# Comparative Analysis of Thermal Time Constants in Iron-Core and Ironless- Armature DC Servo Motors

An important criteria in the selection of drive motors for machine tools and robots has been, and continues to be, the armature thermal time constant. In these applications where holding force or torque at low speeds or stall is required, the mass of the armature has been related, intuitively, to the magnitude of the motor thermal time constant. Thus, massive, or high inertia armature motors have been selected, foregoing perhaps, the response of low inertia motors.

A study of thermal time constant dynamics in both high and low inertial motors (conventional iron-core and moving coil motors) shows that, in fact, the thermal time constant of the resistive portion of an armature (the copper), is little affected by the mass of iron surrounding or near the copper. The results show that in both types of structure (iron-core and moving coil), the armature copper temperature increases rapidly when power is applied and, if not controlled, can cause insulation failure. Even when controlled, it can cause shortened insulation life.

Controlling power so that work can be done, yet protecting the insulation system from thermal overload, is a feature of today's PWM amplifiers designed with fold-back overload circuits matched to the thermal time constant of the armature copper. PWM amplifiers also produce a current form factor very nearly one (1.005 for example) that allows more work out, less heat loss in the copper, per power unit input. This results from their higher operation frequency of typically 5 kHz compared to 360 Hz for SCR amplifiers.

Starting with a textbook definition, thermal time constant is the amount of time necessary for a particular body or system to change to 63.2% of the total difference between its initial and final body temperatures when it is subjected to a step function change in temperature. This definition assumes that the body is a uniform temperature both initially and throughout the heat transfer process. This definition also assumes that the body is experiencing no internal heat generation.

A typical application of this concept is the simple cooling of a hot body when it is suddenly introduced to cooler surroundings, such as the ambient environment. In this Application Note, only the thermal decay time constant is considered. Theroretically, there is no difference between the thermal decay and the thermal rise time constant. Both describe the response of a particular body or system when it is subjected to a sudden change in temperature. However, the derivation of the governing equation for the one time constant is a bit different fromn the derivation of the governing equation for the other.

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As an example, consider a hot iron nail being quenched in a bucket of cold water. If the temperature history of the nail was recorded as the nail was dropped into the water, the recording would reveal an exponential decay in the temperature of the nail. After some amount of time, the recording would show that the nail temperature had decayed to 63.2% of the total difference between the nail's initial and final temperatures. This amount of time would be the thermal time constant of the nail. This time constant is invariable for any magnitude of difference between the nail's initial and final temperatures.

Mathematically, starting with an energy balance between a hot body and its cooler surroundings, and equation can be derived that describes this cooling effect:

(A) $\dfrac{T - T_{00}}{T_0 - T_{00}} = e^{-(0/RC)}$    Where:

$0$ = Time, typically in seconds

$T$ = Average body temperature at any time 0.

$T_0$ = Initial body temperature

$T_{00}$ = Constant temperature of body surroundings at a point far distant from the body.

$R$ = Thermal resistance of the heat transfer path between the body and its surroundings

$C$ = Thermal capacitance of the body.

The thermal resistance, R, of the heat transfer path between the hot body and its surroundings, is a function of the reciprocal of two parameters. The first parameter is the surface area of that portion of the body surface that is in contact with its surroundings. The second parameter is the average unit surface conductance of the same portion of the body surface (that is in contact with its surroundings).

The thermal capacitance (C) of the body is a function of the volume of the body, the density of the body, and the specific heat of the body.

The product of the thermal resistance and capacitance (RC), has the units of time and therefore, defines the thermal time constant of the body. Note that when $0 = RC$, the thermal time constant, the temperature difference $(T - T_{00})$ is equal to 36.8% of the initial difference $(T_0 - T_{00})$.

$e^{-1} = 0.368$

The thermal decay time constant is dependent upon the thermal capacitance of the hot body and upon the resistance of the thermal path, between body and surroundings, to removing heat.

How then, can the application of this definition be made in the case of DC motors in general, and in particular, in the specific case of moving coil motors?

In the case of a simple cooling body governed by a single thermal time constant and as described by equation (A), it is assumed to be a valid thermal model for the DC motor. It is assumed that the DC motor is a simple, first order thermal body whose cooling effect can be described by equation (A), without exception. For instance, see: *Duty Cycle Characteristics* for Servo Motors, from IEEE Transactions on Industry Applications, Vol. 1A-9, No. 5, September/October 1973 and *Incremental Motion Control,* edited by Benjamin C. Kuo, University of Illinois at Urbana-Champaign, and Jacob Tal, University of Utah, Pgs. 104-109.

Theoretically, in order for equation (A) to be a valid description of a particular cooling body or system, the following conditions must be met:

1. $T_{00}$, the temperature of the body surroundings at a point far removed from the body, must be constant. The hot body surrounding must be a perfect heat sink. The thermal capacitance of the surroundings must be practically infinite, such that the heat flow from the hot body does not increase $T_{00}$ (ambient atmosphere).

2. The thermal resistance within the hot body must be so small with respect to the thermal resistance of the heat path between the hot body and its surroundings, that the temperature within the body is substantially uniform at any instant. The thermal resistance of the heat path 'controls' the heat transfer process since the internal resistance of the body can be considered negligible in comparison.

3. The hot body must be subjected to a step function change in temperature. That is, the hot body must be exposed to the cooler surroundings suddenly (e. g.,: the dropping of a hot nail into a bucket of water).

4. The hot body must be experiencing no internal heat generation during the cooling process.

In incremental motion applications, information such as the expected motor armature temperature rise for a particular applied power pulse is essential in selecting the proper motor and duty cycle restrictions.

*It is true that proper motor temperature rating is of a more critical nature of moving coil motor manufacturers, such as PMI, since exceeding the maximum recommended armature temperature can easily damage a moving coil armature. However, since insulation life is a direct function of temperature in conventional DC motor armatures as well, a proper definition and test procedure for thermal time constant is important in applying any DC motor.*

Therefore, it is fair to ask whether the conventional DC motor meets the 4 above conditions necessary for equation (A) to be a valid description of its thermal capability. It is also proper to raise the question whether the low mass motor is not a special case, with its iron-less moving coil armature, which would invalidate equation (A) as a description of its thermal capability.

A close examination of any DC motor thermal system (including the moving coil motor), reveals that it most definitely does not meet all the necessary conditions. The main shortcoming in applying the simple case of equation (A) to any DC motor is that it is impossible to consider any DC motor as a simple, solid homogenous body with uniform temperature (condition 2). The series of parts which make up a DC motor vary greatly in their ability to transmit heat and respond to temperature changes. Examining only the armature, the main particular when determines the motor temperature rating, it is evident that it has no direct thermal contact with the surrounding ambient. Therefore, the armature 'surroundings' is the motor case. Certainly, the motor case cannot be considered to have a infinite thermal capacity, and has neither a constant temperature nor a thermal conductivity low enough to 'control' the heat transfer process (conditions 1 and 2).

On the contrary, the motor case has a finite thermal capacity that is not nearly small enough to be neglected. The temperature of the case is constantly changing as it responds to both heat influx from the armature and heat dissipation into the ambient. To speak then of a single thermal time constant for an entire DC motor as if it were a simple, solid homogeneous body (like a nail), is somewhat of a misnomer.

The motor thermal system of the more complex DC motor has at least two thermal time constants, and even a third, that affect the total response of the system:
1.     Time constant of the armature with respect to heat transfer into the case.
2.     Time constant of the case with respect to heat transfer into the ambient.
3.     Time constant of the case with respect to heat transfer form the armature.

Historically, moving coil motors have been thought of as thermally-handicapped . It has been thought that the absence of iron in the rotor of moving coil motors has prevented them from obtaining the thermal time constant magnitude that is commonly attributed to conventional ironcore DC motors.

This reasoning comes from the assumption that iron in a motor rotor should be considered part of the armature and not part of the case. From this assumption, it has been hypothesized that as part of the armature, the presence of iron greatly increases the thermal capacitance of the armature to the point that the thermal capacitance of the case can be considered thermally ineffectual. Such an increase in the thermal capacitance of the armature would, it follows, result directly in an increase in the thermal time constant of the conventional motor.

This hypothesis considers the conventional DC motor to be more accurately estimated than by the model described by equation A. It has been thought then, that the conventional DC motor can be thermally modeled as a simple, solid homogeneous body and any heat transfer between armature and case can be ignored when evaluation thermal time constant.

Moving coil motors, on the other hand, have been considered to be limited in their ability to dissipate heat, since their armatures lack the heat sinking effect that the presence of iron is generally thought to provide.

The above hypothesis has been the common explanation as to why there is such a large difference in the magnitudes of thermal time constant between conventional DC motors and moving coil motors.

The main justification for considering the conventional DC motor simply as a solid homogeneous body where internal heat transfer can be neglected is the assumption that iron in the rotor should be considered as part of the armature and not as part of the case. Indeed, the case is not even considered. However, this assumption has been made even though the ironcore is electrically and, consequently, thermally-insulated from the windings (see condition 2 of the necessary conditions for the validation of equation (A) ). The thermal effect of this insulation, in addition to the fact that iron and copper have different thermal capabilities, cannot be neglected when evaluating the thermal time constant.

To consider any DC motor (conventional or not) as a solid homogenous body is a misrepresentiaon and an oversimplification that cannot be justified by thermal tests. Instead, all DC motors should correctly be thermally-depicted by a more complex thermal model.

Simply stated, the presence of iron in the rotor of conventional DC motors does not increase the thermal capacitance of the armature and does not greatly benefit the thermal time constant of the motor, as has been previously proposed. (This is not to say that the presence of iron in the motor rotor provides no thermal benefit; for it is true that the heat sinking effect of the iron lowers the thermal resistance, armature to case, which is beneficial in continuous steady state operation with rated power input). If this is true, the reasons behind the great difference in magnitude of the thermal time constant between the conventional DC motor and moving coil motor, must lie elsewhere.

If ideally, a motor could thermally be considered a solid, homogeneous body, the proper test method for deriving the thermal time constant is to measure the armature temperature over time (as the motor cooled down from some elevated temperature). The time required for the armature temperature to fall to 63.2% of its final temperature drop would be the thermal time constant of the motor.



*This test method is analogous to simply in putting power to a motor and recording temperature over time, which is another widely used method for deriving DC motor thermal time constant. However, this method which derives thermal time constant from temperature rise rather than decay, has the additional complication of internal heat generation during the heat transfer process. (See condition 4, of the necessary conditions for the validation of equation (A)).*

However, this test method does not consider the internal heat transfer that actually occurs during the cooling of any real DC motor. The thermal time constant derived by this method is not constant at all, but is variable and dependent on the initial temperature of the case. Consequently, this test method is invalid for the definition and empirical determination of the thermal time constant. Motor thermal time constants defined by this method tend to be very long (on the order of 10-60 minutes), even for moving coil motors.

What is a proper test method for defining and empirically determining thermal time constant? Since, the bottom line to the practical application of the motor thermal time constant is incremental motion, this suggests that the proper test for the thermal time constant should be to evaluate thermal performance during actual pulse duty cycle operation. The thermal time constant should be analytically-predicted based on duty cycle data obtained empirically. The duty cycle data should be obtained by measuring actual motor armature temperature response to intermittent power pulses that may greatly exceed the rated power of the motor in incremental motion. Motor thermal time constants defined by this method tend to be rather short (on the order of 20 to 60 seconds), even for conventional ironcore DC motors.

Comparisons and tests of this nature plainly demonstrate that the reason behind the great difference in magnitudes of thermal time constant between conventional DC motors and moving coil motors is not a matter of physical makeup, but is a matter of definition. The 'thermal time constant' defined by one test method does not necessarily equal the 'thermal time constant' defined by another.

To summarize and conclude, both conventional ironcore DC motors and moving coil DC motors have a thermal time constant that when properly defined, is of the same order of magnitude.

The mass, particularly iron, in the armature of conventional slot-wound motors, does not provide the intuitive heat sink during short of cyclic overloads (i. e., pulse duty cycle operation). Instead, the practical thermal benefits of the mass is more mechanical than thermal. It tends to hold the copper in place during periods of thermal stress. This retention function has provided only a mechanical safety factor during motor operation and not a thermal safety factor, as most motor specifications suggest.

Nevertheless, the conventional ironcore DC motor has been a common choice in many machine tool and other servo applications. On the other hand, the servo response potential, zero cogging characteristics, and packaging advantages of moving coil motors have not been widely utilized in the United States.

In Europe and Japan, low mass drive motors have been used extensively in both machine tools and robotics where their overall superior performance has contributed to greater precision, accurate and repeatability than otherwise attainable.

With a proper understanding of the thermal time constant and with today's PWM amplifiers, moving coil motors may be safety specified and used in many high performance applications challenging industrial automation.