# Stator Temperature Estimation in Permanent Magnet Synchronous Motors for Low Speed direct-drive Systems

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***Abstract*—Online stator temperature tracking is important for high performance permanent magnet machines especially in direct-drive systems. During contact with the environment the motors operate in the high torque and low speed regime, close to stall, which places thermal stress on the motor windings. This paper proposes a simplification of the PMSM voltage equation by neglecting derivatives of current and the back-emf at near zero speed and stall conditions, to measure the stator resistance for direct-drive systems. A MATLAB/Simulink simulation of a PMSM is used to verify the this method. The results show the maximum temperature estimation error was found to be $\pm$ 2 degrees C.**

## I. INTRODUCTION

Permanent magnet synchronous motors (PMSM) are a common actuator choice for robotic systems due to their high efficiency, compact form, and torque performance. As robots interact with or maneuver through their environment, unexpected loads, certain postures, and contact can induce a high thermal stress on the motor. Consequently, this can impact the operational performance of the motor, since winding resistance and magnetic flux vary with temperature, and also degrade the stator winding insulation [7]. Temperature sensors can be used to track the stator temperature, however design limitations may make this an infeasible option. Alternative approaches are to use sensorless methods to estimate stator winding resistance. Since resistance varies linearly with temperature, it provides a direct measurement of the average winding temperature.

The two main approaches to resistance estimation can be classified as invasive or non-invasive. Invasive methods use an excitation voltage or current as signal injection to measure resistance, proposed in [4, 7]. However, these methods normally cause torque ripple and are unacceptable for certain applications. Non-invasive approaches estimate stator resistance passively. Observer based methods, such as the Extended Kalman Filter (EKF) [3] and the Model Reference Adaptive System (MRAS) [5], perform online motor parameter estimation to determine stator resistance. These typically require accurate initial motor parameters at a known temperature to provide accurate resistance estimates.

direct-drive robots such as Minitaur [2] or the DDHand [1] operate primarily at high torque and low speed or stall, with brief or periodic movement at moderate to high speeds. Thus, a conventional method of resistance estimation can be employed which is fast to implement and utilizes minimal computational resources [4]. In this paper, a sensorless method of stator resistance estimation for monitoring the motor winding temperature is proposed. Since the operating regime is at low speeds, the phase voltage equations are simplified by neglecting the voltage contribution from self-inductance and back-emf under a predetermined angular velocity and current threshold.

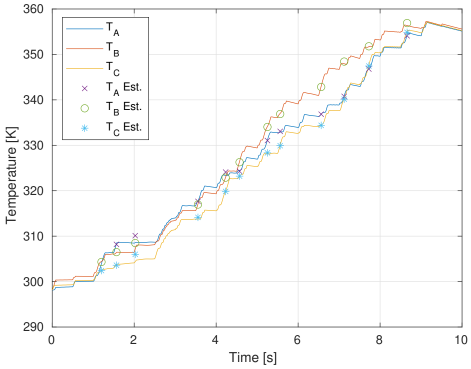

Fig. 1. Comparison of the thermal model winding temperatures to the estimated winding temperatures

## II. PMSM MODEL

The PMSM is modeled in the d-q reference frame, where the voltage equations are defined by [6]:

$$\begin{aligned} v_d &= r_{dq} * i_d + \frac{d\lambda_d}{dt} - \omega_e * \lambda_q \\ v_q &= r_{dq} * i_q + \frac{d\lambda_q}{dt} - \omega_e * \lambda_d \\ \lambda_d &= L_d i_d + \lambda_{pm} \\ \lambda_q &= L_q i_q \end{aligned} \tag{1}$$

where $v_d$, $i_d$, $L_d$, and $\lambda_d$ are the d-axis voltage, current, inductance, and flux linkage, similarly, $v_q$, $i_q$, $L_q$, and $\lambda_q$ are the q-axis voltage, current, inductance, and flux linkage. $\omega_e$, $r_{dq}$, $\lambda_{pm}$, and $P$ are the motor electrical angular velocity, the stator resistance, permanent magnet flux, and the number of magnet pole pairs, respectively.

## III. RESISTANCE ESTIMATION

Stator winding resistance varies as a function of temperature defined by [3]:

$$R_s = R_{ref} + \alpha \cdot R_{ref}(T_s - T_{ref}) \tag{2}$$

where $R_s$ is the winding resistance at temperature $T_s$, $R_{ref}$ is the winding resistance at temperature $T_{ref}$, and $\alpha$ is the temperature coefficient of copper. By neglecting the contribution from the derivatives of current in equation 1, the conventional stator resistance equation can be written as

$$R_s = \frac{v_q - \lambda_{pm}\omega_e}{i_q} \tag{3}$$

since the d-axis current is normally zero. Estimation of the stator winding resistance is challenging for several reasons. The voltage contribution from resistance during moderate to high-speed operation is small compared to the voltage contribution from back-emf or inductance, on the order of a few percent [7]. Futhermore, the stator resistance, shown in (2), and permanent magnet flux are dependent on temperature. To determine the voltage contribution from back-emf during operation the rotor temperature must be known to determine the change in the permanent magnet flux. In equation (3), it can be seen that any error in the permanent magnet flux, motor speed, or voltage measurements will be amplified by current, in particular when current is small [4]. A higher winding resistance improves resistance estimates, since its relative voltage contribution is greater and has a low signal-to-noise ratio (SNR) at low currents. From (2), a temperature resolution of ±10°C requires that the resistance estimate error not exceed 4%. To overcome the problem of needing the rotor temperature and managing with the small relative voltage contribution from resistance, the voltage and current measurements can be acquired when the system is below some threshold angular velocity and at high torque. As a consequence the voltage contribution from back-emf and inductance will be small, such that the voltage equation (1) reduces to

$$v_q = r_{dq} \cdot i_q \tag{4}$$

With a sufficiently fast sample rate, the resistance estimates can be determined during brief joint acceleration or deceleration by averaging the measurements over time.

## IV. Simulation and Results

A PMSM simulation is created in the MATLAB/Simulink environment. In this simulation, the phase current and voltages are measured directly from motor phases. Additionally, an encoder is connected to the motor output shaft to measure the angular velocity. The angular velocity and current thresholds were determined experimentally for the given stator resistance. Table IV lists the parameters of the motor.

TABLE I
Motor Parameters

| | |
|---|---|
| Pole Pairs | 6 |
| Winding Resistance | 1 [Ω] |
| Flux-Linkage | 0.1 [Wb] |
| Winding Inductance | 0.0003 [H] |
| Inertia | $5e-6$ [kg $\cdot m^2$] |

Fig. 2 illustrates the motor tracking a square wave speed reference signal with a random amplitude and a frequency of 0.5 Hz. Fig. 1 shows the resistance estimate at each zero crossing in Fig. 2, since the conditions of being near stall and having large phase currents are met. Over the entire range the error between the thermal model winding temperature and the estimated temperature was within ± 2 degrees C.

## V. Conclusion

This paper demonstrates that the conventional resistance equation can be used to accurately estimate the stator resistance, if an actuator primarily operates in the near zero speed or stall regime. This requires large currents during measurements and taking measurements at stall conditions. The results of the simulation show that, with tuning the current and motor velocity thresholds, the temperature estimation of the winding can be acquired to within ± 2 degrees C.

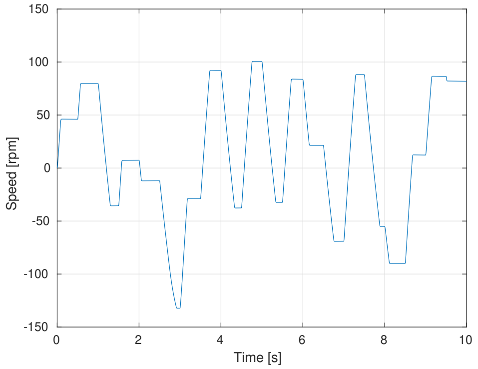

Fig. 2. Angular velocity of the PMSM rotor

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