Metrol. Meas. Syst., Vol. XXII (2015), No. 3, pp. 393–402.

PAN
POLSKA AKADEMIA NAUK

METROLOGY AND MEASUREMENT SYSTEMS

Index 330930, ISSN 0860-8229

www.metrology.pg.gda.pl

M&MS

CALCULATION OF THE BRUSHLESS DC MOTOR SHAFT SPEED WITH ALLOWANCES FOR INCORRECT ALIGNMENT OF SENSORS

Krzysztof Kolano

Lublin University of Technology, Faculty of Electric Drive Systems and Machines, Nadbystrzycka 38/a, 20-618 Lublin, Poland
(✉ k.kolano@pollub.pl, +48 81 538 4342)

Abstract

The paper treats of correcting calculation errors of the BLDC motor speed, based on the time elapsed between successive changes in the shaft position sensor signal. The developed method enables correction of errors of the deployment of sensors as well as rotating elements of the observation system of the motor shaft position. The correction algorithm performance was analysed with the aid of a model implemented in Matlab-Simulink environment. After confirming usefulness of the developed method through simulation, its usefulness was verified in real closed-loop feedback systems with a BLDC motor. The results of measurements carried out at the developed laboratory station are presented.

Keywords: drive systems, BLDC motor, sensor misalignment.

1. Introduction

Market demands for reduction of maintenance of electric drive systems, while improving their performance, encourage constructors to reach for modern structures of drive systems in designing new solutions or modernising existing ones. Such tendency may be seen in the regular replacement of low-power DC motors by brush-less direct-current ones, also called BLDC motors. Use of BLDC motors instead of DC motors enables significant improvement of the operating parameters of such solutions. Replacement of a maintenance-requiring mechanical commutator by an electronic one, besides reducing the maintenance of the drive, significantly increases efficiency of the whole system.

High requirements set for devices make implementation of a speed feedback necessary in order to achieve the desired motor speed, and sometimes define its shaft location. An integral part of a BLDC motor is a device for determining the shaft position to enable the control system to select an appropriate control vector. Usually, this element consists of three binary sensors, which determine the shaft position with the accuracy of 60 electrical degrees [1, 2]. The intention of minimising the production costs of a BLDC motor makes the accuracy of assembling these elements and the method of their regulation sufficient for correct system operation in open-loop, but often too low to ensure a proper rotational speed measurement of the motor speed [5–8]. Systematically developed methods of the sensor-less control of BLDC motors suit higher rotational speeds, but are insufficient for a proper feedback loop at lower shaft speeds, for which it is necessary to use their position sensors [3, 4].

Article history: received on Apr. 03, 2015; accepted on Jun. 23, 2015; available online on Sep. 21, 2015; DOI: 10.1515/mms-2015-0038.

2. Measurement of BLDC motor shaft speed

The presence in the observation system of three independent sensors, monitored by an efficient microprocessor system, enables measuring the rotor speed in several ways, as presented in Fig. 1.

The first way is to measure the time elapsed between successive changes in the state of the sensors in the observation system of the shaft position. This method is advantageous from the point of view of the dynamics of the system's operation, since deceleration of the speed read-out is the lowest at its use. It boils down to incrementing the counter (*e.g.* C_{rst} in Fig. 1) and calculating the speed by a change of the state in any of the three sensors of the motor shaft position ((1), k_{rst} – proportional constant).

$$\omega_f = \frac{k_{rst}}{C_{rst}}. \tag{1}$$

The second, and at the same time easiest, is the method of calculating the duration of frequency of the rectangular signal generated by one freely selectable shaft position sensor. In practice, it is restricted to accomplishing a timely incremented counter (*e.g.* $C_{rL\text{-}H}$ of Fig. 1.) and calculating the engine speed by the change of one shaft position sensor. This method is very accurate, but due to a low refresh rate, defined as follows:

$$f_r = \frac{\omega \cdot p}{2\pi}, \tag{2}$$

its usage is limited to drives of low operational dynamics.

The third way is the method of independent speed calculation for each of the states of the sensor [9]. The result of this measurement is a $p \cdot 6$ array of cyclically and independently changing values (where p is the number of pole-pairs of a motor). This method implies the necessity of using independent measuring units, assuming that each change in any of them is the signal to refresh the speed rate of the whole system. It is necessary to execute six independent counters – two for each sensor (*e.g.* for sensor r – counters $C_{rL\text{-}H}$ and $C_{rH\text{-}L}$).

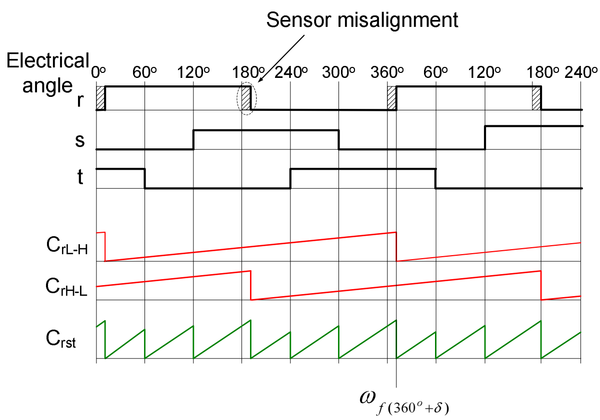


Fig. 1. Operation of the microprocessor system counters in the observation mechanism of BLDC motor shaft position with mistakenly installed „r" sensor for a one-pole-pair engine.

Such a speed measurement increases the frequency of read-outs defined as:

$$f_r = \frac{3 \cdot \omega \cdot p}{\pi}, \tag{3}$$

which improves the dynamic properties compared to the method using only one motor shaft position sensor. Unfortunately, the value of the engine speed calculated by this method is, in fact, an average value of the last $p \cdot 6$ measurements, according to the formula:

$$\omega_{f(360^o+\delta)} = \frac{k_r}{C_{rL-H}} = \frac{k_{rst}}{6} \cdot \left(\frac{1}{C_{rst(60^o)}} + \frac{1}{C_{rst(120^o)}} + \frac{1}{C_{rst(180^o+\delta)}} + \frac{1}{C_{rst(240^o)}} + \frac{1}{C_{rst(300^o)}} + \frac{1}{C_{rst(360^o+\delta)}} \right), \tag{4}$$

where k_r and k_{rst} are fixed determinations of engine speed and $k_{rst} = \frac{k_r}{6 \cdot p}$. Therefore, this method introduces too much delay, particularly at low engine speeds, which is explained in Fig. 2.

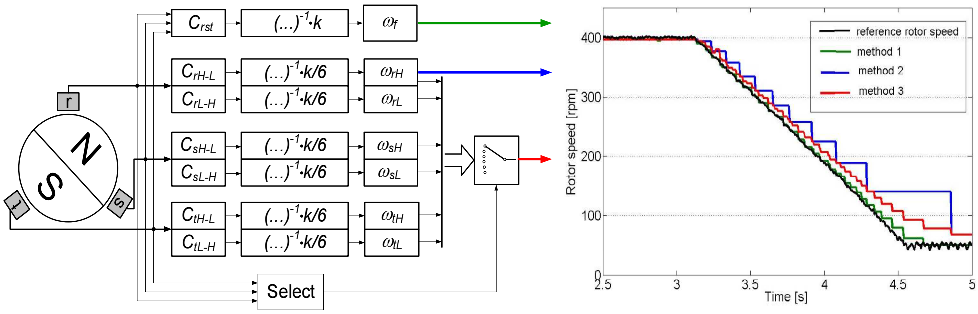


Fig. 2. The structure and measurement results of the BLDC motor speed using three different methods for a proper alignment of rotor position sensors [3–5, 9].

Owing to these properties, the first method is the best way to determine the motor speed taking into account the time elapsed between successive changes of the state of the shaft position sensors (Fig. 2). Unfortunately, the accuracy of the mechanical assembly of the measurement elements in drive systems, where the priority is to maintain a low cost of production, is relatively low. The error of measuring speed, $\delta_{p\%}$, depends on the mechanical angle δ_m of deflection of the axis of correct assembly, which influences the error of determining the position of the commutation point for a BLDC motor in accordance with (5). It is obvious that the precision of manufacturing an engine is particularly important in the case of multi-pole machines, according to the formula:

$$\delta_{p\%} = \delta_{m\%} \cdot p \cdot 6\,. \tag{5}$$

This feature makes it almost impossible in many applications to correctly determine the engine speed based on calculation of the time elapsed between successive commutation points. Fig. 3 shows the course of rotational speed measured by three methods, assuming a 5% error of the alignment of the BLDC motor shaft position sensor *r*. The method in which the delay of speed read-out is the shortest is named method 1. It is the most advantageous method from the point of view of a closed-loop system's operation. However, the influence of precision in sensor assembly is the greatest in this case.

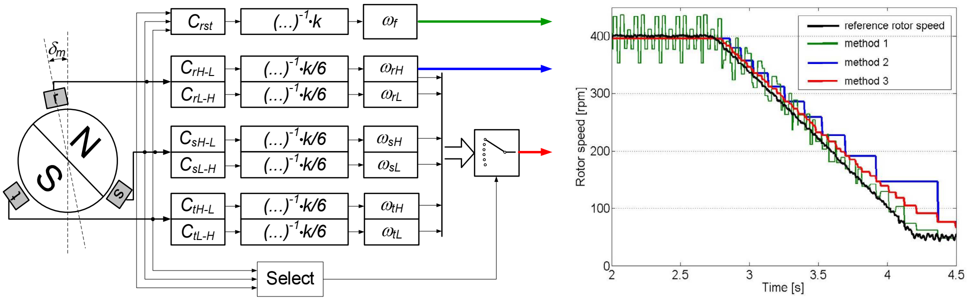


Fig. 3. The structure and measurement results of the BLDC motor speed using three different methods for an incorrect alignment of one of the rotor position sensors.

On the basis of the motor speed waveforms calculated by different methods for a system with an incorrect alignment of shaft position sensors, a strong impact of the accuracy of alignment on determination of the speed by using method 1 can be stated, as well as total insensitivity to alignment errors of methods 2 and 3.

Since the error of sensor installation is repetitive, it is possible to correct the measured value in order to preserve both the advantages resulting from the speed of measurement method 3 and the insensitivity to sensor alignment of the other methods. For this purpose it is necessary to calculate errors of the speed of individual sensors in order to correct them, according to the formula:

$$\omega_f^{'} = \omega_f \cdot [e_x], \tag{6}$$

during their work, as shown in Fig. 4.

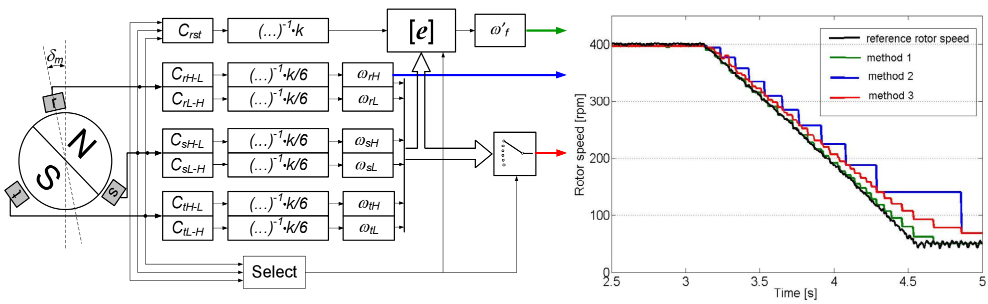


Fig. 4. The structure and measurement results of the BLDC motor speed using three different methods for an incorrect alignment of rotor position sensors, employing a corrective algorithm.

It is possible to determine the sensor alignment error by comparing the speed calculated on the basis of the value of time measured between successive commutation points of a BLDC motor and the real speed measured by an external reference sensor. This method, although the simplest one, complicates drive systems and considerably increases their cost.

To make the withdrawal of a reference speed sensor possible, it is necessary to measure the value of speed using the existing elements in a way which is insensitive to their alignment error. Most often to calculate an error of speed calculation, the reference value is considered to be the value which is an arithmetic mean of the measurements for all commutation points of a BLDC motor [9–11] – in other words, an average speed value measured during a complete revolution of the drive shaft. Unfortunately, such simplification takes into consideration the joint shaft speed, which has an insignificant impact on an average rotational speed of a motor. However, the average speed distorts partial speed measurements, on the basis of which the sensor alignment error is calculated. This leads to incorrect calculation of the correction factors, resulting in a wrong definition of the rotational speed.

3. A model of the system implemented in Matlab-Simulink environment

To analyse an impact of the sensor alignment accuracy of a BLDC motor on the rotational speed measurement, a model of an observation system of the motor shaft position in Matlab-Simulink environment was built. The developed model enabled changing installation precision of the shaft position sensors exactly to $\delta_{m-\min} = \frac{\pi}{1000}$ of a mechanical degree, which is a satisfying value for carrying out simulation studies.

Based on the performed simulations of working the shaft position observation system of a BLDC motor it was confirmed that the second and thirdmeasurement methods are insensitive to sensor installation accuracy, and the impulse is a signal for the time measurement, which is repeated cyclically, regardless of the sensor installation accuracy.

An algorithm has been developed which calculates the difference between the speed measured by method 1 (the most advantageous from the point of view of system dynamics) and by method 3 (insensitive to sensor alignment errors), for a fixed working state of a BLDC motor. Errors specified in this way for each of $p \cdot 6$ measurement points are stored in an array of corrective values **[e]**.

To properly determine the corrective values, the speed measurements should be carried out for a constant actual speed of the rotor – the rotational speed of at least one complete revolution should be stable to make the values calculated by method 1 and method 2 comparable with each other. The rotational speed of a BLDC motor is stable during one complete revolution, if $p \cdot 6$ subsequent speed measurements carried out by method 2 are the same. Such an assumption is very difficult to meet in practice. In this simulation the accuracy of 1% between successive values was assumed – once similar results are obtained by the speed measurements independently for each element (in accordance with method 2), the correction coefficients used to determine the actual speed values for method 1 are being calculated.

To save the calculated correction coefficients it is necessary to book in the program memory a data array of $p \times 6$ dimension, as presented in Fig. 5, where *p* is the number of pole pairs of a BLDC motor.

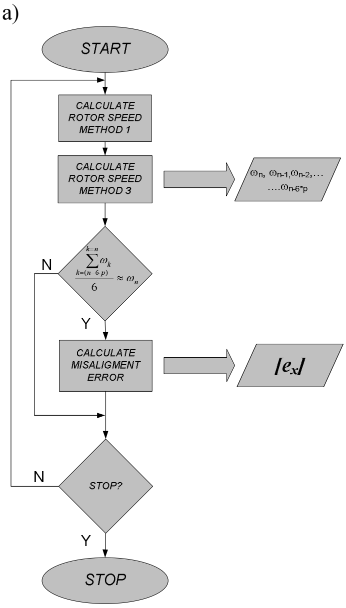
r s t	p=1	p=2	…	p=n
0 0 1	e_{t1}	e_{t2}		e_{tn}
0 1 0	e_{s1}	e_{s2}		e_{sn}
0 1 1	e_{st1}	e_{st2}		e_{stn}
1 0 0	e_{r1}	e_{r2}		e_{rn}
1 0 1	e_{rt1}	e_{rt2}		e_{rtn}
1 1 0	e_{rs1}	e_{rs2}		e_{rsn}

Fig. 5. An array of the values of corrective coefficients for a BLDC motor with the number of pole pairs equal to *p*.

Because the shaft position of a BLDC motor is determined by the state of position sensors only in 1 pole-pair machines, a single calculation of the correction coefficients and saving them permanently in the non-volatile memory of the device is possible in such machines only. In the case of machines with a greater number of pole pairs it is necessary to carry out the procedure in order to determine the sensor location error each time the loss of power supply occurs. This is due to the fact that in the case of multi-pole machines several actual motor shaft positions correspond to the same state of the shaft position sensors.

Figure 6b illustrates the course of the start-up simulation and then implementation of the corrective coefficients of speed measurement. Those simulations were performed for a one-pole-pair machine, assuming a 5% alignment error of one of the shaft position sensors.

a)



b)

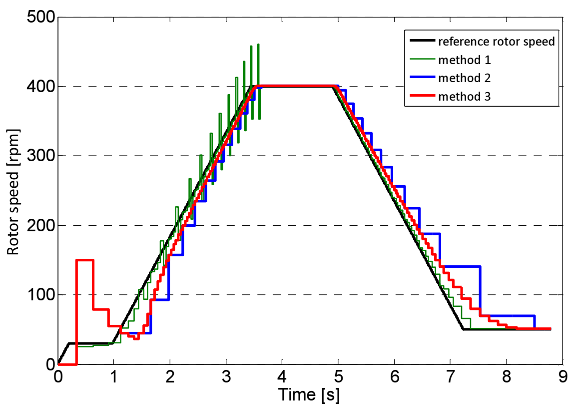


Fig. 6. a) The algorithm for determining errors of sensor location; b) Simulational operation of the algorithm performed in a Matlab-Simulink program.

After determining the speed of the closed-loop feedback system, the corrective coefficients of speed measurement for method 1 are calculated with the algorithm presented in Fig. 6a.

Graph 6b shows a significant error of determining speed by method 1, which is adjusted after calculating the corrective coefficients from about the 4th second of the system's operation.

Simulation studies carried out in Matlab-Simulink environment showed usefulness of the proposed method in correcting the calculated speed independently of correctness of the BLDC motor's sensor alignment. The developed algorithm for determining errors of the sensor location and rectifying the results of speed measurement significantly affects the drive systems, enabling arrangement of a correctly working loop feedback system as well as improving dynamics of their operation.

4. Experiment results

The simulation results were verified practically at a specially developed laboratory station consisting of two BLDC motors coupled with each other, as presented in Fig. 7. The first one acts as a motor and the second as a load. Since practical implementation of a motor shaft observation system in which the error of sensor alignment would be regulated is very difficult due to technical and technological constraints, it was necessary to use another method to generate information on the shaft position of a motor. Therefore, an incremental encoder with the resolution of 2000 CPR was used for this purpose, as well as an appropriate algorithm generating signals from 3 rotor alignment sensors of a BLDC motor, with an accuracy corresponding to the one assumed in the simulation model. Such a solution accepts any configuration of sensor alignment errors, which enables fast and accurate testing without interfering with the mechanical construction of the motor.

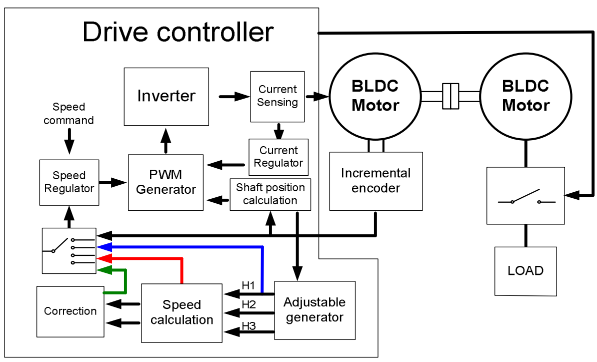


Fig. 7. The structure of the laboratory stand for verifying correctness of the developed algorithm.

In the laboratory, tests were carried out of start-up fixed engine work and the system's response to rapid growth in load torque on the motor shaft, alternatively with and without a corrective algorithm of sensor alignment. The first figure illustrates the operating cycle of the drive system, during which the errors of sensor location may be determined. It can be divided into several sections, as shown in Fig. 8. Area I – operation at a fixed state with the speed of 30 rpm, II – increasing the speed up to 400 rpm, III – operation at a fixed state in an open-loop feedback system, where calculations of the corrective coefficients of speed determination for method 3 are made, IV – introduction of the corrective coefficients to calculate the rotational speed, starting operation in the speed feedback loop, V – a rapid increase of the motor load, VI – a rapid reduction of the motor load.

In areas I, II and III the system should operate in an open-loop feedback system with an arbitrarily given PWM duty ratio. To that extent one can notice a large impact of sensor alignment errors on the speed calculated on the basis of the time elapsed between consecutive commutation points of a BLDC motor. In area III, where the actual speed is almost constant, taking into account the speed values determined by method 2, the corrective coefficients for method 3 of determining speed are calculated, which are introduced into the calculations from operation area IV.

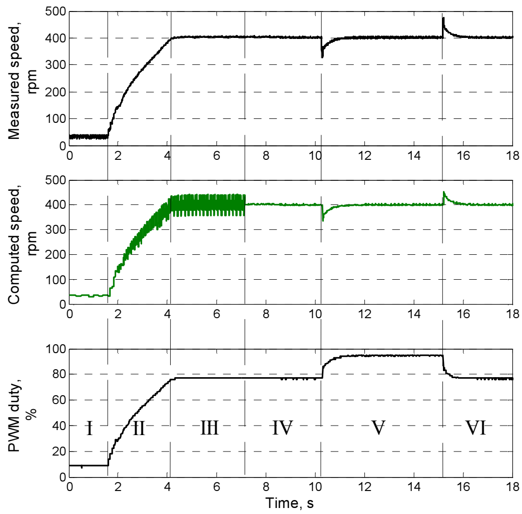


Fig. 8. The waveform of actual speed calculated by method 1, as well as the PWM duty signal coefficient of a BLDC motor with an implemented corrective algorithm.

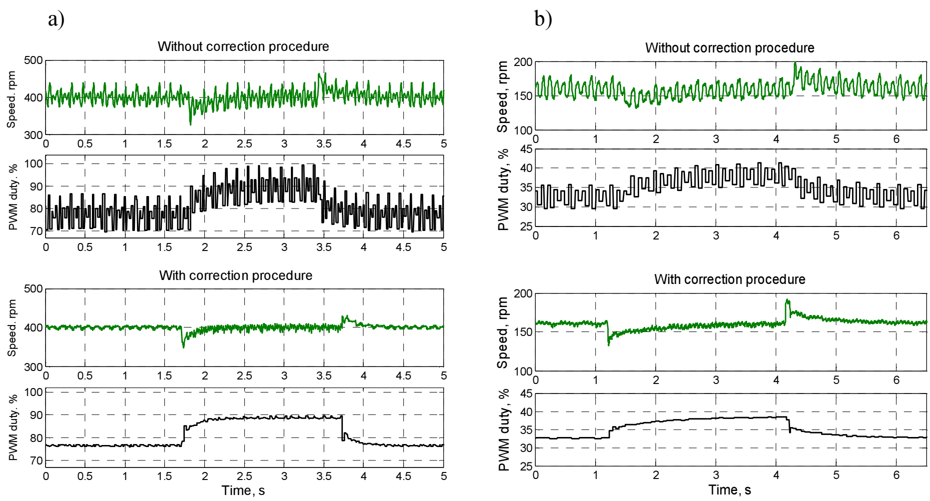


Fig. 9. The waveforms of speed and PWM duty signal coefficient with and without correction with a load rapidly switching on and off for a closed-loop feedback system: a) for 400 rpm commanded speed; b) for 160 rpm commanded speed.

Within the scope of practical verification the measurements of speed data for the rotor of a BLDC motor were carried out (Fig. 9) for the same working conditions, either with a corrective algorithm or without it. The tests were carried out for a 150 Watt BLDC 3 pole-pairs motor with 24 V rated voltage and 500 rpm rated rotational speed and the assumed alignment error δ_m = 5%. The plots of motor speed and inverter's PWM duty ratio, measured at the laboratory station, are presented in Fig. 9.

5. Conclusions

The proposed method of speed calculation with allowances for an error in the alignment of the sensors monitoring the shaft position of a BLDC motor significantly increases the operation features of the drive system with unchanged investment outlays. It seems to be particularly useful for applications using slow-speed motors operating in a closed-loop system, in which the low frequency of speed read-out makes implementation of averaging algorithms impossible.

Even a small error in deployment of one of the motor shaft position sensors causes significant deterioration of the drive operation. Determining the speed with an error of a few percent almost disables the correct layout work, especially at a low rotational speed. The proposed method combines the advantages of a large frequency of speed readings and speed sensor deployment error corrections. This makes the error of speed determination minimal and largely depends on the quality of components used in the measurement system construction and the speed of the microprocessor structure that is used to synthesize the control system. The error of determining the actual rotation speed of the motor using the developed algorithm during laboratory tests does not exceeded 1% of the measured value, regardless of the deployment error of the shaft position sensor.

This method is useful for systems with incorrectly placed sensors, as well as those where the rotational element of the shaft position measurement system was made with an offset error.

References

[1] Goryca, Z., (2012). Controlling methods of BLDC motors. *Prace Naukowe Instytutu Maszyn, Napędów i Pomiarów Elektrycznych Politechniki Wrocławskiej*, Wrocław, 66, 32–47.

[2] Sudhoff, S.D., Krause, P.C. (1990). Operation Modes of the Brushless DC Motor with a 120° Inverter. *IEEE Transacions on Energy Conversion*, 5(3), 558–564.

[3] Kia, M., Rezayieh, K.R., Taherkhani, R. (2011). A novel method for measuring rotational speed of BLDC motors using voltage feedback. *Control, Instrumentation and Automation (ICCIA), 2nd International Conference*, 791–794.

[4] Damodharan, P., Vasudevan, K. (2010). Sensorless brushless DC motor drive based on the zero-crossing detection of back electromotive force (EMF) from the line voltage difference. *IEEE Transaction on Energy Conversion*, 25(3), 661–668.

[5] Sikora, A., Zielonka, A., Kulesz, B. (2012). Impact of Hall sensor positioning on symmetry of BLDC control signals Power Electronics, Electrical Drives. *Automation and motion (SPEEDAM). International Symposium*, 249–252.

[6] Choi, J.H., Park, J.S., Gu, B.G., Kim, J.H., Won, C.Y. (2012). Position estimation and control of BLDC motor for VVA module with unbalanced hall sensor. *Power and energy. IEEE International Conference*, 390–395.

[7] Samoylenko, N., Han, Q., Jatskevich, J. (2008). Dynamic performance of brushless DC motors with unbalanced hall sensor. *IEEE Transactions on Energy Conversion*, 23(3), 752–763.

[8] Alaeinovin, P., Chiniforoosh, S., Jatskevich, J. (2008). Evaluating misalignment of hall sensor in brushless DC motors. *Electric Power Conference, EPEC, IEEE*, Canada, 1–6.

[9] Baszyński, M., Piróg, S. (2014). A novel speed measurement method for high-speed BLDC motor based on signals form rotor position sensor. *Industrial Informatics, IEEE Transactions*, 10(1), 84–91.

[10] Samoylenko, N., Han, Q., Jatskevich, J. (2007). Improving dynamic performance of low-precision brushless Dc motors with unbalanced hall sensor power engineering. *Society General Meeting, IEEE*, 1–8.

[11] Hung, C.H., Lin, C.T., Liu, C.W., Yen, J.Y. (2007). A variable-sampling controller for brushless DC motor drives with low-resolution position sensors. *Industrial Electronics, IEEE Transactions*, 54(5), 2846–2852.