Application Note 72

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DC Servomotors – Graphical Analysis

Permanent magnet DC servomotors excel in demanding industrial applications. These motors are permanently excited machines with output torque proportional to current, producing excellent servo characteristics.

Equivalent Circuit Model.

Fig. 1 below shows an idealized equivalent circuit for a permanent magnet servomotor.

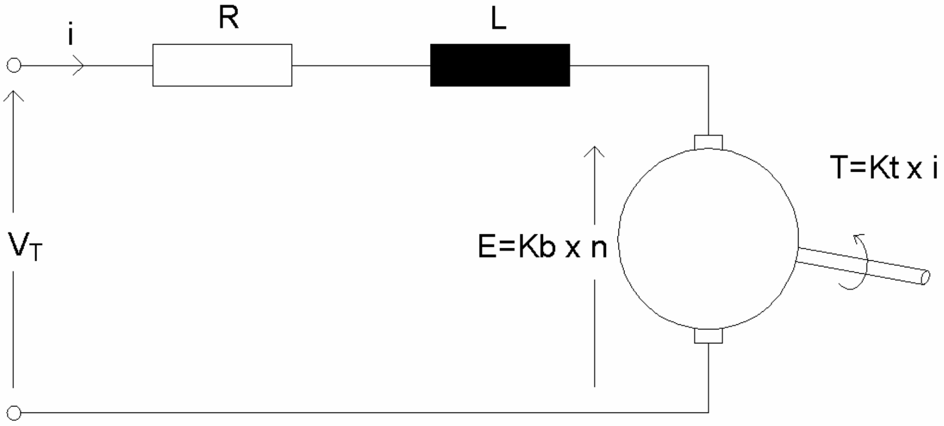

Fig. 1 Equivalent circuit of a permanent magnet, DC servomotor.

V_T = Terminal Voltage (V)
R = Motor Resistance (Ω)
L = Inductance (mH)
I = Motor Current (A)
E = motor Back EMF (V)
T = Generated Torque (Nm)
N = Speed (krpm)
Kb = Back EMF Constant (V/krpm)
Kt = Torque Constant (Nm/A)

Clearly it can be seen that for the DC servomotor, torque is proportional to current (const. of proportionality, Kt) and back EMF is proportional to current (const. of proportionality, Ke).These two constants are not independent. In fact

Kt (Nm/A) = Ke (V/krpm) / 104.7

This is an extremely important equation for DC motor operation.

Graphical Analysis

At any steady state condition, it can be seen

$$V_T = E + I \times R$$
$$\Rightarrow V_T = Ke \times n + (T/Kt) \times R$$

$$\Rightarrow \mathbf{n\ (krpm) = (V_T/Ke) - (R/[Ke \times Kt]) \times T}$$

The value of torque at zero speed is usually approx 10% - 15% lower than the value calculated above. This is because at very high current, the magnetic field produced by this current in the armature weakens the field produced by the magnets and so reduces the torque produced. This effect is known as “armature reaction”. Therefore the torque predicted by the above equation, at zero speed should be reduced by 10%-15% in graphical analysis.

This equation describes the torque-speed relation for the DC motor. The first term is the “no-load” speed and in the case of the permanent magnet motor (fixed Ke) it is directly proportional to the terminal voltage

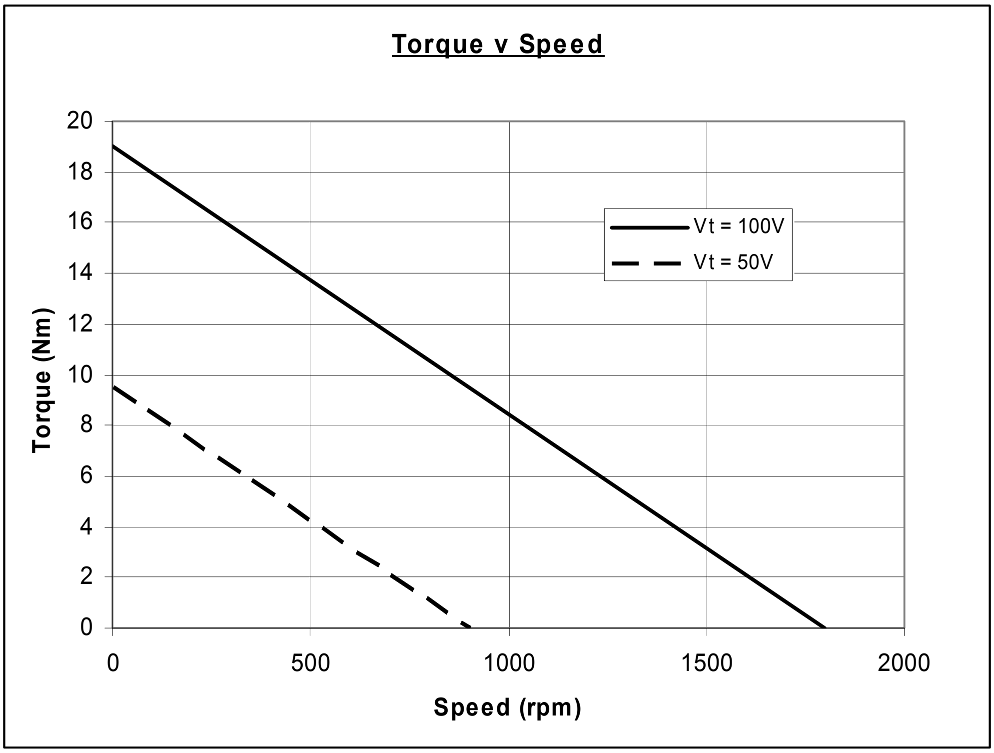

Fig. 2 Motor Torque-Speed relationship.

In order to find the operating point at any given load, it is necessary to find the intersection of the above line with the “load-line” characteristic for the driven load. Fig. 3 shows a typical characteristic loadline for a “hoist “ load.

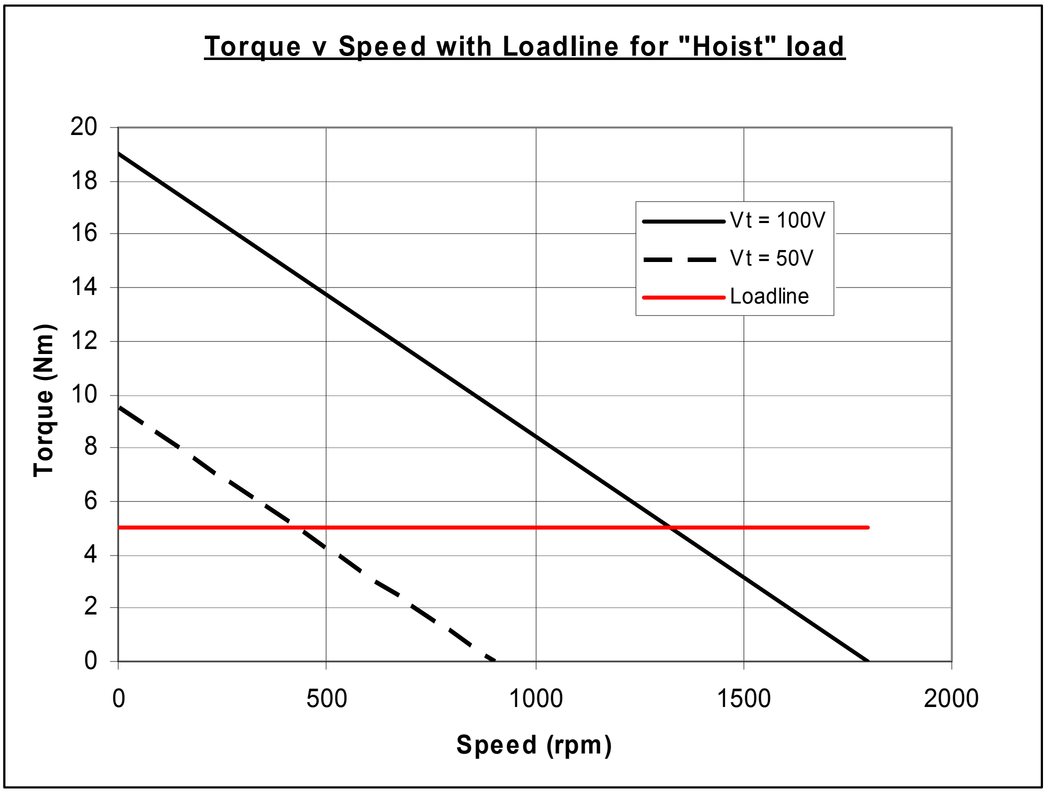

Fig. 3 Intersection of Motor Characteristic and Load-line.

The actual operating point is found at the intersection of the load-line and the motor characteristic for a given terminal voltage. It can be seen that if the terminal voltage is increased, the motor accelerates until it settles out at a new higher speed and depending on the type of load-line – possibly also a new higher load torque.

It is important to recognize that the value of resistance used in calculating the motor characteristic line in temperature dependent. The value given in the motor data sheets is the nominal resistance at 20°C. As the motor heats up the resistance rises and at max operating temperature the resistance is typically 50% higher than the data sheet value. For graphical analysis it is advisable to use the higher value of resistance – which unfortunately reduces the available torque for a given speed.

The maximum allowable terminal voltage for the motor is usually limited by the commutator and is stated on the motor electrical data sheet. The motor can be run at a lower terminal voltage and the torque speed line reduced accordingly as shown above.

The torque produced by the motor is proportional to motor current. This current dissipates power in the winding which raises the temperature of the winding accordingly. In a steady state condition (constant torque & speed) the winding temperature eventually reaches a settled value. For a class F motor the permissible maximum winding temperature is 155°C. At low speed, almost all the heat dissipation in the windings is caused by “copper” loss – where the motor current heats up the motor windings. The value of torque (and thereby current) which brings the settled winding temperature to 155°C is termed the “Continuous Stall Torque”, Tc, for the motor.

At higher speeds another heating mechanism emerges. This is due to losses in the motor steel laminations due to magnetic hysteresis and eddy currents and are collectively known as “iron” loss. Therefore the permissible rated torque at higher speeds us usually somewhat lower than the Continuous Stall torque.

A line characteristic can be drawn for the motor representing the rated (or permissible) torque throughout the speed range. This characteristic must be determined experimentally by the manufacturer for each motor type.

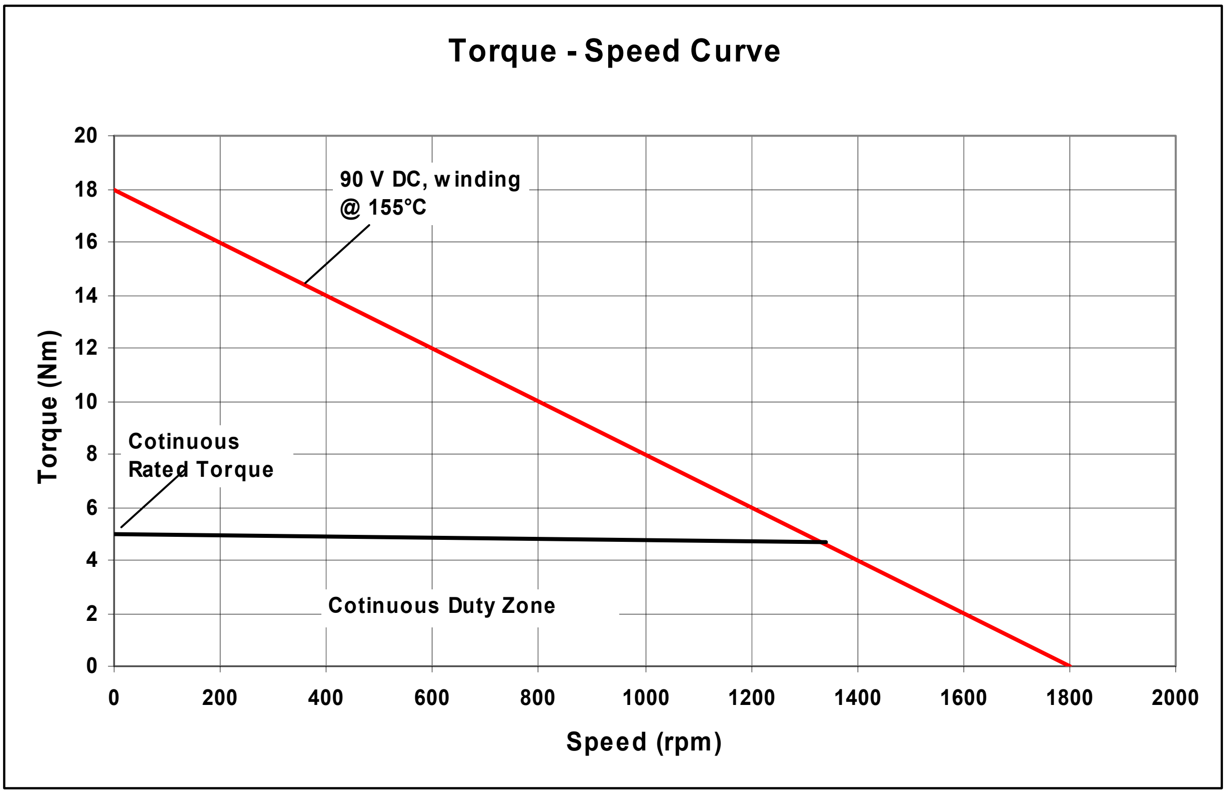

Fig. 4 Motor Characteristic with continuous duty zone.

The motor can operate continuously anywhere within the continuous duty zone. However any attempt at continuous operation at torque levels outside the continuous duty zone will eventually lead to motor burn-out due to overheating of the motor windings.

It is permissible to operate at a value of torque greater than continuous rated torque for short periods. In fact servomotor applications typically require the motor to accelerate and decelerate repeatedly. This requires torque values greater than the continuous rated torque and calls for the motor to make short duration excursions into the torque region above than the continuous duty zone. If this happens repeatedly, it is important that the RMS value of the torque waveform yields a value of torque and speed that falls securely into the continuous duty zone. The area above the continuous duty zone is termed the “intermittent” duty zone. It is bounded by an absolutely maximum value of torque (& current), termed “peak torque” (& “peak current”). The peak current is usually limited by the brushes and/or the specific motor winding.

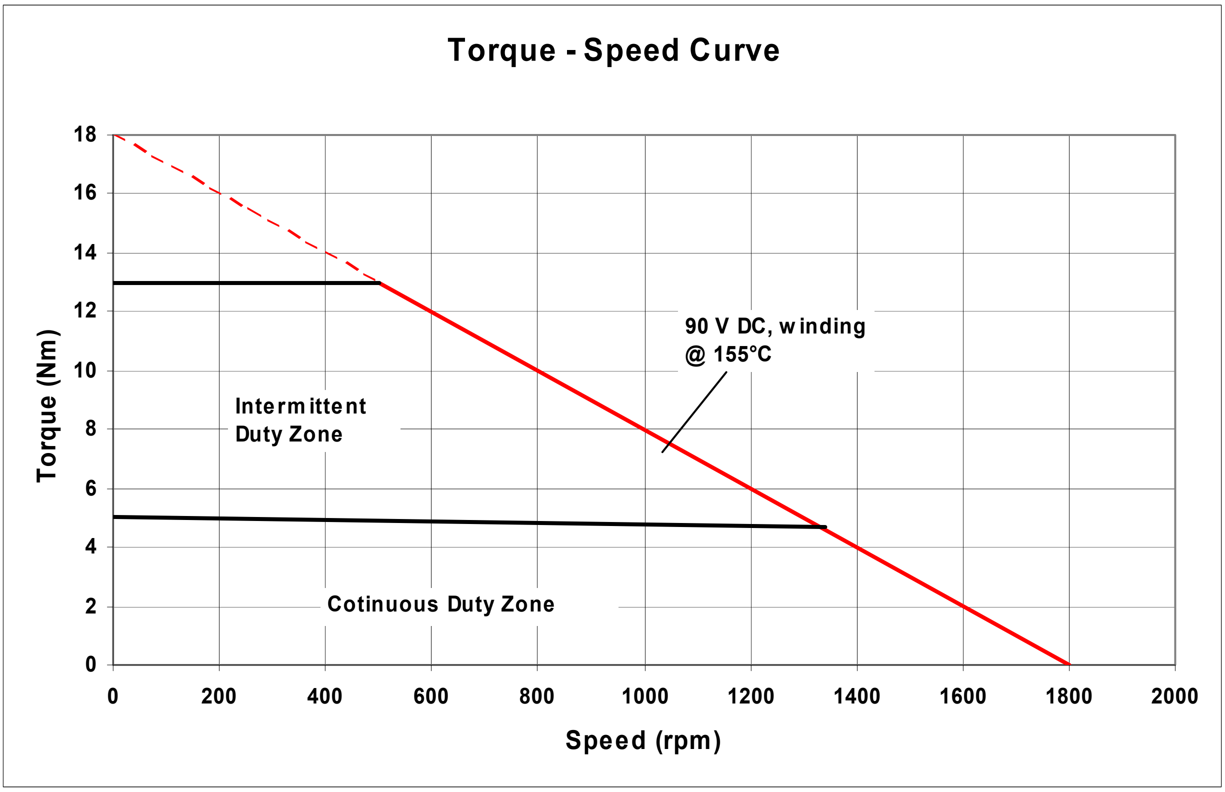

Fig. 4 "Continuous Duty" zone & "Intermittent Duty" zone.

Brush DC servomotors normally have an absolute max power limit imposed. This is a result of the capacity of the brushes to switch current without sparking so seriously as to risk flashover. At low speed, a commutator bar takes longer to pass under a brush, giving more time for the current to change (commutation) without serious sparking. As speed increases, the time available reduces in inverse proportion and so the current has to be reduced pro rata. This results in a constant power curve.

A lower power limit is usually also imposed in order to give good brush life. This limit is normally termed "Motor Rated Power". Usually there is an inverse square relationship between the two power curves ….that is, if power doubles then brush life reduces four fold.

Therefore the zone between the max power curve and rated power curve is only used for brief periods, usually only during speed changes. It must never be used continuously. This zone is normally termed "Acceleration/Deceleration" zone. The resultant graph is termed the "Performance Curve" for the motor and is most useful when sizing a motor for a particular application.

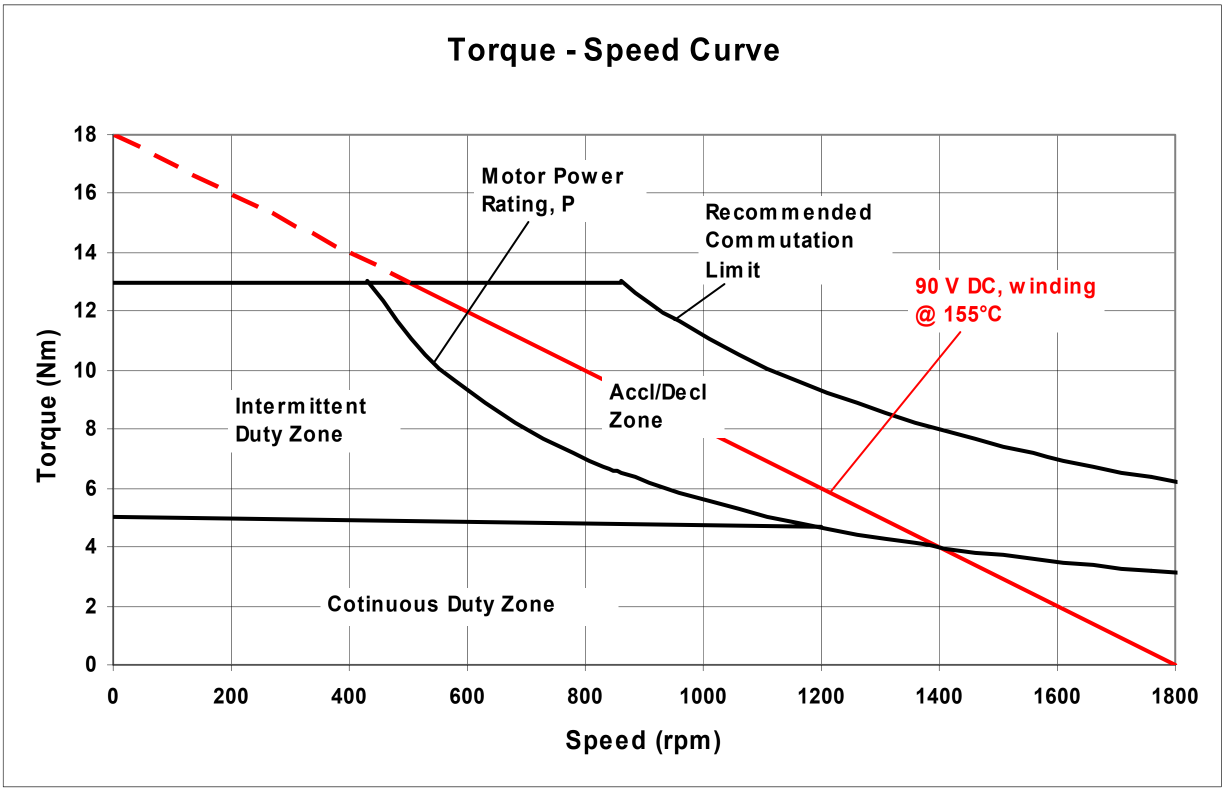

Fig. 5 Motor Performance Curve.