ADAPTIVE ENCODER ALIGNMENT FOR MAXIMIZING TORQUE AND SPEED IN SYNCHRONOUS MOTORS

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Abstract
The encoder alignment dictates the resulting direction, speed and torque of the motor at any current. In this paper, an adaptive encoder alignment method and its results are presented. The proposed method achieves high torque at low rotational speeds and allows high rotational speeds simulating the effects of field-weakening techniques.
Keywords: Synchronous motor, encoder alignment, field-weakening, servo controller.

Introduction

Permanent magnet synchronous motors (PMSM) [1] have emerged as a significant technological advancement in the field of electric motors. With their efficient and reliable performance, PMSMs have gained considerable attention in various industries and applications. In contrast to traditional brushed DC motors, PMSMs offer several advantages, including higher efficiency, improved power density, enhanced speed control, and longer lifespan due to the absence of mechanical brushes, so they don’t have any mechanical wear and tear. These features make these motors an ideal choice for numerous applications, such as electric vehicles, robotics, aerospace systems, industrial automation, and more [2].

It is worth noting that depending on the application of the synchronous motor, the requirements for it might be different. This paper concentrates on an encoder alignment used in a control system for a motor that was going into an anthropomorphic robotic leg. Therefore, the priorities for this actuator were getting maximum possible torque, unlike drones, for example, that require speed over torque.

Understanding the underlying principles, design considerations, and the control systems of synchronous motors is crucial for maximizing their performance and unlocking their full potential. As the name implies, the motors control system has to have feedback on the position of the rotor. This feedback can be achieved with many different devices, such as hall sensors, incremental encoders, absolute encoders and others. Using the raw feedback from the encoder, however, is not the solution. Two things have to be taken into account: rotor and encoder angle misalignment (further as angle misalignment) and number of motor pole pairs. The angle misalignment is a result of the “0” angle of the rotor not facing the same way as the “0” angle of the encoder. In this paper, a variable encoder alignment method is discussed.

Methods

Popular controllers based on the open-source project “simpleFOC” [3] utilize (field-oriented control) FOC [4] without encoder feedback in order to find the “0” position of the rotor. This is done by setting a static Iq current component setpoint, letting the electromagnetic field align the rotor himself. After the rotor aligns with the electromagnetic field the feedback from the encoder is saved as the angle misalignment value. This method never reaches the optimal value for this angle, since the rotor never perfectly aligns with the electromagnetic field. This can be due to many factors such as: cogging torque, spinning friction and others. This method is widely used due to its simplicity and general effectiveness.

“Open loop method” consists in making the motor spin in “open loop control” at slow speeds while tracking the position of the rotor. This way, the “0” position of the rotor can be recorded over several revolutions, that can be either clockwise or counter-clockwise. These zero positions of the rotor angle are later averaged out from all the previously taken measurements. This method is more complicated but more accurate that the method previously mentioned. It is worth noting that this method was not tested, and will not be mentioned anymore in this paper.

“Speed maximization method” involves setting the *Iq* current to a fixed value and then adjusting the angle to find the smoothest rotation and lowest current consumption while maintaining speed or increasing it. The idea behind this method is that the angle difference that results in the smoothest rotation and lowest current consumption is likely the optimal angle difference between the encoder and the rotor. This method is focused on optimizing the motor’s efficiency and performance, as the smoothest rotation and lowest current consumption indicate the best alignment between the encoder and the motor. The main drawback of this method is that it also takes into account the field-weakening effect [5], reducing the motors torque but making it spin faster while drawing less current. It is also worth mentioning that the values for the alignment for clockwise rotation are not the same as the values for anti-clockwise rotation.

One more approach to find the encoder alignment is a “torque maximization method”, which consists in finding the value while measuring the torque of the motor with a constant current. The main drawback of this approach is the speed limitations, since it does not take field-weakening effects into account. It is worth noting that the result of this method is usually a single value both for clock wise and counter-clockwise rotation of the rotor.

To find the encoder misalignment value, it is necessary to measure the torque of the motor. A very easy to implement method is attaching a 3-D printed arm of known length to the rotor, and then setting a constant *Iq* current on the motor. This makes the motor spin, making the arm press the scale, measuring the weight the motor created with its torque. Using the formulas (1) and (2) the values of torque are calculated and both torque and angle are recorded:

$$F = m \cdot g \, , \tag{1}$$

$$M = F \cdot l \, , \tag{2}$$

where F is force, m is mass, g is the gravitational constant, M is torque and l is the distance from the applied force to the axis of rotation. Then the experiment must be repeated spinning the motor in the opposite direction.

The adaptive approach for encoder alignment presented in this paper is a fusion of the two last mentioned methods. At lower speeds, the control system uses the value from the torque maximization method. When approaching higher speeds, the control system checks that the motor is not under a heavy load. This is done with the help of the current, since the current is proportional to the torque. If the motor is free of heavy loads, the control system will gradually switch the encoder alignment value while the motor is running, allowing it to go faster, get a smoother speed waveform, and consume less current. When the motor slows down again, the control system will automatically return the value of the encoder alignment back to the torque optimized value.

Results

To conduct the experiments the motor BGM5208-75 was used. This motor has a 24N22P configuration, i. e. it has 11 pole pairs. Thus, the electromagnetic field of the stator has to spin 11 times for the rotor to spin once, so 360 mechanical degrees mean 3960 electrical degrees. To get the feedback of the current angle of rotor, the encoder AS5048b was used. This is an absolute magnetic encoder with a resolution of 12 bits using I2C communication protocol. This allows the feedback of the encoder to be read with a frequency of 2 kHz. As a controller, the development board STM32F411CEU6 was used. The control system has an FOC current controller with space vector PWM integration [6].

Tests using the “simpleFOC” method were conducted. After setting a stationary *Iq* current, therefore creating a static electromagnetic field to which the rotor can align itself to, the feedback from the encoder gave a value of 13.6 degrees. This meant that the electrical zero of the rotor was at a mechanical angle of 13.6 degrees. In order to account for this in the control system, the value was turned into electrical degrees by multiplying it to the amount of pole pairs (i.e. 11). This resulted in an encoder shift of 149.6 electrical degrees or 13.6 mechanical degrees.

Using these values in the FOC based current controller resulted in sub-optimal performance. The motor was not able to spin using negative currents due to bad encoder alignment, and the angular velocity of the motor with positive currents was less than 5 revolutions per second. This showed extremely bad encoder alignment. However, this method could be improved by taking several measurements and calculating the average value.

Then, the "torque optimization method" was implemented with the same components. As mentioned before, the arm attached to the motor had a length of 0.1445 m. This arm pressed on a scale while the same FOC based current controller held the current of the motor constant, at ±0.1 A during all the experiments. The weight the motor exerted on the scale and the correspondent encoder adaptive angle were recorded. The results for the experiments are shown in tables 1 and 2.

Table 1. Results of torque maximizing method for encoder alignment with positive current values

Current, A	Angle, mechanical degrees	Weight, g	Torque, N*m
0.1	-1	26	0.03685
0.1	0	27	0.03827
0.1	1	29	0.04111
0.1	2	30	0.04252
0.1	3	32	0.04536
0.1	4	30	0.04252
0.1	5	28	0.03969

Table 2. Results of torque maximizing method for encoder alignment with negative current values

Current, A	Angle, mechanical degrees	Weight, g	Torque, N*m
-0.1	4	29	0.04111
-0.1	3	30	0.04252
-0.1	2	31	0.04394
-0.1	1	30	0.04252
-0.1	0	29	0.04111
-0.1	-1	28	0.03969
-0.1	-2	26	0.03685

As it can be seen from tables 1 and 2, the highest torque was achieved with an encoder alignment of an angle in between 2 and 3 degrees, with changes in either direction decreasing the output torque. It was decided to take the average of both values, so an encoder alignment value of 2.5 mechanical degrees was used to align the rotor with the encoder. The speed of this method was measured by setting a higher current setpoint and letting the motor spin freely, as fast as it could. The current draw and the speed of the motor are shown in the graphs in figures 1 and 2.

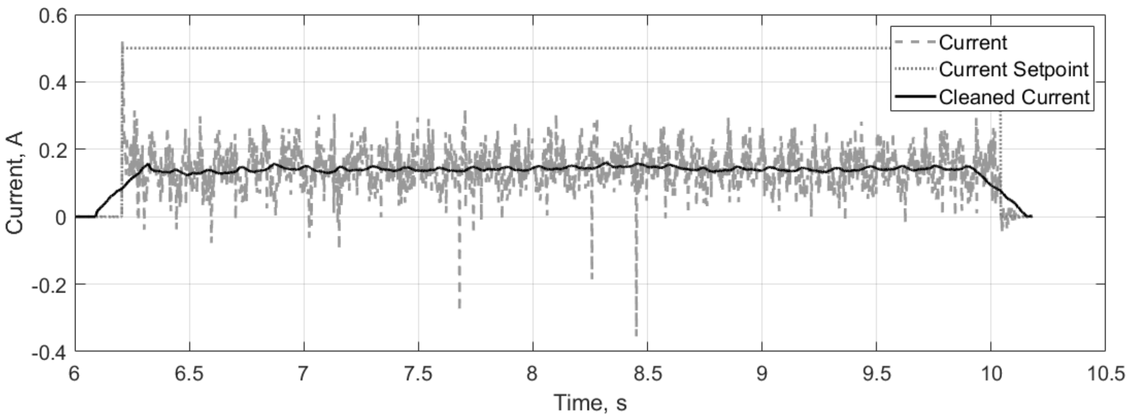

Fig. 1. Current draw of synchronous motor with an encoder alignment maximized for torque

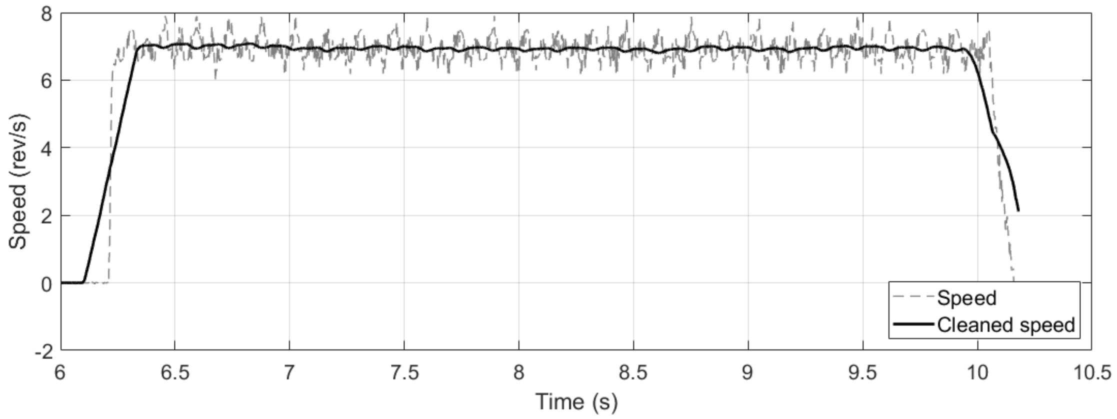

Fig. 2. Rotational speed of synchronous motor with an encoder alignment maximized for torque

From figures 1 and 2 it can be seen that the motor can reach a maximum rotational speed of around 7 revs/s consuming around 0.15 A of current. Given that the current consumption was very high under no load and the speed was very ripply, it was decided to further tune the encoder alignment variable in electrical degrees to have finer control over the angles.

Further fine tuning was done while the motor was running by the same principle of the "velocity maximizing method". The final angle, on top of the 2.5 mechanical degrees, was 45 electrical degrees, or 4.091 mechanical degrees. This resulted in a 6.591 mechanical degree shift, where the current consumption was less than 0.02 A on average and the speed was around 9.5 revolutions per second on average. It is worth noting that the lower current consumption and higher speed are due to this extra angle shift, which takes into account field-weakening.

As per the results of the torque maximizing methods testing, this angle shift would greatly reduce torque. Thus, in the control system, an adaptive encoder alignment algorithm was implemented. This algorithm checks the speed and the current of the motor. If the motor has a rotational speed higher than 5 revs/s and the current draw was less than 80 % of the maximum current, then the encoder alignment adds 45 electrical degrees to the angle, allowing the motor to spin faster, smoother and with less current consumption. If these conditions were not met, then the motor would use the 2.5 mechanical angle alignment that was previously gotten to maximize torque. The results for speed and current consumption of the motor with the adaptive method can be seen in figures 3 and 4.

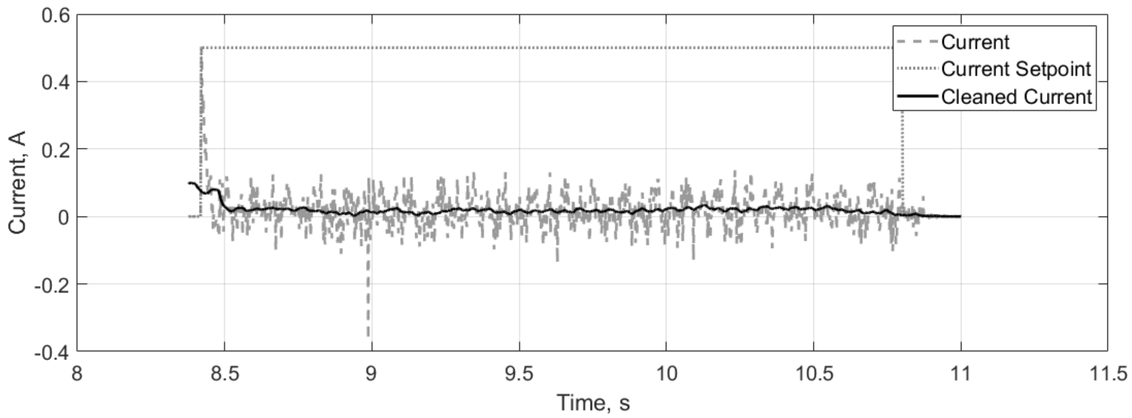

Fig. 3. Current draw of the motor with adaptive encoder alignment at maximum speed

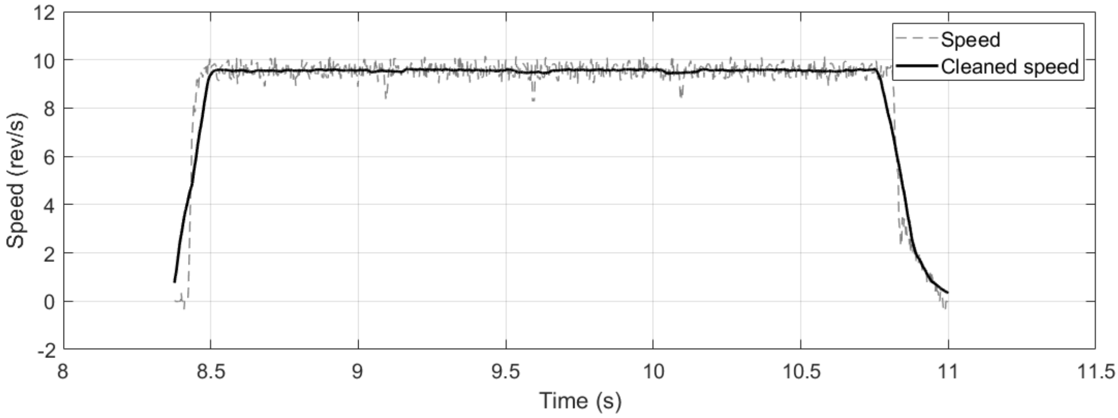

Fig. 4. Maximum speed of the motor with adaptive encoder alignment

Figures 3 and 4 show how the current consumption dropped and the rotational speed is smoother and higher in comparison to the "torque maximizing method". This creates a controller with high-speed capabilities while retaining the possibility to switch to a high torque encoder alignment when it is necessary.

A point could be made that these speeds could increase and become less ripply by making the feedback from the encoder faster. In this paper, the encoder was read with a frequency of 2 kHz, which is not fast enough for a highly dynamic system due to the communication protocols limitation. A "sin/cos" or a "quadrature output" encoder could help making this feedback loop faster.

Conclusion

By making the encoder alignment method adaptive, it was possible to give the system both high torque and speed capabilities. This allows for more complete utilization of the motor's capabilities giving it a wider possible applications range and making it suitable for the original purpose of this servomotor.

It is worth mentioning that the speeds could further be increased by replacing the components of the system, like the encoder, to meet system requirements, or implementing actual field-weakening methods instead of taking it into account in the encoder alignment value.

In the future, it is planned to change the encoder to a quadrature output or a sin/cos one, in order to further research and achieve the optimal encoder alignment method.

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