

MEASUREMENT OF BLDC MOTOR EFFICIENCY FOR COMMUTATION ANGLE OPTIMISATION

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ABSTRACT

This paper describes an approach for measuring efficiency of BLDC motor fan for different commutation angles. Such measurement is needed for commutation angle optimisation. Experimental measurement shows that fan speed fluctuates around the long time average value. Therefore, the statistical approach is used to define the number of samples in moving average calculation of efficiency for selected confidence interval. In most cases, the commutation angles are derived from the fixed position Hall sensor. Presented measurement shows that efficiency is a continuous function of several angle parameters with the global maximum. Commutation angle of this global maximum does not match the Hall sensor signal exactly. Hence, simple gradient optimisation method can be used to find optimal commutation angles for the highest efficiency.

1. INTRODUCTION

Brushless DC motors (BLDC motor) are used in a wide range of applications from small cooling fans to electric vehicle drives. They are often compared to brushed DC motors, switched reluctance motors (SRM) and to induction motors (IM) widespread in the industry. Usage of various types of motors underline the fact that ease of control, a high power density and low maintenance of BLDC motors is not the only criteria for choosing the motor for the particular application. An example can be found in [1]. Authors state that not BLDC motor but SRM is the most appropriate motor for electric vehicle application because of its weight, reliability, and fault tolerance. Furthermore the acceleration time of SRM is better than that of BLDC motor and IM.

On the other hand, there are many applications, where permanent magnet motors including BLDC motors dominate: unmanned aerial vehicle (UAV) propulsion systems, disk drives, servo drives for speed and position control, etc. An important market for BLDC motors is fan application. There is need to design fans with optimised efficiency for battery-powered applications such as laptops and in intensive cooling situations such as servers and server rack cabinets. Two main requirements for fan are high efficiency and silent operation, where the second one is linked to the minimum torque ripple. Basic properties of the motor are influenced by mechanical and electrical design [2], [3]. However, the methods to drive motor do the rest. Most fans are driven by one chip driver with integrated Hall sensor for cost effective mass production. The commutation angle of phase currents is derived from a fixed place Hall sensor. Static angle is not optimal for the motor efficiency

as is documented in [4], [5] for single-phase BLDC motor and in [6], [7] for three-phase BLDC motor. Optimal commutation angle is different for every operating point.

There are different approaches to find right commutation angle, maximise efficiency and minimise torque ripple. The first approach is based on knowledge of a principle of operation. Torque is produced by mutual interaction between the back EMF's and the phase currents. Therefore, the commutation angle and current waveform can be deduced from analytical model [7], lookup table [8] or from rules, e.g. the sign of current and the back EMF must be the same [4]. Different approach uses maximisation (or minimisation) of defined criterion function by changing the commutation angle. Lelkes and Bufe in [4] suggest efficiency estimation from measured speed and current. Chiu, et al. in [5] evaluates current waveform smoothness. Lee, et al. in [6] analyses dependence between commutation angle and acoustic noise and vibration.

2. SINGLE-PHASE BLDC MOTOR

Small fan D12SH-12 with single-phase BLDC motor with four-pole external rotor was measured. Fig. 1 shows the structure of the motor. Iron core has four poles with variable air-gap which is important to start spinning. Single-phase winding creates pulsating magnetic field only that cannot produce torque. Air gap causes difference between rotor position in not energised state and energised state of the winding. Applying the power starts the motor rotation moving rotor beyond neutral point. Following change of Hall sensor signal reverses the orientation of a magnetic field of the stator that creates torque.

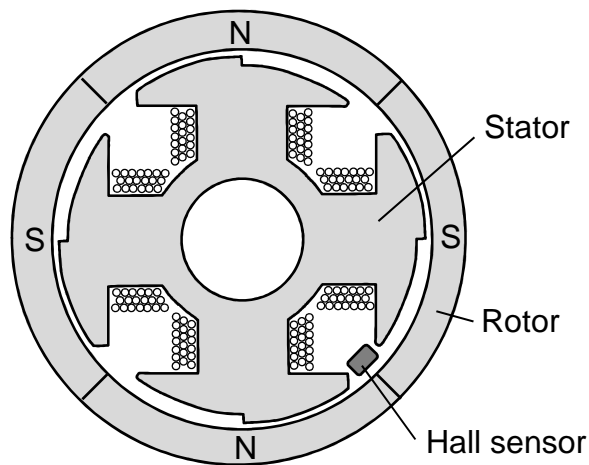


Fig. 1
Cross section of a single-phase four-pole external rotor BLDC motor
with variable air gap

Stator winding is split into two opposite parts L_A and L_B , what enables to use two power transistors T_A and T_B instead of full transistor bridge to create magnetic fields in the reverse direction. Fig. 2 shows schematics diagram of motor driver and stator windings. The motor has nominal voltage 12 V and nominal current 0.3 A.

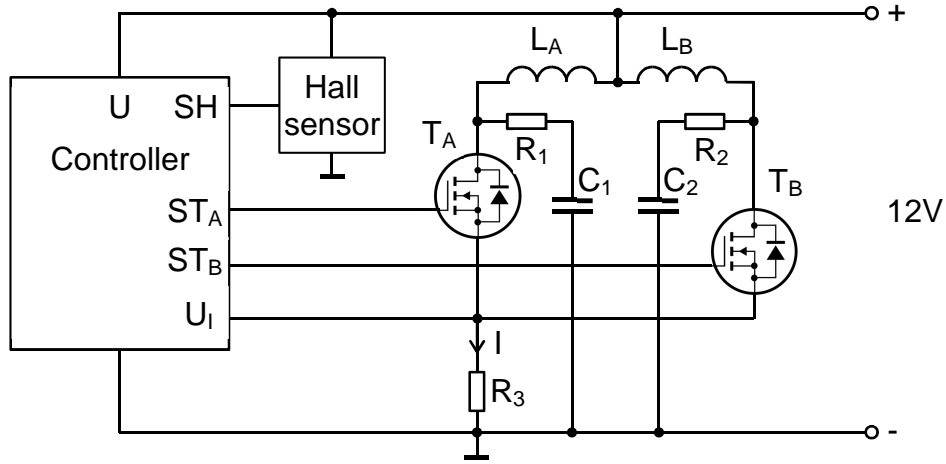


Fig. 2
Schematic diagram of motor driver

3. EFFICIENCY ESTIMATION

The efficiency is the ratio between the mechanical output power P_2 and the electrical input power P_1 . The measurement of efficiency has some technical difficulty. Especially the mechanical output power for a small fan is difficult to measure. However, the output power P_2 as a function of speed n is known for fans and pumps:

$$P_2 = kn^3 \quad (1)$$

where k is factor that does not depend on the motor parameters. Consequently the efficiency η can be written as

$$\eta = \frac{P_2}{P_1} = \frac{kn^3}{P_1} \quad (2)$$

Electrical input power P_1 is calculated as a product of DC voltage U and the current of the motor I . If the voltage U is stable the efficiency can be estimated as proportional to the value E :

$$E = \frac{n^3}{I} \quad (3)$$

Efficiency estimation value E is influenced by commutation angle and can be used as criteria to find the optimal angle value. Calculation of E requires measurement of values n and I .

4. SPEED AND ELECTRICAL CURRENT MEASUREMENT

Fig. 3 and Fig. 4 show preliminary speed measurement by digital multimeter UT70D (frequency measurement precision 0.1%) at constant voltage 12 V. The sampling rate is one sample per second. Fig. 3 shows the speed in [rpm] starting from cold motor state and Fig. 4 shows speed deviation after warming up. These measurements reveal the facts:

1. Measured value depends on temperature.
2. Data contain random errors and are autocorrelated (see correlation coefficients in Fig. 5).
3. Moving average of 100 samples is slowly drifting around long time average.

Temperature influence can be eliminated by inserting warm up period before the actual measurement. Noise in data can be reduced by a filter if the mean value of noise is zero. The cause of slow drift is unknown.

The moving average is selected as a filter. Average value represents the point estimation of the mean value. The question is how many samples should be in moving average to acquire desired precision. Everything what was said about speed measurement concerns the electrical current measurement as well.

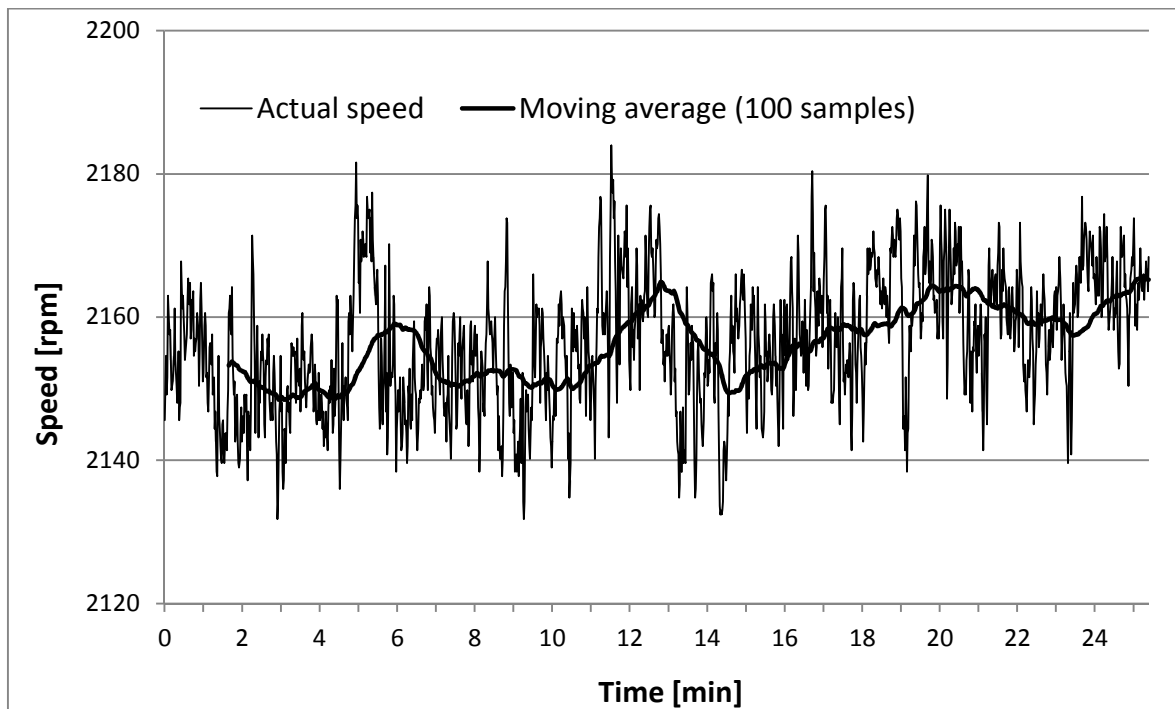


Fig. 3
Speed measurement during motor warm up (one sample per second)

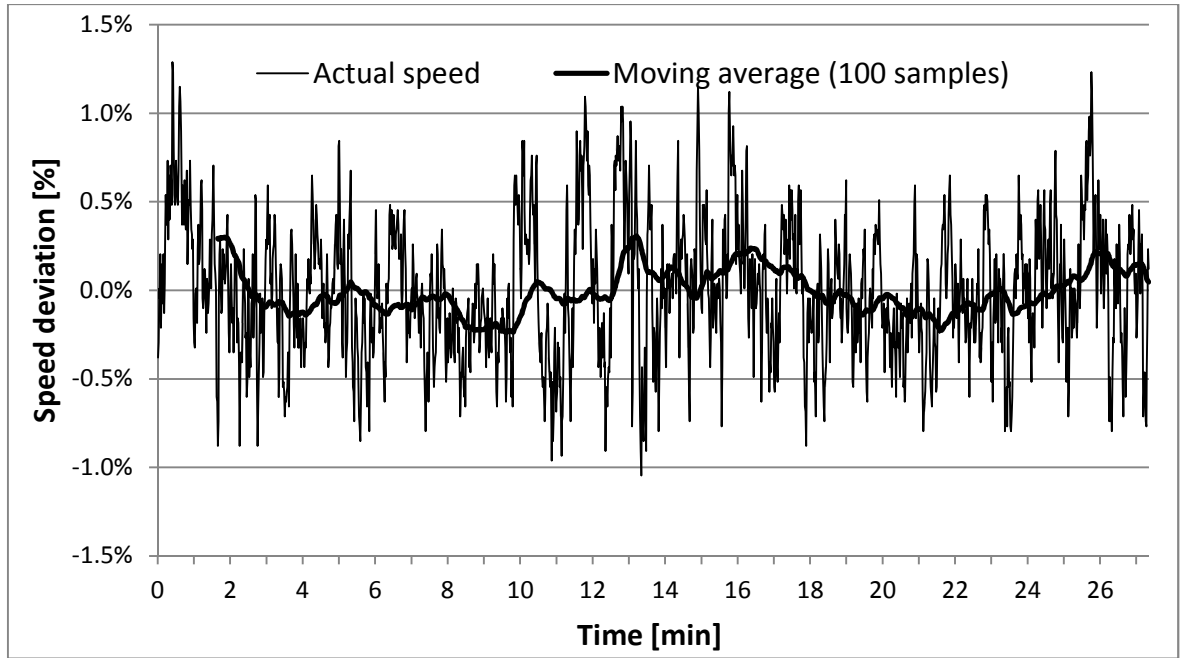


Fig. 4

Deviation from the average speed after warm up (one sample per second)

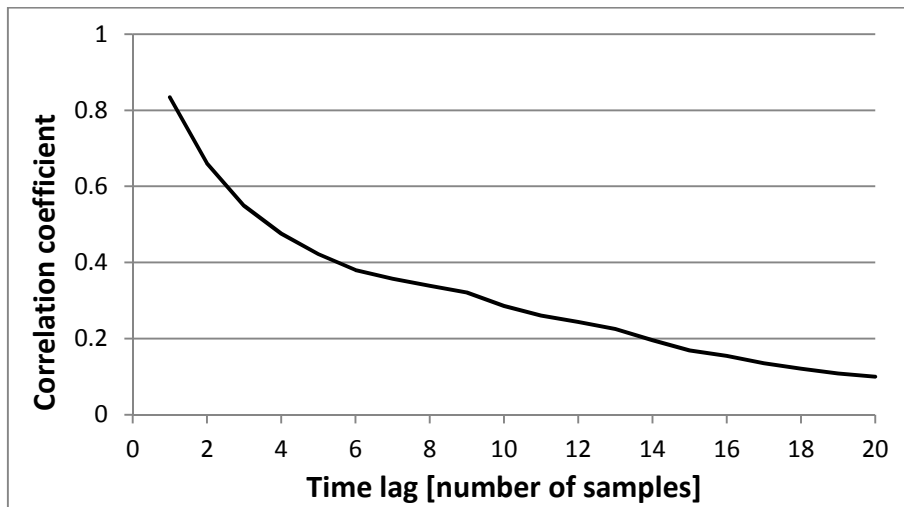


Fig. 5

Correlation coefficient for different data sample time lag

5. CONFIDENCE INTERVAL

The average values are used to estimate the speed and the current. Optimisation function uses calculated efficiency estimation E and changes parameter of optimisation that is the commutation angle in this case. The optimisation process can choose a wrong direction for parameter change due to estimation errors. Many wrong decisions will be made if the difference of criteria function E in successive optimisation step is comparable to measurement error. For this reason, the confidence interval of the estimated speed and the current must be small enough.

Measured data are not random sampling data with normal distribution but autocorrelated time series. Calculation of confidence interval is not straightforward for such data [9], [10]. The number of samples required for the mean estimation was determined by means of the experimental method from the long time measurement. First the maximum and minimum for given number of samples was determined. Then the interval $(x_{max}, x_{min})_{100\%}$ of samples was narrowed by removing the most extreme value x_i until only 95% of samples left. Resulted interval $(x_{max}, x_{min})_{95\%}$ approximates the confidence interval on 95% confidence level. Fig. 6 shows the relative difference of minimum and maximum values of moving averages and confidence interval for different sample number along all data set. Reasonable value of sample number is 300 samples in moving average. For that value the relative confidence interval is $(-0.0013, 0.0013)$. It means that the long time average value is within that interval for 95% of computed averages.

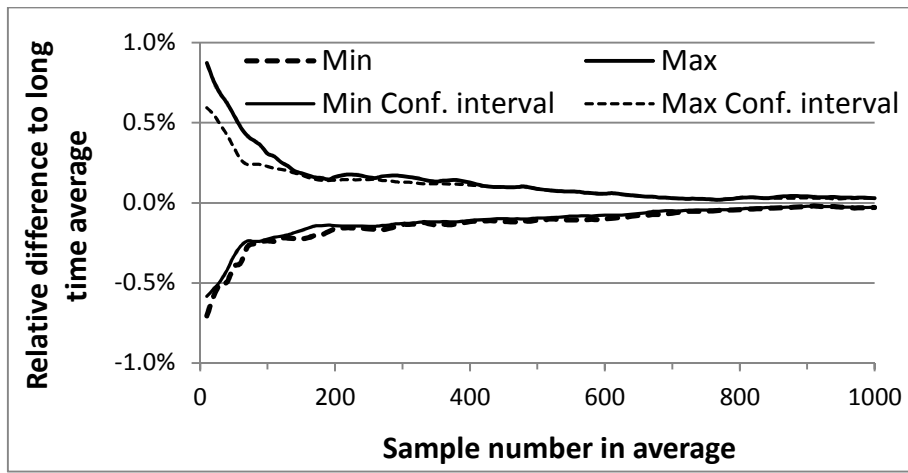


Fig. 6

Min-Max values for moving averages with different sample number

6. MEASUREMENT OF EFFICIENCY ESTIMATION

Automated measurement procedure was set up for measurement of efficiency estimation E for different commutation angle parameters. The used single-phase four-pole BLDC motor has four commutation angles α_1 to α_4 per one mechanical revolution (see Fig. 7). All four angles can change independently with respect to mechanical reference point and are possible parameters for optimisation.

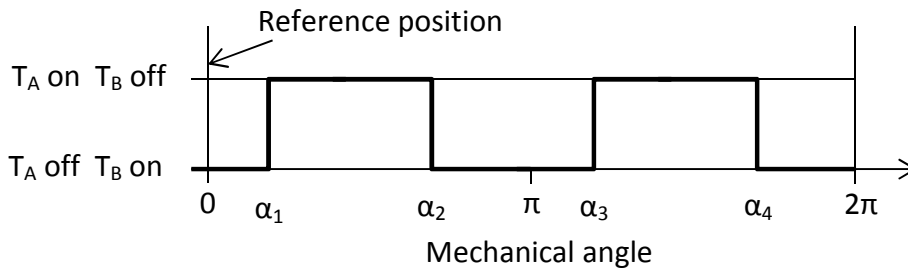


Fig. 7

Commutation angles per one mechanical revolution

Fig. 8 shows processed data from measurement of efficiency estimation E where angles α_1 and α_3 are changed. Surface response could not be reasonably viewed for more parameters. It can be seen that function E has one global extreme. For this reason, simple optimisation algorithms of the gradient method can be used. Some irregularities in response surface may be explained by measurement errors. The global extreme at $\alpha_1 = 5.6^\circ$ and $\alpha_3 = 60.6^\circ$ is slightly different from Hall sensor signal according comparison on oscilloscope (not exact measurement were done).

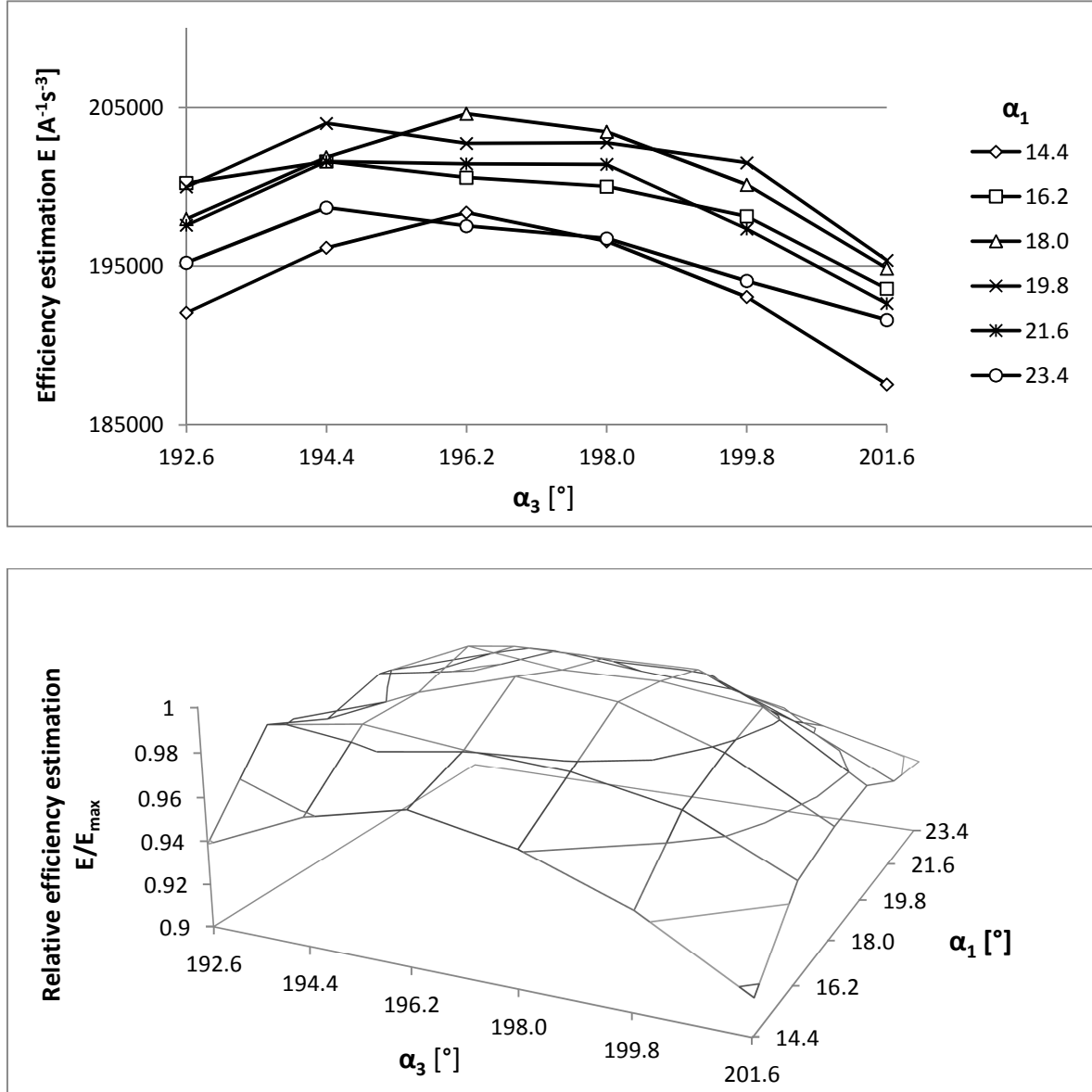


Fig. 8
2D and 3D representation of measured efficiency estimation E

7. CONCLUSION

This article presents results from experimental measurement of single-phase BLDC motor efficiency. The efficiency is estimated from measured speed and electric current. Error in measurement is reduced by averaging. The number of

samples in average is determined by desired confidence interval. The confidence interval is calculated from the experimental data. Measurement shows that the surface response is smooth with a global maximum. As a result, the gradient optimisation method will be appropriate for on-line experimental searching of optimal commutation angles.

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