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Selecting motors for battery-powered medical devices

The design of battery-powered medical instruments requires thorough analysis to optimize performance and reliability while staying within power consumption limits. However, motor selection involves more than determining efficiency, and you should be prepared for some intuitive surprises.

The demand for smaller, higher performance, more reliable electromechanically actuated medical devices requires careful selection of the motors used in a design to minimize power requirements.

DC motors, properly designed and used, normally provide the highest efficiencies in the conversion of electrical energy to mechanical power. Even at that, a DC gearmotor with an efficiency approaching 50 percent is extraordinary. If the mechanical power losses in the drive system can be reduced by one-half watt, it results in a savings of at least one watt of electrical power. Since typical efficiencies out of the gearmotor assembly will be less than 25 percent, savings in the drive system pay back enormously.

Close attention to the selection of bearings, gears, lubrication, shaft loading, and coupling ratios will produce a more efficient drive system. And since the overall efficiency of the system, and not just the motor, is critical, the analysis should also include losses in the electronics.

Selecting the proper motor winding requires careful consideration to optimize the design. Overly conservative selection will cost power. However, selecting a winding too close to the limit could result in an inoperable design. Particular attention should be paid to motor specifications, especially in regard to the tolerance of the torque constant and resistance. Tolerances vary from lot to lot, and the failure to analyze the application closely after a sample or two could result in a design that does not always work.

When selecting a gearbox, be pre-

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pared for some intuitive surprises. The most efficient gearbox may not be the best. Generally, the more rugged the gearbox, the higher the input friction, even if the efficiencies are identical. Note that motors and gearboxes from one production batch will usually have very small variations in most parameters. That is normal because they were all probably manufactured from a single production lot of magnets, wire, and bearings.

If the application involves a small range of temperatures, optimizing lubrication of the motor and gearbox can reduce internal coulomb and viscous losses.

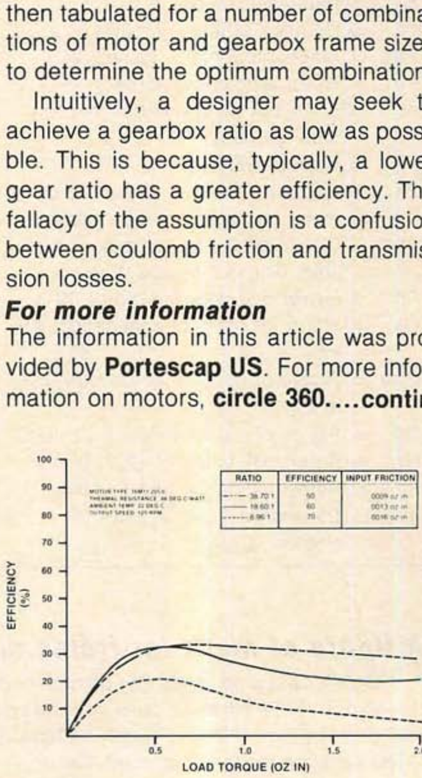
In battery powered applications, a gearbox or other device such as a belt and pulley will normally be used if the load speed is less than 1000 rpm. The coupling ratio has an enormous effect on motor and system efficiency. Usually the greater the reduction ratio, the better. DC motors are more efficient operating at a load of 10 to 15 percent of its nominal stall torque. However, the reliability, cost, and mechanical noise compromises must be weighed.

The steps involved in selecting a gearbox are fairly straightforward. The frame size of the gearbox must have a torque rating greater than or equal to the load torque. Also, the ratio should be selected to have an input speed as high as possible without exceeding maximum recommended input speed. Then, a motor frame size and winding are selected (see "A figure of merit for frame size" elsewhere in this article). The results are then tabulated for a number of combinations of motor and gearbox frame sizes to determine the optimum combination.

Intuitively, a designer may seek to achieve a gearbox ratio as low as possible. This is because, typically, a lower gear ratio has a greater efficiency. The fallacy of the assumption is a confusion between coulomb friction and transmission losses.

For more information

The information in this article was provided by **Portescap US**. For more information on motors, **circle 360.** **...continued**



Selecting a gearbox with the highest efficiency may not always be the best choice, as shown here. In this case, the gearbox with the highest efficiency rating (0.70) also has the highest input friction. As a result operating efficiency is lower than the designs using gearboxes with 0.50 and 0.60 efficiency ratings.

Nomenclature

B = Viscous damping constant, oz-in/rpm
I_T = Total motor current, A
I_O = No load motor current, A
K_T = Torque constant, oz-in/A
K_E = Back EMF constant, V/rpm
L = Inductance, H
N = Reduction ratio
n_R = Gearbox efficiency, percent
P_{MD} = Mechanical motor losses, W
n_M = Motor efficiency, percent
n_S = Efficiency of power delivery to load, percent
P_{IN} = Input power to motor, W
P_N = Mechanical power delivered by motor (includes gearbox losses), W
P_{OUT} = Output power at gearbox or motor shaft (without gearbox), W
P_D = Power dissipated in motor, W
Q_A = Figure of merit of application, oz^2-in^2/C
Q_{GM} = Figure of merit of gearmotor, oz^2-in^2/C
Q_M = Figure of merit of motor, oz^2-in^2/C
R_{22} = Rotor resistance at 22 C, ohms
R = Rotor resistance at T_R, ohms
R_{TH} = Thermal resistance, rotor to ambient, C/W
R_{TH1} = Thermal resistance, rotor to case, C/W
R_{TH2} = Thermal resistance, case to ambient, C/W
T_R = Rotor temperature, C
T_{AMB} = Ambient temperature, C
T_L = Load torque, oz-in
T_S = Static friction torque, oz-in
T_{LR} = Load torque reflected to motor shaft, oz-in
T_C = Coulomb friction torque, oz-in
T_{GF} = Gearbox input friction torque, oz-in
T_{ML} = Motor internal torque losses, oz-in
T_{RM} = Maximum recommended rotor temperature, C
T_T = Total torque produced by motor, oz-in
T_V = Viscous friction torque, oz-in
V = Applied voltage, V
V_I = Motor induced back EMF, V
V_M = Measuring voltage, V
V_{MAX} = Maximum voltage available to drive motor, V
W_L = Load angular velocity, rpm
W_M = Motor angular velocity, rpm

A figure of merit for frame size

This technique is a good starting point to choose a particular motor frame size. The choice of windings will be iterative, but a starting point for winding selection could be that the back EMF must be less than the supply voltage. Tolerances on back EMF must be included.

The equation for figure of merit, Q_M is:

$$Q_M = [.912\, T_T^2 + .004\, T_R\, T_T^2]/(T_R - T_{AMB})$$

To find the minimum Q_M required, it is necessary to redefine Q_M as Q_A, the minimum figure of merit for the application. To do this, it must be assumed that the rotor is at its maximum rotor temperature (T_{RM}), and that T_T is equal to T_L. Therefore:

$$Q_A = [.912\, T_L^2 - .004\, T_{RM}\, T_L^2]/(T_{RM} - T_A)$$

This figure is useful because it allows the choice of case size selection based on the thermal constraints of that case size, regardless of winding.

In a given application, the maximum rotor temperature must not be exceeded. Therefore, by inserting the maximum recommended rotor temperature into the equation, the minimum Q_M factor for the motor can be determined.

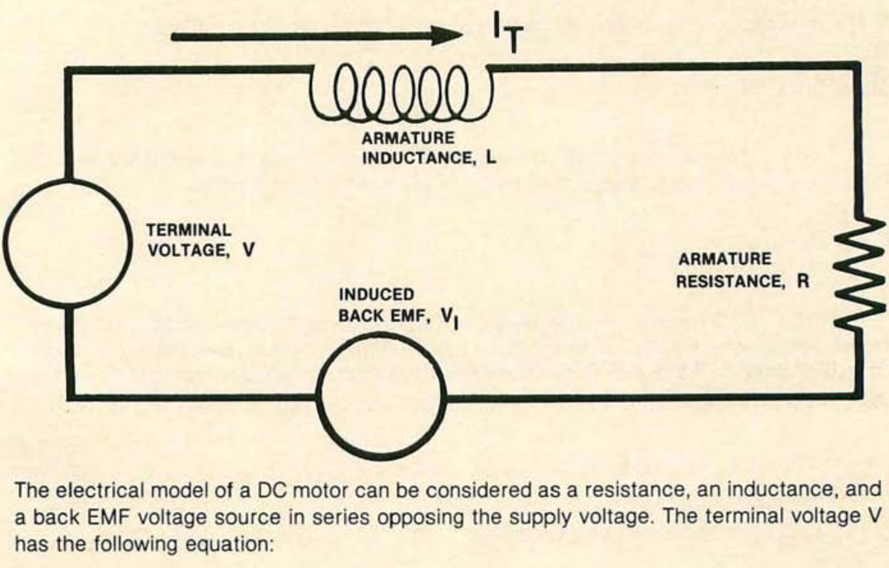
The procedure is then simple: a frame size is chosen that has a Q_M greater than the minimum Q_A of the application.

A gearbox will amplify the motor Q_M factor by:

$$Q_{GM} = Q_M (N\, n_R)^2$$

This has the effect of allowing the use of a smaller motor. The Q_{GM} must be greater than Q_A to avoid overheating.

The motor model



The electrical model of a DC motor can be considered as a resistance, an inductance, and a back EMF voltage source in series opposing the supply voltage. The terminal voltage V has the following equation:

$$V = L\,di/dt + I_T R + V_I$$

To simplify this equation, the inductance will be considered to be negligible. This simplification is valid in constant speed applications with linear servos. For pulse width modulated servos and incremental motion applications, this model, however, may not be valid for conventional iron armature and brushless DC motors.

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In most applications using ironless motors, the assumption of negligible inductance can be considered valid:

$V = I_T R + K_E W_M$

A rigorous expression for mechanical losses in DC motors is seldom used. Thermal effects from coulomb and viscous losses are often ignored or simplified. For high-speed applications, such as in dental drills and bone saws, such omissions or simplifications are invalid.

The total motor current, I_T, under constant-speed conditions, is converted by the torque constant into the torque required to overcome various loads reflected to and within the motor:

$T_T = T_{GF} + T_{ML} + T_{LR}$

The reflected load (when a gearbox is used) is simply:

$T_{LR} = T_L/(N\, n_R)$

The motor power dissipation can be modeled by Ohms Law of Heat Flow:

$T_R - T_{AMB} = P_D R_{TH}$

The motor power dissipation can be separated into two sources: The ohmic losses in the rotor and the mechanical losses in the motor. This can be expressed by:

$P_D = I^2_T R + P_{MD}$

The motor mechanical losses can be described as a function of the viscous and coulomb friction losses multiplied by the speed of the motor. This mechanical power can be assumed to be dissipated in the form of heat. To simplify the analysis, it is assumed that this heat together with the ohmic heat originates in the rotor:

$P_{MD} = W_M (T_V + T_C)/1352.4$

The current in the motor is described by:

$I_T = T_T/K_T$

and the resistance of the rotor can be expressed as a function of rotor temperature:

$R = R_{22} (1 + .004 [T_R - 22])$

If this equation is solved for T_R by substituting where appropriate, the following equation for rotor temperature results:

$$T_R = [.912\, I_T^2\, R_{22}\, R_{TH} + T + (T_V + T_C)\, W_M\, R_{TH}/1352.4]\,/(1 - .004\, I_T^2\, R_{22}\, R_{TH})$$

The efficiency of the DC motor (or gearmotor) from a system standpoint is the ratio of output mechanical power (P_{OUT}) to electrical input power (P_{IN}).

The mechanical output power can be expressed as:

$$P_{OUT} = W_L\, T_L/1352.4$$

The electrical input power is simply:

$$P_{IN} = V\, I_T$$

Therefore, the efficiency of the system is:

$$n_S = [(P_{OUT})/(P_{IN})] \times 100$$

It is important to consider the efficiency of the motor. It is defined as the motor speed, multiplied by the motor torque that is delivered to overcome the reflected load and the torque that is used to overcome the gearbox friction or divided by the input power.

$$n_M = ([W_M\, (T_{LR} + T_{GF})/1352.4]/P_{IN})\, 100$$

The motor speed W_M is a function of the load speed and gearbox reduction ratio:

$$W_M = N\, W_L$$

The voltage, V, applied to the motor must be less than the difference between the battery supply voltage and the voltage drop across the driving transistor.

Important equalities used in these derivations are:

$K_E = K_T/1352.4$ when
K_E is in volts/RPM
K_T is in oz in/A

Also, the product of the angular speed in rpm and the torque in oz-in divided by 1352.4 equals the mechanical power in watts:

The equations presented here are necessary to properly analyze a DC motor for given constant speed applications with linear power supply. Obviously, if no gearbox is used, the ratio will be considered to be one with an efficiency of 100 percent.