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Load angle estimation for dynamic stepping motor motion applications☆

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ABSTRACT

Stepping motors are well-suited for open-loop positioning tasks at low power. Every time the user sends a next pulse, the stepping motor driver excites the correct stator phases to rotate the rotor over a predefined discrete angular position. In that way, counting the step command pulses enables open-loop positioning. However, when the motor is overloaded or stuck, step loss occurs, and the relation between the expected rotor position and the actual rotor position is lost. Nowadays, the vast majority of the open-loop stepping motor methodologies do not detect this step loss. Especially for dynamically demanding applications where the stepping motor is used close to its operating boundaries, step loss is highly probable. Using a mechanical position sensor to detect and counteract step loss would increase the overall cost, the size of the machine, complexity of the system. Therefore in this paper, a dynamic sensorless load angle estimator based on the classical Transfer Function Analyzer (TFA) technique in the angular domain is presented. This load angle reflects the capability of the system to follow the position setpoint and gives an indication of the robustness against torque disturbances. The algorithm needs no tuning and can be used with the conventional full-, half- and micro-stepping algorithm. The estimation algorithm only needs one current and one voltage measurement and the electrical parameters of the stator winding to estimate the load angle. The proposed algorithm is validated through measurements on a hybrid stepping motor.

1. Introduction

The possibility to accurately position without the need for a position sensor makes stepping motors very appealing for industrial and domestic positioning applications. The rotor position of the machine is controlled by sending digital step command pulses. Every time the user sends a step command pulse, the rotor of the machine makes a step of which the value is determined by the motor geometry and stepping algorithm. In this way, it is easy to control the position without the explicit feedback of a mechanical position sensor. In addition, stepping motors are characterized by high nominal torque density [1]. These are one of the reasons why stepping motor drives are easy to use and require little effort from the user to implement in motion-control positioning applications.

Stepping motors are often used in mechatronic applications as in packaging machinery, weaving looms, medical scanners or digital photography and for the positioning of valve pilot stages for fluid control systems, etc. [2]. In all of the applications, machine developers want to obtain high dynamics with small and cheap stepping motors [3]. For that reason, stepping motors are used at its limits as much as possible. However, a drawback of this open-loop control is the continuous risk of missing a step due to overload. In that case, the relation between the setpoint and the actual rotor position is lost. In the vast majority of stepping motor methodologies, this step loss will not be noticed and results in malfunctioning of the application. Due to this uncertainty robustness is a major issue in stepping motor applications. Until today, to reduce the possibility of step loss, the motor is typically driven at limited velocity, maximum current level or is over-dimensioned with results in low-efficiency [3].

For these reasons, the basic open-loop algorithms are unsatisfactory to drive a stepping motor in more demanding motion applications. The implementation of a mechanical position sensor to obtain field-oriented or direct torque control is interesting to optimize the torque/power ratio of the motor [4–7]. However, it is an impractical option for the assembly to align the sensor with the motor shaft makes the drive more complicated and increases the overall cost and size of the machine. Therefore, so-called sensorless closed-control techniques surface.

Research on sensorless control algorithms to detect the rotor angle without position sensor based on electrical measurements are already well discussed in the field of Permanent magnet synchronous motors

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(PMSM) [8,9] induction motors (IM) [10,11] and switched reluctance machines (SRM) [12,13]. The most common sensorless techniques described in the literature can be classified into two categories. On the one hand, there are model-based techniques [9,11,13] and on the other hand there are the signal injection methods which make use of the response on the injected test signals [8,10,12,14].The majority of the model-based techniques use observers loops [9] to compensate model errors. These observers need extensive offline tuning by the user. The optimal settings of the observer highly depend on the mechanical load parameters such as inertia and friction of the application which complicates the general employability. Signal injection methods [8,10,12,14] perform better compared to observer-based techniques, certainly at lower speeds. The signal injection methods do not need information about the application. However, the drawback of these methods is the need to have access to switching state and the additional requirement for the power electronics to generate the electrical test signals. On top of that, all of these sensorless techniques are not compatible with the conventional open-loop control of a stepping motor which is characterized by a rotational angle directly proportional to the input pulses sent by the user. Therefore, it is less common to apply these largely high-end methods to low-cost stepping motors. Furthermore, in practice, the implementation of a mechanical position sensor is still required for accurate positioning applications. These sensorless techniques for PMSMs, induction motors and switched reluctance machines are used solely for optimization of the torque generation [15,16] or speed control [11,17] and not for positioning.

Therefore, a sensorless feedback mechanism indicating the actual load and a controller preventing step loss, without noticeably increasing the cost, is very useful in stepping motor applications. Moreover, to enable general employability such techniques should take into account the unique character of stepping motors and their drive algorithms. All of these issues in stepping motor motion applications are solved in [18,19]. In [18], an estimator is presented in which the back-electromotive force (back-EMF) is considered to estimate the load angle. Derammelaere et al. [19] presents a sensorless load angle controller in which the focus is on the stability of the closed-loop system. A big disadvantage of the estimator in [18] is that the load angle is only obtained after four full steps at a constant speed. Therefore, the estimator in [18] is only applicable in fixed speed applications which excludes a wide range of motion applications. Therefore in this paper, the principles of the estimator elaborated in [18] are built upon to develop an estimator able to provide feedback of the load angle during speed transients by making use of a Transfer Function Analyzer (TFA) [20] technique in the angular domain. The main contributions of this paper are summarized as follow:

1. The estimation algorithm only needs the complex components of the current and voltage measurement and the stator winding resistance and inductance to estimate the back-EMF and subsequently the load angle as is described in Section 3.
2. In dynamic stepping motor applications, the speed and thus the fundamental signal frequency can vary a lot. The proposed estimator can determine the phase and amplitude of the measured signals with varying frequency to obtain the complex components which is accomplished by transforming the signals from the time to the angular domain as is discussed in Section 3.1. A classical TFA technique in the angular domain is used to determine the complex components of the measured current and voltage signal.
3. In contrast to more complex observer algorithms, this estimator needs no tuning and does not depend on mechanical load parameters and is characterized by a low computational cost. Additional requirement for the power electronics to generate the electrical test signals is not required.
4. An important advantage of this approach is the fact that performance information can be obtained without changing the control-architecture because the algorithm is compatible with the conventional open-loop control of a stepping motor. The typical full-, half- and micro-stepping control algorithms can be extended easily with the proposed feedback mechanism.
5. This feedback mechanism can be used to control the current level to drive the motor in an energy efficient way or to detect step loss. This could seriously enhance the stepping motor robustness without noticeably increasing the cost.
6. The convergence and dynamic behaviour of the estimator are mathematically described in Section 3.3.
7. Experimental results are presented to demonstrate the behaviour of the estimator during speed and load torque transients.

The rest of the paper is organized as follow. The conventional open-loop stepping motor control algorithms are shortly discussed in Section 2. Section 3 describes how the algorithm determines the complex components of signals represented in the angular domain. Finally, in Section 4 the practical implementation is presented together with measurements validating the proposed sensorless estimator. In Section 5 the conclusions of this research are formulated.

2. Conventional open-loop stepping motor drive algorithm

The two-phase hybrid stepping motor principle is illustrated in Fig. 1(a) and (b). The stator is equipped with two phases containing the concentrated windings. The stator coils are wound on alternate poles. Usually, two coils per phase placed in the same direction and two coils referred in opposite connection to create north and south poles [21]. Each pole is covered with uniformly spaced teeth. Means of one axially-oriented permanent magnet magnetizes the multi-toothed rotor. The north-stack and south-stack of the rotor both have 50 rotor teeth and are shifted with a half a tooth pitch relative to each other. By magnetizing phase A, the rotor teeth are attracted by the excited stator phase (A^+ and A^-). Fig. 2(a) and (b) shows the wide-used open-loop stepping motor control algorithm and the simplified representation of a hybrid stepping motor. To obtain this simplified representation, the number of pole pairs is taken into account. In this way, a mechanical step is represented as an electrical rotation of 90°. The relationship between the mechanical and electrical displacement is $\theta_{mechanical} = p.\ \theta_{electrical}$ with p the number of pole pairs.

When a new full-step command pulse *NXT* is given by the microcontroller as is visualized in Fig. 2(b), the excitation of one phase is released while a second phase is excited. As a result, the rotor moves from one discrete steady-state position to another. An electrical rotation of $\frac{\pi}{2}$ rad or 90° is made which is equal to one mechanical step. This means, one electrical rotation is equal to four full steps. By counting the step command pulses, open-loop positioning is achieved.

For half- and micro-stepping algorithms, two phases are excited simultaneously with varying current level to increase the position resolution. By doing so, the number of rotor-position steps is increased. Controlling a stepping motor with 1/4th micro-step instead of full-step

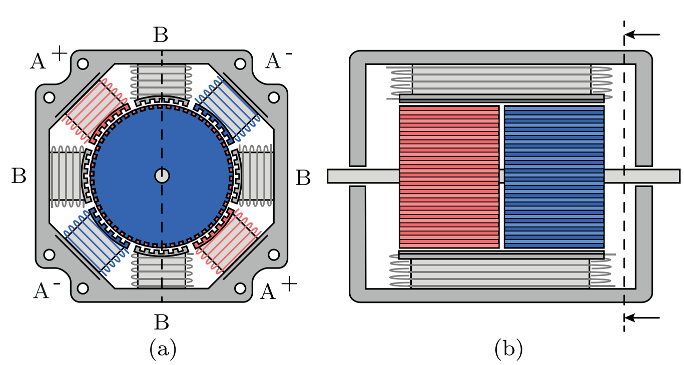

Fig. 1. Two-phase hybrid stepping motor with 50 rotor teeth per stack, front view (a) and cross section (b).