Managing PM AC Servo Motor Overloads: Thermal Time Constant

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White Paper

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When intermittent power density is of a required high value, you may ***not*** want to use classic RMS calculations and speed-torque performance curves as your only method to select a servo motor and drive. Doing so might cause an under-sizing of the motor or drive.

Utilizing classic performance curves with RMS calculations is perfectly acceptable for most servo applications; but if an application's intermittent torque is large, relative to a motor's continuous capability for some relative period of time, the thermal time constants of the proposed solution require consideration. These thermal limits are of an additional concern when further exasperated by the lack of available space.

This paper presents a visual enhancement for risk management and understanding, of the severity of the dynamic effects on thermal time constants of a servo motor when an application requires an I_actual > I_continuous for an extended time.

Servo motors generate heat due to their internal losses; and, each motor's specific ability to dissipate its own heat losses determines its rated continuous capacity. Conventional servo motor applications see multiple demands for different velocities, with torque requirements in and out of a motor's intermittent capability over a defined motion profile. Traditionally, peak currents in excess of a servo motor's continuous capability have been utilized to meet established acceleration and deceleration requirements. Motion profiles most often require these peak currents for specific periods of time (often in the millisecond range) not exceeding the typical maximum 4-5 seconds available from a drive amplifier. In these routine cases of intermittent duty operation, it is not typically necessary to select a motor based on an application's peak torque requirement, within the motor's continuous capability. We simply utilize a Root Mean Square (RMS) equation to find the application's effective continuous torque (Trms) and velocity (Nrms), requirement and then ensure that this equivalent operating requirement falls within the continuous, and thus thermal, capability of the motor chosen; while verifying that the required peak Torque (Tpk_required) < available peak Torque (Tpk_available) from the selected motor and drive, at its required RPM (revolutions per minute).

Applications: Special Conditions

The expansion of closed-loop motion control technology into less conventional applications often results in specific requirements and/or conditions of operation that exceed ordinary intermittent duty operation. However, even in conventional applications we sometimes have special conditions that must be met.

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Example:

There may be a specification that in the event of an E-stop (Emergency Stop) *all controlled motion must stop before the removal of mains power*, within a specific amount of time. This is typically not an issue for most applications, but on large machines with significant kinetic energy, the time required to bring an axis' motion to a stop can easily exceed the typical maximum 4-5 seconds of available peak current from a paired motor-drive combination [Ic(drive) equal to approximately Ic(motor)].

This requirement, though generally not demanding a larger motor, often requires a higher continuous current drive to insure the required peak current (Ipk_required) is available during an E-stop deceleration. For some large machines, time requirements for an E-stop are not uncommon in the 20_seconds and 40_seconds, range.

Many of today's Pulse Width Modulation (PWM) drives are designed with foldback overload circuits or an algorithm, utilizing the thermal time constant of the copper coil (TCT_coil), whether the current is folded back to the drive's or motor's, continuous current. However, to meet some of these non-typical servo applications the normally paired motor-drive combination that would typically be selected otherwise is not satisfactory.

A considerable number of today's servo motor applications have specific conditions of operation or specific events that can occur, that need to be accounted for during servo motor sizing and selection.

Other examples:

- There could be a vertical axis requirement for the servo motor to be capable of holding a load greater than its continuous capability for a specific amount of time before the engagement of a static brake [It being typically undesirable to cycle (engage and dis-engage) a static holding brake during normal production cycles.].
- There could be an axis requirement in preparation for an undesired event in-which the load becomes stuck or otherwise hindered from movement, where the motor must be capable of surviving some peak current for the full duration-time of a commanded move (but not properly functioning).

Whether there is an easy ability or inability to replace the motor due to its environment (e.g. normal atmosphere, radiation, space, or subsea, environment), it is desirable to select a servo motor and drive combination in such a way that minimizes the risk of failure, due to the specific events or operating requirements; and thus, maximize reliability and safety.

Overload: Effect of Power Losses

Depending on the complexity of requirements, many of these applications require torques and thus currents, above the motor's continuous capability (Ic or I_rated) as a function of the application's required RPM (e.g. Npk, Nrms). Hence, the potential limiting or control of the motor's power losses needs to be considered so that the work or specific event can be accomplished, while protecting the motor's insulation system from thermal overload. At this juncture, the motor's demanded current (I_actual) is greater than the motor's continuous rated current (Ic) capability for a significant enough period of time relative to the motor's overall thermal time constant (TCT_motor), that the TCT_motor becomes dominated by the TCT_coil due to the relative heat transfer rates between the utilized non-homogeneous materials. For these specific cases or events under evaluation, the [above] referenced RMS calculations over a given Motion Profile are most often invalid, though still desired to insure overall product selection requirements. Events requiring overload situations can differ greatly from one application to the next.

So, for these applications with some potential event or otherwise, that requires a specific peak current (I_actual) to produce a peak torque (Tpk) for a qualified period of time, we also need to understand and determine if the motor's winding/coil can sustain the overload current required without damaging the motor's insulation.

The available life of a motor's insulation (based on its continuous rating) is considered to approximately half for every 10°C reached beyond its continuous rating.

We can estimate the time to rated ultimate temperature (t_ ultimate) of the motor's coil/winding from a cold start (ambient) using the equation:

t_ultimate = -TCT_coil(mounted) x ln[1-(W_loss(rated)/W_loss(actual))]

or

t_ult. = -TCT_winding x ln[1-(Ic^2/I_actual^2)]

where W_loss(rated) is substituted with: Ic^2 or I_rated^2, and W_loss(actual) with: I_actual^2

> ***Technical Note:***
>
> *For these conditions, I_actual will be greater than the motor's Ic (continuous rated current of the servo motor at low [stall] rpm; and, under this condition the actual W_loss will continue to rise above rated values potentially causing thermal runaway depending on timely power removal).*

Formula Assumptions

Of course, the above substitution with the appropriate I^2 for watts in both the numerator and denominator, assumes constant power dissipation with a constant applied [step input] current; which due to the actual winding temperature rise from ambient temperature (e.g. Rm(25°C)) to the target temperature based on W_loss(actual), is incorrect; but offers a conservative approach with Rm(hot) assumed constant, over solving a dynamic non-linear differential equation. Additionally, the real-world application of the motor starting from a non-ambient temperature based on an Irms value requires even further manipulation.

However, whether the equation is manipulated or not; the preformed calculations tend to be done at only one or two points when needed; and the substantial effect of an actual current (I_actual) greater than continuous capability (Ic), being applied for some period of time is often missed (not specifically visualized). Thus, the intent of this paper is to present a graphical enhancement (Figure A) to demonstrate the effects of demanded Watts_loss greater than continuous capability and graphically determine a relative, if not effective, TCT for a specific condition under evaluation to overcome design challenges where the ratio: I_actual (under evaluation) / Ic (continuous current) is greater than one and known for the production of the application's required torque (T_required). The user may also determine relative comparisons of the effective TCT_motor and TCT_coil(air), under their specific condition utilizing the graph (Figure B). However, it is important to note that under the subject condition, the thermal time constant of the motor's mounted coil (TCT_coil(mounted)) is dominate over the TCT_motor; and the TCT_coil(air) is likely too conservative to be of reasonable use (it being calculated from the magnet wire's specific mass without any consideration of it being mounted within the motor's frame). *The TCT_coil(mounted), henceforth identified as the TCT_winding*, represents the first level of materials contact of the thermally non-homogeneous motor materials (e.g. coil to epoxy/air and lams).

> *Most servo motor designs in our present time, have good thermal conductivity between motor windings, laminations, and frame, especially with epoxy encapsulation; however, these are still non-homogeneous materials with significantly different heat transfer capabilities (thermal conductivity).*

Since I_actual (under evaluation) > Ic, the published TCTs [coil(air), winding (coil mounted), and motor] are no longer constant as when I_actual <= Ic, the thermal time constant under consideration is dynamically changing with the motor's actual watts loss (W_loss(actual)). For example, when the actual current (under evaluation) is <= Ic, the published TCTs for a given servo motor may have a relative range of TCT_coil(air) = 25_seconds, TCT_winding = 60_seconds, and TCT_motor = 600_seconds; however, when I_actual > Ic the effective TCTs will be significantly reduced from those published as a function: W_loss(actual) verses W_loss(rated).

Effects of Overloads on Thermal Time Constants (TCT)

In Figure A, shown below, the significance of I_actual greater than Ic(motor) under a specific condition can be seen by the resulting percentage of W_loss(actual) / W_loss(rated), both being plotted against the calculated thermal time constant (TCT) multiplier (e.g. An I_actual = 5xIc requires that the winding dissipate 2500% (25x) more watts than its rated continuous capability).

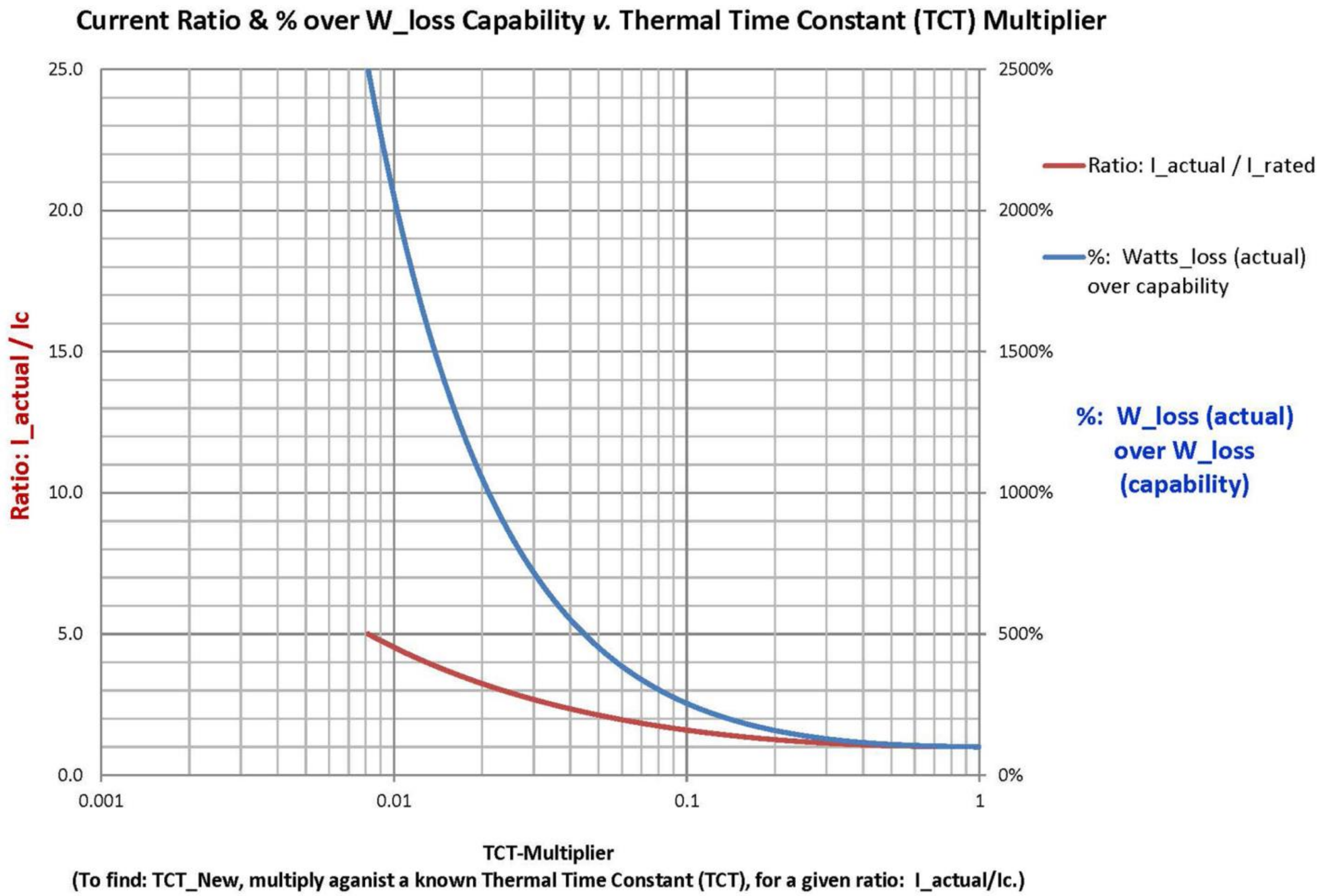

Figure A: *Presents the Thermal Time constant (TCT) effects as I_actual is increased greater than Ic.*

Figure B, on the following page, allows us to graphically determine a specific TCT and thus the time to ultimate temperature for the specific condition under evaluation, by applying the graph's X-axis' corresponding (TCT) multiplier as a function of the required I_actual against a known TCT; and then multiplying that result by 5 to achieve the time to ultimate temperature.

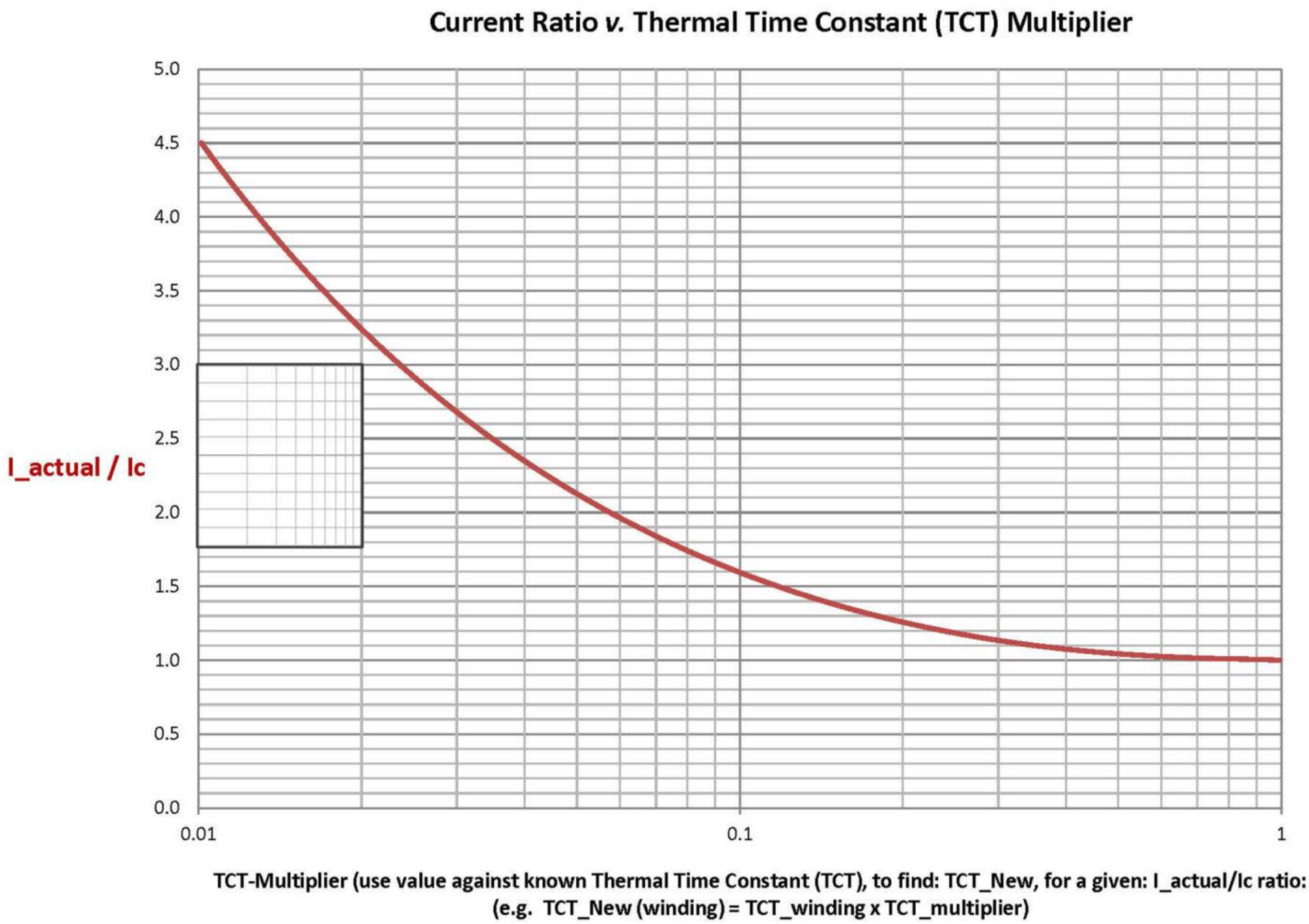

Figure B: *Presents the Thermal Time constant (TCT) MULTIPLIER for I_actual slightly greater-than Ic up to 4.5Ic.*

As an example:

Question-1: Irrespective of the drive's ability to supply current, can the motor handle 20_seconds of a peak current = 3xIc, assuming we are at an ambient temperature of 25°C from the start? Given the initially proposed motor to solve the application's normal operation has a TCT_winding = TCT_coil(mounted) = 60_seconds.

> ***Q1 Answer:*** Using Figure B, we would simply go to the vertical scale on the left in terms of 3 (3xIc) and move horizontally along until we intersect with the curve, then read the corresponding X-axis multiplier on the semi-log scale, applying its value against the published TCT_winding.

This intersection for 3Ic occurs at ~0.023 on the X-axis log scale. Thus, at 3Ic, the effective TCT_winding(3Ic) = 0.023 x 60 = ~1.38_sec.

> ***Note:*** *95% of your thermal rise will occur in 3x (thermal time constant) or ~4.14_sec [3x1.38_sec.], where 5xTCT = 99.3% of rise or 6.9_sec (the total time to ultimate rated winding temperature).*

Thus, for this application we will need to select a larger motor or a motor with a longer TCT_winding; or change the specification for the condition under consideration.

If we had utilized the formula for calculating t_ ultimate = -TCT_winding x ln[1-(Ic/I_actual)^2]; t_ ultimate = -60_sec. x ln [1-(1 /3)^2] = 7.06_seconds; yielding a TCT_winding(3Ic) = 7.06/5 or ~1.41_ seconds.

Question-2: Since the 3Ic is not possible for 30_seconds with the desired motor of Question-1, can we utilize an Ipk of 2Ic for 20_seconds?

> ***Q2 Answer:*** Again, using Figure B, our intersection for 2Ic occurs at ~0.057 on the X-axis log scale. Thus, at 2Ic, your effective TCT_winding(2Ic) = 0.057 x 60 = ~3.42_sec.; knowing that 5xTCT = 99.3% of the temperature rise is ~17.1_sec, it is still less than the proposed specification: 20_seconds.

So even with this changed specification: 2Ic for 20_seconds, we will need to select a larger motor or one with a longer TCT_winding or again change the specification for the condition under consideration.

> ***Note:*** *Smaller multiples of Ic will present a less physically dominate TCT_winding over the motor's overall thermal time constant (TCT_motor), where I_actual/Ic approaches one (1), the motor's other thermally non-homogeneous materials (e.g. Aluminum housing) come into play.*

Conclusion

Clearly, there are many factors to address during the machine design planning phase. Servo motor and drive selection for a given application affects the mechanism's chance of success for achieving desired performance for all conditions: normal operation, E-stops, and foreseen potential events. Where a motor's capability of torque and current, is required above continuous capability to achieve specific goals for an extended period of time; utilizing a simplified graphical approach (Figure B) can help overcome initial design challenges for broad risk management decisions.

This paper gives the reader a visual reference of the severity of the I_actual/Ic overload conditions. Where I_actual/Ic is high, one can estimate TCT_winding(new) or the time to ultimate temperature, fairly accurately, due to the inability of the non-homogeneous materials to transfer heat in the relative times necessary to maintain TCT_motor dominance.

However, as the ratio: I_actual/Ic approaches one, the thermodynamic response engages two exponential functions, each with its own time resulting constant (TCT_winding & TCT_motor). This blending of the distantly different thermal time constants due to the non-homogeneous materials is beyond the intent of this paper, and often needs further evaluation and understanding.

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