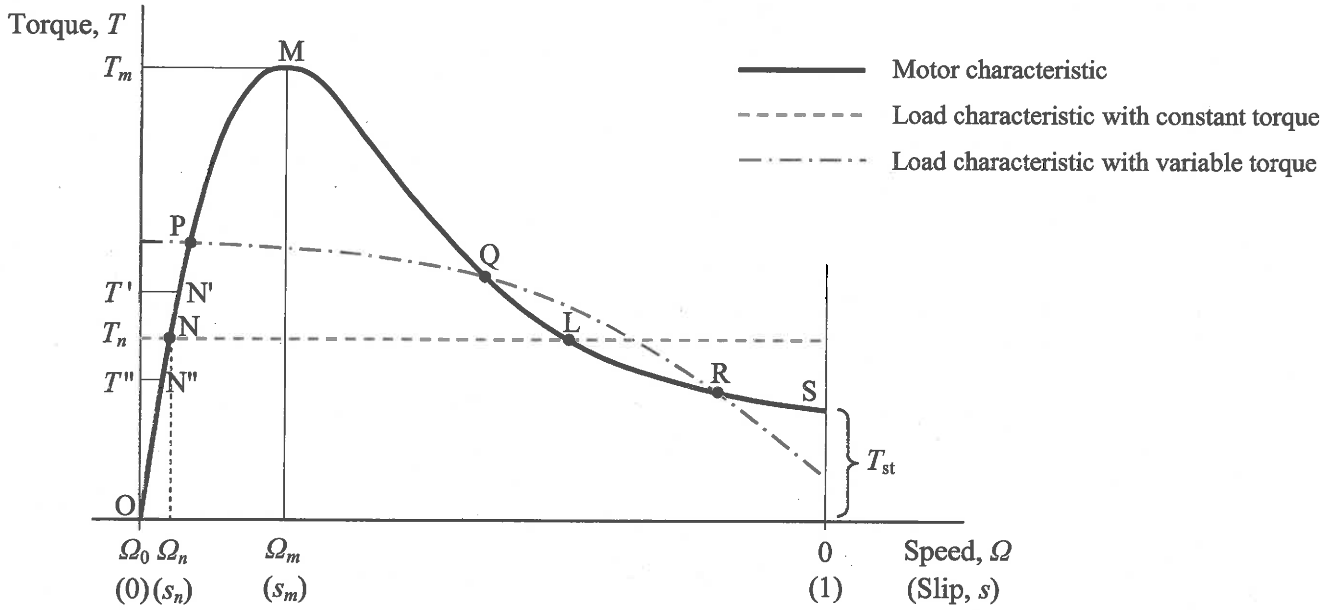
Operating Stability of Loaded Induction Motor



The above figure illustrates mechanical characteristics (torque vs. speed) of a 3-phase induction motor and two types of load – (i) constant load toque vs. speed and (ii) variable load torque vs. speed. In a steady-state operation the motor torque matches the load torque i.e. the speed changes cease ($\mathrm{d}\Omega/\mathrm{d}t = 0$) and the motor normally operates on the 'linear' part of the characteristic where the slip is small and hence the efficiency is high. Such operating points are denoted as N and P for the load types (i) and (ii), respectively.

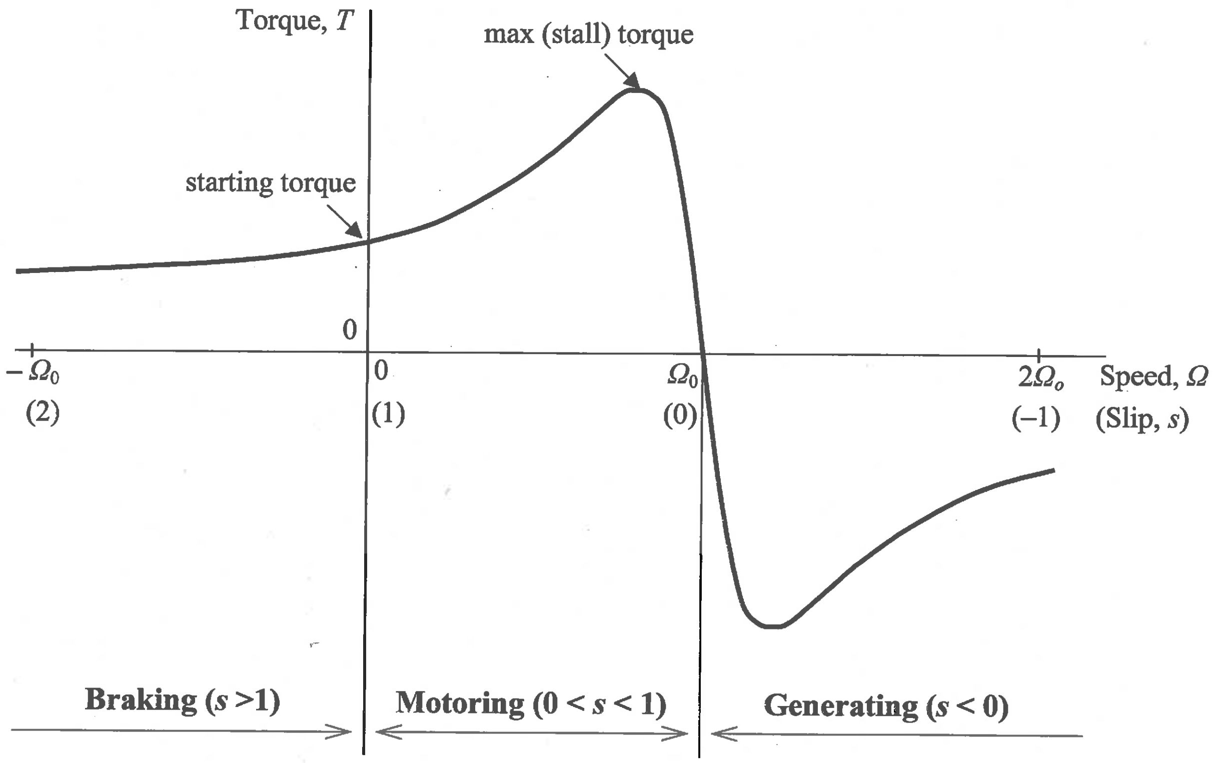
In some cases the load torque at the start is higher than the starting torque and then it is necessary to engage some external provision for starting. For instance, in a slip ring machine a starting provision can be provided by adding external resistance of appropriate value to each phase of the rotor circuit via slip rings and brushes. The external resistance changes the value of critical slip [$s_m=(R_2'+R_{2ex}')/X_\sigma$] and it can be selected so that the machine produces maximum torque (T_m) at the start ($s_m = 1$). As the machine accelerates the value of additional resistance can be reduced and eventually short-circuited so that the motor operates efficiently at the steady-state operating point (N) developing the rated torque (T_n) at the rated speed Ω_n and the corresponding slip s_n. If the load torque is now abruptly increased to a new value T' below the maximum torque, for instance due to a disturbance in the system, the speed will not respond instantly because of the system rotational inertia, and therefore there will be a sudden deficit of the driving torque which causes a deceleration which in turn increases the motor torque until it matches the new load torque. This process corresponds to the change of the operating point from N to N'. Similarly if the load torque is abruptly reduced to a new value T'', there will be a sudden surplus of the driving torque which causes an acceleration, and this in turn decreases the motor torque until it matches the new load torque. This process corresponds to the change of the operating point from N to N''. In summary, on the segment OM of mechanical characteristic, the motor responds to the load torque demands and the operation is stable.

The condition for steady-state operation with constant load torque is apparently satisfied also at the operating point L. However, for an abrupt increase of load torque, a sudden deficit of the driving torque causes a deceleration, and this in turn leads to a further motor torque reduction until the motor finally stalls. (In such a case, the protection circuit should cut off the supply to prevent the overheating of the motor.) For an abrupt reduction of the load torque, a sudden surplus of the motor torque causes acceleration and this in turn leads to a further increase of the motor torque until the motor finally reaches a new steady-state operating point on the segment OM of mechanical characteristic. Hence the operating point L is unstable.

For the load type (ii), it can be shown by applying similar analysis as above that the operating point P is stable and so is the point R, whereas the point Q is unstable. It should be noted that now at the start the motor torque is larger than the load torque, but the motor will not reach the steady-state operating point P without external provision, because it must be 'pulled out' from the first stable operating point R. For a slip-ring induction motor this problem can be overcome by adding temporarily external resistance to the rotor circuit. If the drive system is based on a cage induction motor, then either an appropriate 'constant Volts per Hertz' electronic converter (to be studied later) can be engaged with the motor to enable the starting and speed control, or a new motor should be selected so that its mechanical characteristic does not intercept the load characteristic other than at the operating point P on the stable part of the motor characteristic.

Operating Modes of Induction Machine

Using the earlier derived analytical relationship between torque and slip, i.e. Eqs.(3) and (7), it is possible to plot the torque v.s. slip (speed) characteristic not only for slip variation in the region where $0 < s \leq 1$, but also beyond these boundaries, i.e in the regions where $s < 0$ and $s > 1$. The form of the complete characteristic is shown below.



When an unloaded 3-phase induction motor is connected on the mains supply, the speed will reach a steady-state value which is almost equal to the synchronous speed. (Friction and windage torque prevent the rotor to reach the synchronous speed.) If a driving torque is now applied to the shaft by another machine or a turbine so that the rotor speeds up above the synchronous speed, i.e. above the speed of the rotating flux wave, the slip and electromagnetic torque become negative. The direction of developed electromagnetic torque opposes to the driving torque, and the induction machine now operates as an induction generator. Referring to the equivalent circuit, the resistance R_2'/s and its component $R_2'(1\text{-}s)/s$ are negative, and hence the power associated with each of them is also negative. This means that the direction of power flow is from the source of mechanical power $[3I_2'R_2'(1\text{-}s)/s]$ to the mains. (The power transferred through the airgap $[3I_2'R_2'/s]$ flows in the direction 'from the rotor to the stator'.)

If the rotor is driven in the opposite direction to the rotating flux wave, the slip and electromagnetic torque are positive, but the rotor speed is negative and hence $s > 1$. The developed electromagnetic torque acts in the same direction as the rotating flux wave and it opposes to the driving torque. However the induction machine does not operate as a generator, because the power transferred through the airgap $[3I_2'R_2'/s]$ is positive, i.e. the power from the mains flows through the airgap in the direction 'from the stator to the rotor'. On the other hand, the power from the mechanical source $[3I_2'R_2'(1\text{-}s)/s]$ is negative. Hence the rotor receives the power from both the supply and the mechanical system, and the received power is converted into heat in the rotor resistance $[3I_2'R_2']$. The machine operates as an electrical brake.