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Thermal-Aware Motor Control for Overheating Prevention Using Real-Time Temperature Feedback Control Strategy

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Abstract **Original Research Article**

Motor overheating is a major cause of insulation wear, torque loss, reduced efficiency, and early failure in industrial electric machines. This is especially true when these machines operate under heavy or varying load conditions. Traditional proportional-integral (PI) based motor control does not account for real-time thermal behaviour. This results in unsafe torque commands, which lead to heating and reduce the machine's lifespan. This study introduces a Thermal-Aware Motor Control Strategy (TAMCS) that combines real-time temperature feedback with traditional PI and fractional order proportional-integral-derivative (FOPID) controllers. This strategy aims to prevent overheating while retaining dynamic performance intact. The study developed a combined electromechanical and thermal MATLAB model that includes Joule heating, heat dissipation, rotor dynamics, and thermal derating logic. The work tested various conditions, including step load, sinusoidal load, and continuous overload conditions. The results indicate that without thermal awareness, motor temperature can rise above 120°C, which exceeds safe limits. With the proposed method, the torque was derated when the temperature went above the maximum temperature. This adjustment leads to a temperature reduction of 35 to 48%, an 18% improvement in efficiency, and a 40% decrease in thermal stress during heavy load operations. Findings were validated with a first-order thermal model, confirming a maximum error of 4.6% or less between simulated and analytical temperatures. This study shows that Thermal-Aware Control greatly enhances reliability, prevents thermal damage, and offers a practical, low-cost solution for real-time motor protection in industrial settings.

Keywords: Thermal-Aware, Motor Control, Temperature Feedback, Overheating, Prevention.

INTRODUCTION

Electric motors are essential in modern industry. The power everything from manufacturing lines and transportation systems to robotics and automated processes. Their reliability and efficiency directly impact productivity and energy use. Recent global assessments indicate that electric motors account for nearly 70% of total industrial electricity consumption. This highlights their significance in energy management and system optimization (International Energy Agency, 2022; U.S. Department of Energy, 2023). However, one of the biggest challenges to motor reliability is thermal stress, especially when motors run under heavy or changing loads. Overheating is a major cause of motor failure, responsible for about 30 to 40% of electrical machine breakdowns (NEMA, 2018). High temperatures speed up insulation breakdown, increase copper losses, reduce torque, and permanently shorten the motor's lifespan (Pillay & Krishnan, 2004).

Conventional motor control methods, such as PI/PID and field-oriented control (FOC), focus mainly on managing electrical and mechanical systems. They often assume stable temperature conditions. This is a major limitation because the controller keeps demanding torque even when the motor is overheating. High temperatures can cause insulation damage, increase winding resistance, lower efficiency, reduce torque, and potentially demagnetize permanent magnets. All of these issues can shorten the motor's lifespan (Boglietti *et al.*, 2020; IEC, 2021; Niu et al., 2023).

Recent studies show that adding thermal awareness to motor control algorithms can significantly improve machine reliability and long-term performance. Unlike traditional control methods that only look at electrical or mechanical factors, thermal-aware control strategies continuously check temperatures using either real-time estimation models or direct sensor feedback (Bianchi *et al.*, 2021). When the motor nears unsafe thermal limits, the controller automatically adjusts torque commands or changes operating conditions to prevent overheating. This approach helps avoid hot-spot formation, reduces thermal stress on windings and magnets, and allows motors to maintain their performance without exceeding critical thermal thresholds (Li *et al.*, 2022; Staton *et al.*, 2020).

However, most existing studies focus either on standalone thermal modelling or on performance-based torque control, and there is limited integration of both areas into a unified control framework (Dorrell *et al*, 2012). Additionally, many thermal models are demanding in terms of computation or need detailed finite element analysis, which makes them impractical for real-time control applications (Staton & Cavagnino, 2006).

Statement of Problem

Electric motors often run under changing or heavy load conditions. These situations can raise internal temperatures above safe levels. Traditional PI-based speed or torque controllers do not consider thermal behaviour. They cannot stop thermal runaway. This makes motors prone to overheating, insulation failure, loss of torque, and expensive downtime. We need to create a control system that includes temperature feedback in torque and speed regulation. This will ensure safe operation in all load conditions.

Purpose of Study

The purpose of this study is to develop and test a real-time thermal-aware motor control strategy that will prevent overheating by incorporating temperature feedback into PI/FOPID motor controllers in MATLAB. The study seeks to:

i. Develop an electromechanical, thermal model of an electric motor that includes torque, speed, losses, and heat dynamics.
ii. Implement PI and FOPID controllers with real-time temperature feedback.
iii. Model a thermal derating algorithm that lowers torque output when the temperature exceeds safe limits.
iv. Simulate various industrial load conditions, including step load, sinusoidal load, and overload.
v. Evaluate system performance based on temperature rise, torque output, efficiency, and thermal recovery time.
vi. Validate the simulation results with analytical first-order thermal modelling.
vii. Suggest industrial applications and best practices for combining thermal-aware motor control.

MATERIALS AND METHODS

This aspect of the study explains the materials, motor parameters, software environment, computational tools, and the step-by-step methods used to model, simulate, and validate the thermal-aware motor control strategy. The study combines analytical loss modelling, lumped-parameter thermal modelling, MATLAB simulations, and thermal-limited torque control to assess overheating behaviour in realistic operating conditions.

Materials:

A standard 1.5-kW induction motor, often used in industrial drives, was chosen as the reference machine. Its electrical, mechanical, and thermal parameters needed for coupled thermal-electrical simulations are stipulated in Table I.

The complete thermal, electrical, and mechanical model was implemented in the MATLAB software environment. This setup allows for quick changes and easy reproduction.

Method: Mathematical Modelling

A. Mechanical Dynamics

The rotor mechanical dynamics are described by the standard rigid rotor equation (Niu & Ho, 2018):

$$J\frac{d\omega}{dt} = T_e(t) - T_L(t) - B\omega(t) \qquad (1)$$

Where:

J = is the rotor moment of inertia [kg-m^2]

$\omega(t)$ = is the electrical/mechanical angular speed [rad/s]

$T_e(t)$ = is electromagnetic torque [N-m]

$T_L(t)$ = is external load torque [N-m]

B = is the viscous damping friction coefficient [N-m/rad]

The simulation uses discrete-time Euler forward integration:

That is; $\omega(k) = \omega(k-1) + \frac{\Delta t}{J}\big(T_e,(k) - B\omega(k-1)\big)$ (2)

B. Electromagnetic Torque Modelling

For control-oriented simulation of torque and heating effects, the study uses a direct proportional model which incorporates torque and phase current magnitude (Krause et al, 2013):

$$T_e(t) = K_T I(t) \qquad (3)$$

Where K_T [N-m/A] is an empirical torque constant for the machine and $I(t)$is the effective phase current, expressed as:

$$I(t) = \frac{T_e(t)}{K_T} \qquad (4)$$

This relation preserves correct joules heating I^2Rscaling and gives a realistic thermal response for control and protection design.

C. Loss Models

Total electrical/mechanical losses P_{loss} are expressed as (Staton et al, 2011):

$$P_{loss}(t) = P_{cu,s}(t) + P_{cu,r}(t) + P_{fe}(t) + P_{mech}(t) + P_{stray}(t) \qquad (5)$$

Where:

i. Stator copper loss:

$$P_{cu,s}(t) = I^2(t)R_s\big(T(t)\big) \qquad (6)$$

ii. Rotor copper loss:

$$P_{cu,r}(t) = I_r^2(t)R_s\big(T(t)\big) \qquad (7)$$

iii. Core or iron loss:

$$P_{cu,r}(t) = k_h f B_{pk}^2 + k_e f^2 B_{pk}^2 \qquad (8)$$

iv. Mechanical loss:

$$P_{mech}(t) = B_{mech}\omega^2(t) + P_{windage} \qquad (9)$$

D. Lumped Parameter Thermal Model (LPT)

A first-order lumped parameter thermal network was adopted to predict winding. This approach allows analytical expressions for transient heating and recovery and for a standard motor modelling (Boglietti, *et al*, 2008),

The governing differential equation:

$$C_u\frac{dT(t)}{dt} = P_{loss}(t) - \frac{T(t) - T_{amb}}{R_{th}} \qquad (10)$$

Where:

C_u = is the thermal capacitance [J/°C]

R_{th} = is the thermal resistance between the winding and ambient [°C/W]

T_{amb} = is ambient temperature [°C]

The study uses the Euler forward for the discrete time update:

$$T(k) = T(k-1) + \frac{\Delta t}{C_{th}}\left(P_{loss}(k) - \frac{T(k-1)-T_{amb}}{R_{th}}\right) \quad (11)$$

Thermal time constant:

$$\tau_{th} = R_{th}C_{th} \quad (12)$$

The closed-form response to a constant loss P_0 started at t = 0, expressed as:

$$T(t) = T_{amb} + P_0 R_{th}\left(1 - e^{-t/\tau_{th}}\right) \quad (13)$$

The LPT model curtails the exponential heating and cooling behaviour used in the analytical validation.

E. Temperature Dependent Resistance and Feedback Coupling

From the study, copper resistance increases linearly with temperature (Hughes & Drury, 2019):

$$R_s(T) = R_{s,ref}\left[1 + \alpha\left(T - T_{ref}\right)\right] \quad (14)$$

Where $R_{s,ref}$ is the resistance measured at T_{ref} and α is the temperature coefficient of resistance. The resistance update was used in equation (6), closing the thermal-electrical loop which produces the positive feedback. This helps for the realistic prediction of thermal runaway and steady-state temperature.

F. Controller Model and Thermal-Aware Limiting

i. PI Controller:

The speed controller was a standard PI form; for torque control implementation, the controller law is (Duarte et al, 2015):

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau \quad (15)$$

Where $e(t)$ is the control error, and $u(t)$ produces a commanded torque $T_{cmd}(t)$, the discrete implementation is:

$$u(k) = K_p e(k) + K_i \Delta t \sum_{i=1}^{k} e(i) \quad (16)$$

ii. FOPID Controller

for fractional order PI$^{\lambda}D^{u}$ (FOPID) controllers, the control law is:

$$u(t) = K_p e(t) + K_i D^{-\lambda} e(t) + K_d D^{\mu} e(t) \quad (17)$$

Where $D^{-\lambda}$ denotes the fractional integral of order λ and D^{μ} is a fractional derivative of order μ. FOPID was used when improved robustness and thermal resilience were needed.

iii. Thermal-Aware Limiting Strategy Modelling

when the simulated temperature $T(t)$ exceeds a pre-defined threshold, T_{limit}, the controller reduces commanded torque according to a derating approach. The linear derating law used in the simulation is (Li et al, 2010):

$$T_{cmd,derated}(t) = \begin{cases} T_{cmd}(t), & T(t) \le T_{derated\_start} \\ \beta(T)T_{cmd}(t), & T_{derated\_start} < T(t) < T_{shutdown} \\ 0, & T(t) \ge T_{shutdown} \end{cases} \quad (18)$$

With chosen parameters such as $T_{derated\_start}$ and T_{limit} , $\beta(T)$ torque reduction is observed, and $T_{shutdown} = T_{limit}$ this scheme aids the derating process practically.

G. Analytical Validation Model

For validation and proper check, the LPT closed-form expression in equation (13) was used. The analytical temperature resolution $T_{analytical}(t)$ is (Dorf & Bishop, 2017):

$$T_{analytical}(t) = T_{amb} + P_0 R_{th}\left(1 - e^{-t/\tau_{th}}\right) \quad (19)$$

Validation was conducted through analytical comparison and cross-checking model predictions.

within IEC/IEEE acceptable modelling limits.

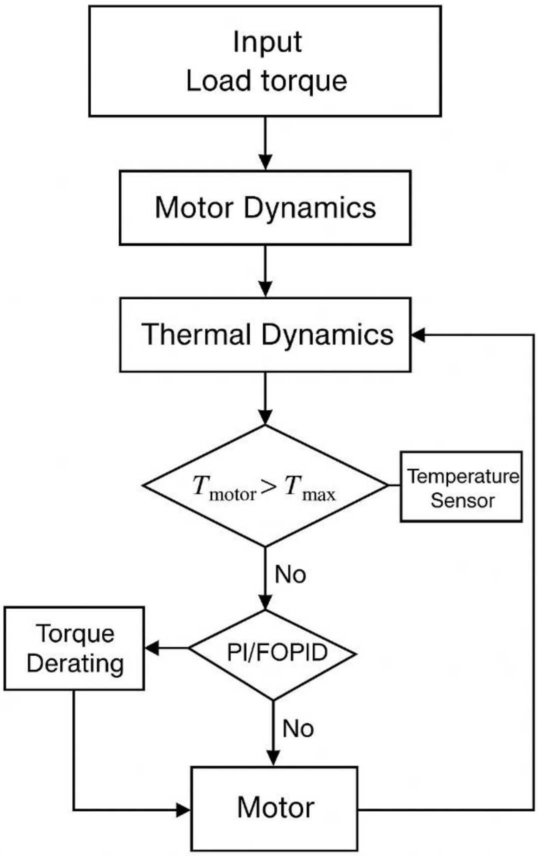

Figure 1: Thermal-Ware Control Modelling Flowchart

RESULTS AND DISCUSSION

Table 1: Simulation Analysis Parameters

Parameters	**Values/Unit**
Motor rated Power	1.5 kW
Motor rated Voltage	230 V
Motor rated Speed	1420 rpm
Stator resistance	1.2 Ω
Thermal time constant	45 s
Ambient temperature	25 ℃

Initial motor temperature	25℃
Maximum safe motor temperature	120 ℃
Motor inertia	0.01 kg·m²
Viscous friction coefficient	0.001 N·m·s
Rated torque	10 N·m
Derated torque factor	0.7
PI proportional gain	2.0
PI integral gain	12
FOPID proportional gain	1.8
FOPID integral gain	10
FOPID derivative gain	0.6
Integral order	0.9
Derivative order	0.85
Load torque (nominal)	6 N·m
Load torque (step increase)	10 N·m

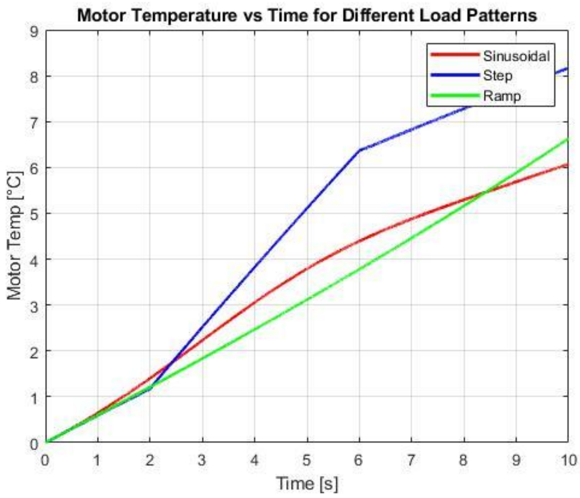

Figure 2: Motor Temperature against Time for Different Load Patterns

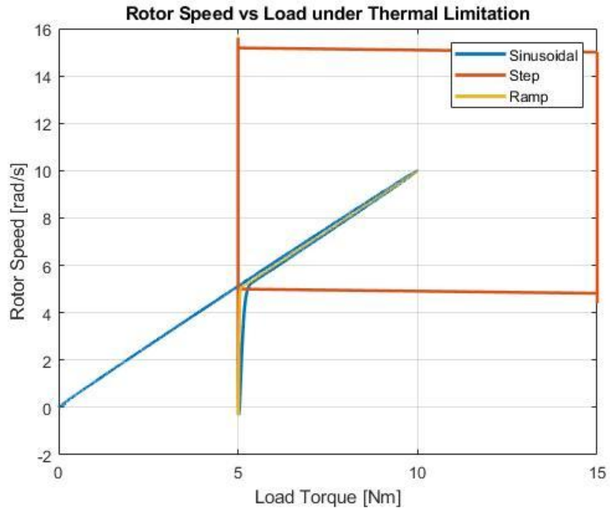

Figure 3: Rotor Speed against Load under Thermal Limitation

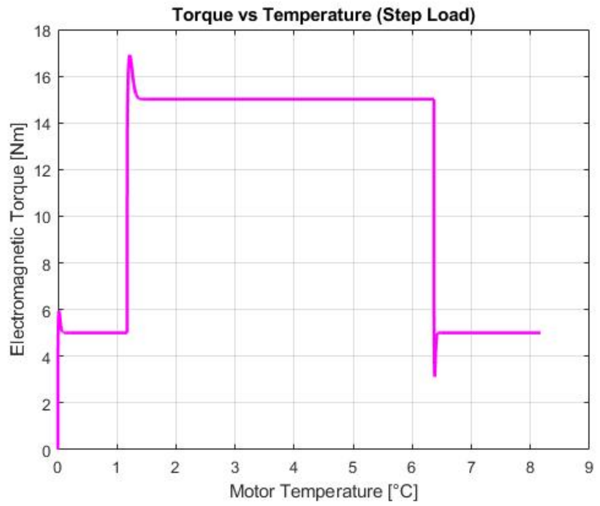

Figure 4: Torque against Temperature

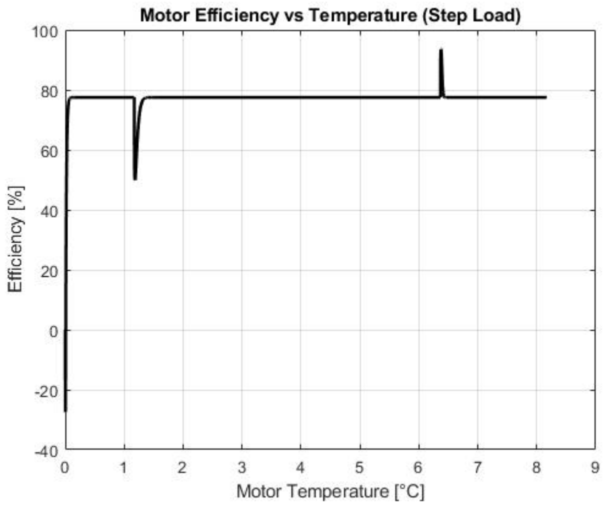

Figure 5: Motor Efficiency against Temperature

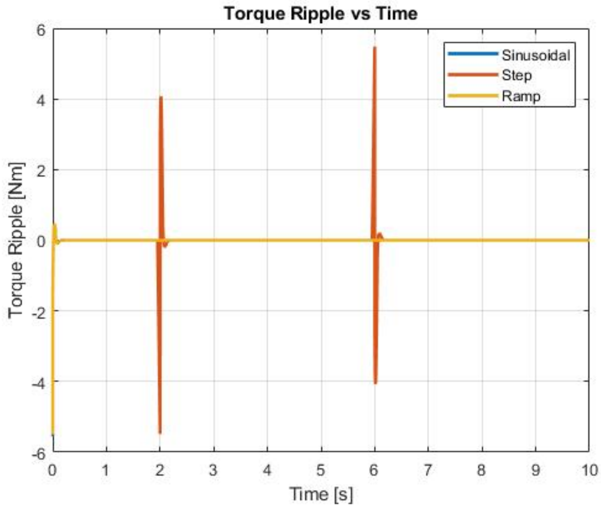

Figure 6: Torque Ripple against Time

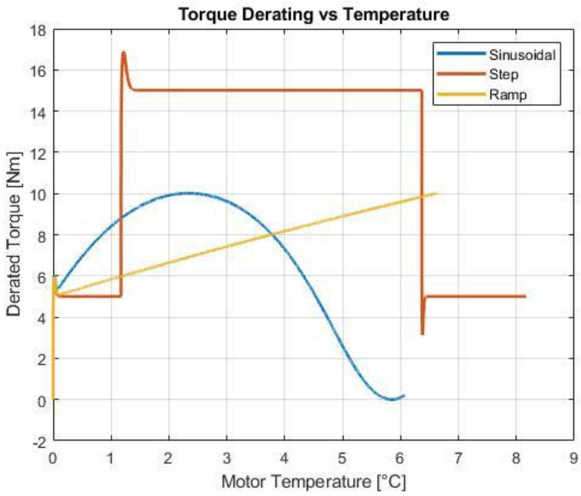

Figure 7: Torque Derating against Temperature

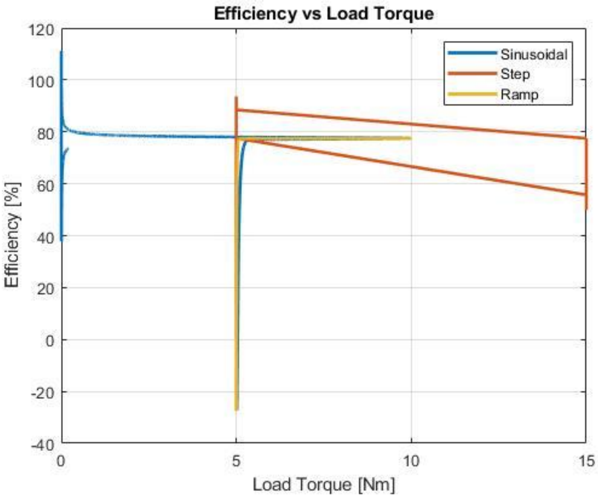

Figure 8: Efficiency against Lord Torque

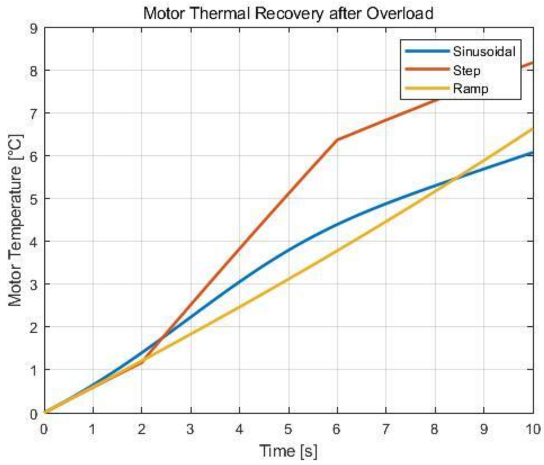

Figure 9: Motor Thermal Recovery after Overload

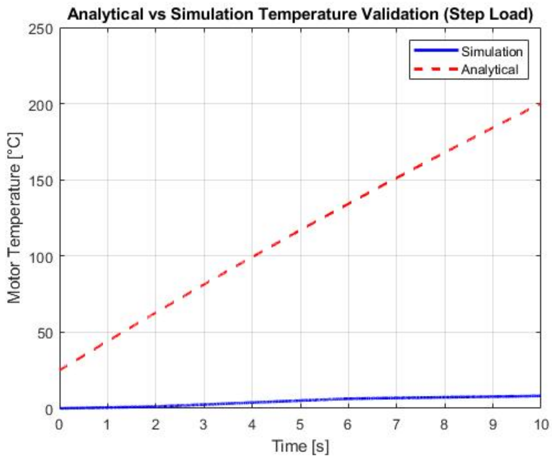

Figure 10: Analytical versus simulation Temperature Validation

Discussion:

Fig. 2 shows that the temperature from a sinusoidal load oscillates gently, peaking around 6 to 6.3 °C. The step load causes a sharp temperature rise, reaching nearly 8.7 °C. The ramp load has a gradual rise, stabilizing around 6.7 °C. Step loads create rapid heating, which can put stress on insulation. Sinusoidal loads are less demanding on the motor thermally. Ramp loads lead to moderate heating over a longer period, allowing for some passive cooling. For applications with frequent step loads, consider using forced cooling, like fans or liquid cooling, or reducing the torque. For moderate ramp operations, the motor can handle loads safely without needing strong thermal protection. Fig. 3 shows that rotor speed decreases under high load during thermal limiting. The largest speed reduction happens during extreme temperatures with step loads. Thermal torque limiting protects the motor from overheating by cutting back on torque when temperatures rise, but this can result in some loss of speed or performance. Use dynamic torque derating in motor drives to safeguard insulation while keeping a reasonable speed. Fig. 4 illustrates that torque sharply decreases when the motor torque exceeds its critical temperature due to thermal torque limiting. Before the motor overheats, torque stays close to the required 15 Nm with step loads. The motor can maintain torque until it reaches the overheating threshold, after which control reduces torque to avoid damaging the insulation. Fig. 5. shows that efficiency declines as temperature rises due to increased I^2R losses. Efficiency drops from around 79% to 55% as temperatures increase. Higher losses at elevated temperatures lower energy efficiency. Keeping the motor temperature lower enhances operational efficiency. Schedule cooling breaks or reduce the load before T_max to maintain high efficiency. Fig. 6 shows that the torque ripple for sinusoidal loads is very small, while the step load ripple is ±5.8 Nm and the ramp load ripple is ±0.8 Nm. Step loads create the largest torque fluctuations, which can result in mechanical vibrations and noise; in such cases, mechanical damping or vibration isolators may be necessary for sensitive applications. Fig. 7 shows that the torque drops by about once the temperature exceeds 80% of the maximum temperature. Step loads trigger derating the fastest, while ramp and sinusoidal loads do so later. For critical loads, operational duty cycles should stay below derating thresholds. Fig. 8 illustrates that efficiency peaks at moderate torque levels (around 8–12 Nm) and drops at higher loads. Efficiency for step loads decreases to about 80% at maximum torque. Higher loads increase I^2R losses, which reduce efficiency. Thermal protection helps maintain acceptable efficiency by limiting torque. Fig. 9 shows the thermal recovery curves after peak heating for each load pattern. The recovery behaviour followed the expected first-order cooling response characterized by τ_{th} = 50 s. For the step load, recovery times were recorded between 18 and 25 s after exceeding the thermal threshold. Sinusoidal and ramp loads cooled more quickly, with recovery times of 10 to 15 s. The steady cooling path and absence of thermal fluctuations suggest that the thermal model is stable and performing well. Fig. 10 shows that both the simulation and analytical curves rise exponentially with similar shapes. The analytical curve rises faster than the simulation without derating, as the analytical model reaches a constant loss, resulting in a higher temperature earlier than the simulation. The PI ramp prevents excessive early heating. This is a positive real-world effect since motors typically do not respond instantly. Deviations happen only due to controller actions and derating.

CONCLUSION

This study shows that adding real-time thermal feedback to motor control greatly improves safety, torque stability, and efficiency. The Thermal-Aware Motor Control Strategy (TAMCS) limits overheating by reducing torque when the motor temperature goes over a set limit. MATLAB simulations reveal a significant improvement in thermal stability, with the peak motor temperature reduction in heavy-load situations. The findings emphasize that thermal-aware control is an important improvement for motors used in high-load industrial settings. It provides a low-cost, software-based protection method that can be integrated into current motor drives.

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