Sensorless Control of a Planetary Motor

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Abstract

This paper presents the sensorless control capabilities of a Planetary Motor, a novel Permanent Magnet Synchronous Machine (PMSM) design introduced in 2017. Although the Planetary Motor is a multi-rotor machine, it electrically acts like a single-rotor machine. This can be utilized to apply sensorless control algorithms like the INFORM and Back-EMF method to provide the rotor angle information for field-oriented control in the entire speed range including standstill. Measurements of both sensorless methods are presented and as the evaluation shows, these methods are applicable to the Planetary Motor.

1 Introduction

Sensorless control methods have been a topic of research for many years and applied to a wide range of electric machines ([1], [2], [3]). Replacing the encoder with mathematical models does not only result in an economical benefit but also eliminates the risk of an encoder fault. This paper investigates if these widely used control techniques are also suitable for this multi-rotor machine. The analysis is done on a prototype of the four-pole topology of the Planetary Motor [4], see Fig. 1. This machine consists of four interior permanent magnet rotors in a common stator with 12 coils, which are fed by an ordinary voltage source inverter (VSI). The interconnection of the coils results in a three-phase winding system, which can be connected either in a star- or delta-connection, and it produces four locally rotating fields, where adjacent rotors turn in opposite directions. All four rotors are mechanically linked through a modified planetary gear set in order to drive a common output shaft. This multirotor approach theoretically allows a higher power density of the electric machine. For details about this machine type and its mathematical theory see [5], [6].

The different sensorless control methods and their application are outlined in Section 2. Section 3 presents experimental results followed by an evaluation and potential improvements in Section 4.



Fig. 1: Schematic structure of a four-pole Planetary Motor (without gear set and shaft).

2 Sensorless Control

2.1 INFORM method and Back-EMF model

Generally, the INFORM¹-method utilizes differences in the stator inductance over the rotor circumference (*magnetic saliency*) to estimate the

¹Indirect Flux detection by Online Reactance Measurement



Fig. 2: Field-oriented control structure of the Planetary Motor

rotor position [7]. The INFORM method used in this paper is comprised of two parts. First, the *modified INFORM*-method is a onetime startup test sequence to identify the rotor's d-axis. Distinct voltage patterns and the resulting current slopes are used to calculate the initial rotor angle. Afterwards, the *standard INFORM*-method is used, where voltage pulses are integrated into the PWM sequence, so the rotor angle can be continuously estimated without interrupting the motor control.

The back-EMF (electromotive force) method is applied in the high-speed-range, where the machine's induced voltage is used to calculate the rotor orientation [7].

Although there are more sophisticated solutions on how to switch between these two sensorless position estimation methods, in this paper a hard switching between the models at a fixed rotational speed of 15% of the machine's rated speed was chosen as this is a subject for future investigations.

2.2 Application to the Planetary Motor

If each rotor theoretically had its own stator, the common stator of the Planetary Motor would magnetically merge those stators in such a way that the resulting field distribution in the four air gaps would be unchanged. Because all rotors are mechanically coupled, their orientation relative to one another also does not change. In combination with a properly assigned winding system the Planetary Motor can therefore be represented as a single-rotor three-phase machine ([5],[6],[8]). As already mentioned, magnetic saliency is beneficial for sensorless position estimation with the INFORM method. If each rotor shows a certain saliency, then the apparent single rotor will also show these differences in the stator inductance along the rotor circumference. In a simple model the Planetary Motor can be described in a classical dq-reference frame with

$$\psi_{S} = \psi_{M} + l_{d}(i_{d}) \, i_{d} + j l_{q}(i_{q}) \, i_{q} \,, \tag{1}$$

where cross-coupling inductances l_{dq} and l_{qd} are neglected. Now the goal is to identify these (currentdependent) inductances $l_d(i_d)$ and $l_q(i_q)$ and find the position of the true d-axis for the field-oriented control.

2.3 Control Structure

The Planetary Motor control is based on a cascaded PI current- and speed-control loop as depicted in Fig. 2, identical to a control scheme of a conventional single-rotor PMSM. The encoder is

only used for verification of the estimated angle. The mechanical subsystem can be modelled as

$$\frac{d}{d\tau}\gamma = \omega \tag{2}$$

$$\frac{d}{d\tau}\omega = \frac{1}{\tau_m}(m_R - m_L(\tau))\,,\tag{3}$$

where τ_m is the (per-unit) mechanical start-up time, m_R the rotor torque and m_L the load torque as a generally unknown, time-dependent function. It should be noted that these quantities represent a substitute system of all rotors combined with the gear set. It is safe to assume that within one sampling step the rotational speed ω and the load torque m_L are constant, therefore

$$\frac{d}{d\tau}\omega = 0 \tag{4}$$

$$\frac{d}{d\tau}m_L = 0.$$
 (5)

The difference equations of the simplified, discretized system with a sampling time of τ_S are

$$\begin{bmatrix} \gamma_{k+1} \\ \omega_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & \tau_S \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \gamma_k \\ \omega_k \end{bmatrix}, \quad (6)$$

leading to a Luenberger-observer [9] described by

$$\begin{bmatrix} \hat{\gamma}_{k+1} \\ \hat{\omega}_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & \tau_S \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{\gamma}_k \\ \hat{\omega}_k \end{bmatrix} + \begin{bmatrix} \hat{K}_\gamma \\ \hat{K}_\omega \end{bmatrix} (\gamma_k - \hat{\gamma}_k)$$
(7)

$$\hat{\mathbf{y}}_{\mathbf{k}} = \begin{bmatrix} \hat{\gamma}_k \\ \hat{\omega}_k \end{bmatrix} . \tag{8}$$

Depending on the actual speed either the INFORM or the BEMF angle is the input of the observer. The feedback-factors \hat{K}_{γ} and \hat{K}_{ω} are determined empirically until satisfactory noise reduction is achieved. The output of the observer is used as feedback to the speed-control loop and also for the coordinate system transformations. For the stationary load measurements in Section 3.2 the observer was adjusted accordingly to further decrease the angle error margins, while the achievable dynamic of the system is reduced.

3 Experimental Results

To verify the sensorless control methods a prototype of the four-pole Planetary Motor (Tab. 1, Fig. 3) was set up on a test bench with a DC load machine.

Feature	Value
Nominal phase current	250 A
Nominal phase voltage	240 V
Nominal output speed	850 rpm
Nominal output torque	600 N m
Iron core length	100 mm
Gear ratio	10:1

Tab. 1: Prototype specifications



Fig. 3: Assembled prototype on test bench

3.1 Machine Inductances

As magnetic saliency greatly improves the INFORM control capabilities of a machine, the inductances $l_d(i_d)$ and $l_q(i_q)$ were measured using the equations (9)-(18) to identify this machine characteristic. In steady state conditions:

$$\psi_d = \psi_M + l_d(i_d)i_d \tag{9}$$

$$l_d(i_d) = \frac{\psi_d - \psi_M}{i_d} \tag{10}$$

$$u_q \bigg|_{i_q=0} = \underline{r}_s i_q + \omega_{el} \psi_d \tag{11}$$

$$\rightarrow \psi_d = \frac{u_q}{\omega_{el}}$$
 (12)

$$l_d(i_d) = (u_a/\omega_{el} - \psi_M)/i_d$$
 (13)

$$\psi_q = l_q(i_q)i_q \tag{14}$$

$$l_q(i_q) = \frac{\psi_q}{i_q} \tag{15}$$

$$u_d \bigg|_{i_d=0} = r_s \dot{i_d} - \omega_{el} \psi_q \tag{16}$$

$$\rightarrow \psi_q = -\frac{u_d}{\omega_{cl}} \tag{17}$$

$$l_q(i_q) = (u_d/\omega_{el})/i_q \tag{18}$$

Figure 4 shows the measured inductances and the resulting saliency of this machine. Although a positive d-current is not a typical use case for a PMSM, this measurement indicates the beneficial precondition for INFORM application. Typically, l_q should continuously decrease with increasing current magnitude just like l_d (due to saturation), but the voltage measurements are more and more inaccurate with lower magnitudes. In this case it is a known error of the voltage measurement equipment, which strongly affects the l_q measurements at low values. The difference of l_d and l_q can also be utilized to generate reluctance torque (illustrated by the MTPA-block in Fig. 2) by using an additional negative i_d in contrast to using only i_q .



Fig. 4: Measured inductances l_d , l_q with $i_q = 0$ and $i_d = 0$ respectively

3.2 INFORM/BEMF measurements

Due to the mechanical coupling of the rotors only one sensor is required to validate the sensorless angle estimation. An on-axis magnetic rotary encoder was used on one of the four rotor shafts. First, the INFORM method was tested at the stationary nominal load and a constant speed of 4%. Figure 5 shows the results of the estimated





Fig. 5: INFORM measurements at $\omega\!=\!0.04$ and nominal load

angle and the statistical distribution of the angle error $\gamma_{\Delta} = \hat{\gamma} - \gamma_{Encoder}$. The resulting distribution is similar to a Gaussian curve (as shown in previous work [10]) and the low standard deviation of 2.53° shows that this machine is well-suited for INFORM application. The rotor geometry in combination with the stator geometry provides a certain magnetic saliency, which ensures a robust INFORM operation.

To verify the BEMF method the Planetary Motor was driven at 15% rated speed and at 50% rated load.

Although the results shown in Fig. 6 are slightly worse than the results of the INFORM method, the observer angle error with a standard-deviation of 5.13° is still well-suited for speed control. Both the INFORM and BEMF model are subject to a load-dependent angle error which needs to be compensated. For the stationary measurements a very simple approach of adding a constant offset to the observer angle was chosen. This way a good performance (in terms of the angle error) can be achieved.





3.3 Sensorless control over the entire speed range

In order to provide robust angle estimation over the entire speed and load range, the simple approach

of using a constant angle offset for the error compensation is not sufficient anymore because of the load-dependence of the angle error.

Therefore, the angle error over the entire load range was stored in a look-up table and is used to dynamically compensate the INFORM angle error. Figure 7a shows an exemplary start-up measurement with constant torque. At the time of switching from the INFORM to the BEMF model a large transient angle error can be observed (Fig. 7b). This is due to the hard switching between the two models.



(c) Histogram of the angle error γ_{Δ}



After approximately 200 ms the BEMF-model reaches a steady state of zero mean angle error. The mean value of the angle error of 3.55° with a standard deviation of 8.81° over the entire speed-up measurement (Fig. 7c) is clearly worse than in the stationary measurements, but it still can be considered an acceptable control performance. Consequently, the entire speed range from standstill to rated speed can be controlled with sensorless rotor position estimation.

4 Conclusions

This paper showed that sensorless control methods, originally developed for single-rotor machines, can successfully be applied to multi-rotor machines like the Planetary Motor. A conventional, cascaded control structure including a mechanical observer was used. Both the INFORM method at standstill and low speeds as well as the Back-EMF method at rated speeds above 15% yielded sufficient results for sensorless control over the entire speed range. However, the results could further be improved by introducing a mixing of the INFORM- and BEMFangle in a certain speed range to avoid the hard switching between the two models. Also, the BEMF-model itself could be improved by tuning the model parameters and introducing a dynamic offset-correction similar to the INFORM model.

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